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Interactive aerial-3D-touch holographic light-field display

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ABSTRACT

We present an interactive aerial-3D-touch user interface enabled by a holographic light-field display consisting of a holographic screen and a projector. 3D images are reproduced midair between the screen and a user, and the user can interact with the aerial 3D image. A technique to automatically align the 3D image and gesture sensing is developed to achieve direct-3D-touch interaction. It can be combined with a conventional 2D display thanks to the see-through capability of the volume holographic optical element. Some examples of 3D-touch interactions are demonstrated, such as 3D swipe, grabbing, object moving, and free-drawing. The experimental result of the usability evaluation is also reported.

Keywords: 3D user interface, light-field display, holographic screen, volume holographic optical element, aerial 3D touch, full-parallax, 2D-3D hybrid display, usability test

1. INTRODUCTION

3D is one of the most important aspects of next-generation display technology, including VR, AR, and metaverse applications. The reproduction of highly realistic 3D scenes will be possible with holographic or light-field technology [1,2]. For reproducing high-resolution and deep 3D scenes, however, a spatial light modulator with a huge number of pixels is necessary, and a bit more time is required for the development of such a device. On the other hand, the application of 3D display to the advanced user interface is also expected, in addition to the realistic 3D reproduction, where the requirements for image resolution and quality are less rigorous. Though wearable devices are receiving commercial interest, desktop or standalone displays for a 3D user interface are also awaited.

Touch displays are commonly adopted as 2D user interfaces, and interface with similar usability is highly desirable in 3D as well. As a 3D user interface technology, a gesture interface has been commercialized and adopted in some systems such as gaming, etc. However, the user operations are performed in a separate space from the image contents on the display in a conventional gesture interface as shown in fig. 1 (a). If a 3D display reproduces an image in midair in front of the user as shown in fig. 1 (b), the user can directly touch and manipulate the 3D contents reproduced by the 3D display. This enables a natural and intuitive user interface, just like a human is manipulating a real object in the real world. This work aims to develop a "direct 3D touch" user interface using a desktop or standalone display suitable for digital signage, digital kiosk terminal, and presentation screen.

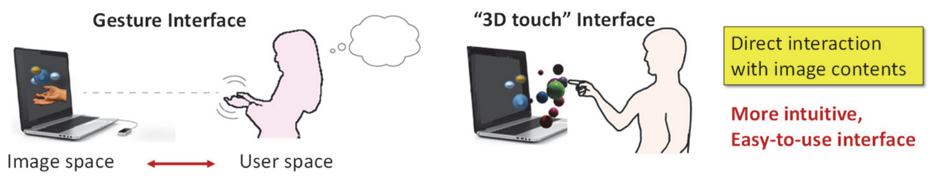

Figure 1. “3D-touch” interface (right) is different from gesture interface (left).

A light-field (LF) 3D display is suitable for the "3D touch" user interface because it reconstructs real images midair between the user and the display screen. In particular, a full-parallax (FP) LF display, which reproduces both horizontal and vertical parallax, is advantageous for suppressing the positional error in the vertical direction that appears in horizontal-parallax-only (HPO) 3D displays. There are various approaches for FP-LF displays, and the direct-3D-touch interface presented in this paper can be applied to an FP-LF display that forms "real" images in the midair between the screen and the user. In our work, a holographic LF display (HLFD) has been developed [3] using a holographic screen made of a volume holographic optical element (vHOE) and a projector. As the vHOE screen is transparent, the HLFD fits the augmented reality (AR) applications or is capable of combining a conventional 2D display as explained in section 3.3.

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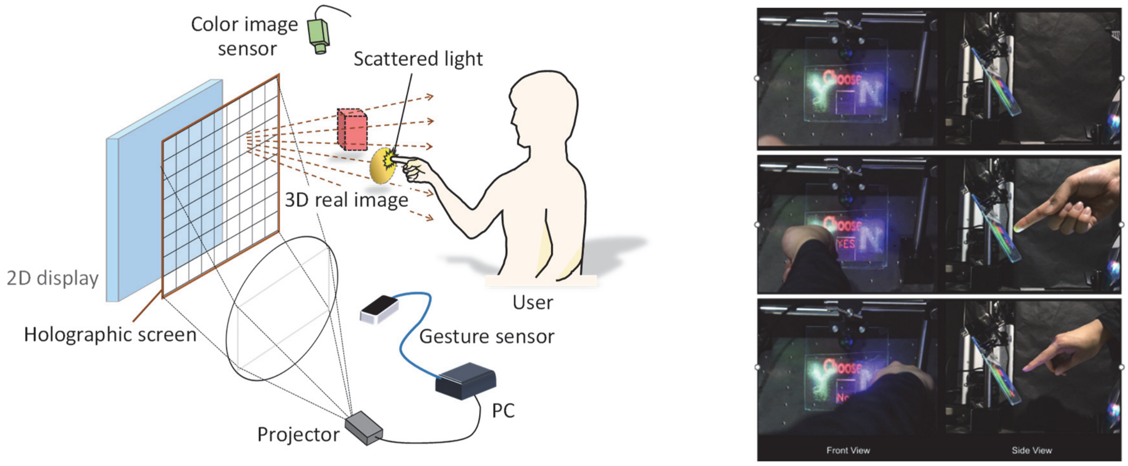
Some user interface systems have been reported that enable direct interaction with 3D images [4,5], but it is not yet clear what kind of 3D interaction will be effective. The demonstration of a direct-3D-touch user interface is still limited. It is an important issue to clarify easy-to-use and attractive 3D user interfaces in the future. Recently, aerial 2D interfaces have become commercialized [6], particularly for non-contact interfaces as anti-infection measures. Although it facilitates aerial interaction, the interface is 2D; the 2D computer screen is reproduced in midair, and the sensing technology is 2D, namely, it is not a 3D interface.

In this work, we develop a prototype 3D-touch display system [3,7,8] aiming to investigate the 3D touch interaction suitable for the future 3D user interface. For this purpose, direct touch 3D gesture sensing is necessary, which means not only gesture recognition, but also the registration between the user's hand and the 3D image contents reproduced by the LF display. For direct touch 3D gesture sensing, this paper introduces a technique that uses the detection of the color of the fingertip and the integration of the off-the-shelf gesture sensing device and the color detection for the registration of the coordinates of gesture sensing and 3D display contents. Some examples of the direct-3D-touch interface are demonstrated using the developed system. Finally, we also present the preliminary experiments on the subjective evaluation of user experience of direct-3D-touch using the developed system.

2. OVERVIEW OF THE PROPOSED SYSTEM

Figure 2 (a) shows the overview of the proposed system. A holographic screen is a vHOE that generates arbitrary LF by the image generated by a projector. The details of the vHOE and the LF generation are described in section 3.1. The image from the projector is geometrically aligned with the vHOE by the method depicted in section 3.2. Based on LF reconstruction, both virtual and real images (the images back and front of the screen) can be reproduced. A user can touch the real image reconstructed midair between the user and screen, though no tactile stimulus is presented. The interaction of the user's hand with the reconstructed image is detected by the color image sensor and an off-the-shelf gesture sensor by the method explained in chapter 4. Figure 2 (b) shows a simple demonstration of the 3D-touch interface. When a user touches the floating image of "Y" or "N," a red text "YES" or "NO" is displayed in the center bottom of the screen [3].



(a) (b)

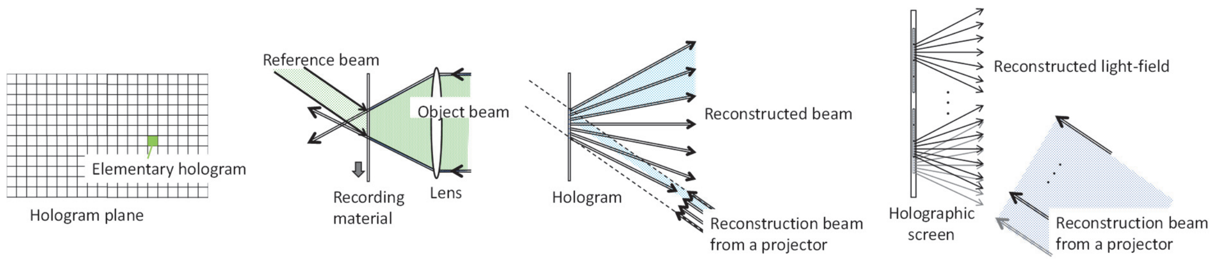
Figure 2. (a) Overview of the 3D-touch interface using a holographic LF display. (b) A preliminary demonstration of the direct-3D-touch interface by detecting the color of the user's fingertip. The pictures in the left and right columns are front and side views, respectively. Top row: the characters "Y" and "N" are reproduced in front of the screen in green and blue, respectively, and the text "Choose" in red is reproduced beyond the screen. Middle row: The touch to "Y" is detected as the fingertip becomes green, then the text "YES" in red is displayed in the center bottom of the screen. Bottom row: The touch to "N" is detected as the fingertip becomes blue, then the text "NO" is displayed.

3. SEE-THROUGH LIGHT-FIELD DISPLAY USING A HOLOGRAPHIC SCREEN

3.1 Holographic screen

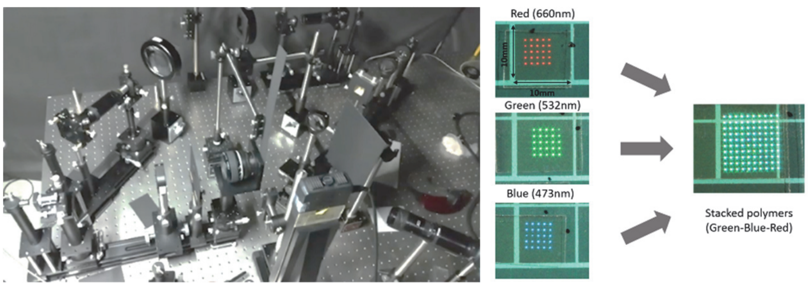
The vHOE screen is a 2D array of small elementary holograms (sometimes called hogels) recorded by the optical system of a hologram printer [9], as shown in fig. 3 (a, b) and fig. 4 (a). The object wave is a converging beam slightly defocused, and the reference wave is a narrow oblique beam incident from the opposite side of the hologram plane. Using a thick recording medium, a volume reflection hologram is recorded. After the exposure of an elementary hologram, the recording medium is moved in a horizontal and/or vertical direction to fill the whole surface of the hologram plane. Each elementary hologram reconstructs diverging beam, as shown in fig. 3 (c), the arbitrary LF can be generated by the parallel beam illumination modulated by the image displayed on the projector [fig. 3 (d)]. Similar HLFD was also reported by using the vHOE recorded using a lens array [10].

In our following experiment, we used photopolymer (Covestro, HX200) for the recording material, the size of each elementary hologram is 1mm, and the screen size is 120mm × 67mm, i.e., consisting of 120×67 elements. When we use a 2K-resolution projector (1920×1080 pixels), 16×16 pixels are assigned to each element, and the light rays to 16×16 directions are reconstructed. For the color LF image, we fabricated the vHOEs with red, green, and blue lasers, and three vHOEs are stacked as shown in fig. 4(b). The vHOE reproduces light of the same wavelength as when recorded based on the Bragg condition.



(a) (b) (c) (d)

Figure 3. (a) The holographic screen consists of a 2D array of small elementary holograms. (b) The optical system for recording each elementary hologram. (c) A diverging beam is reconstructed from an elementary hologram by a parallel beam. (d) By illuminating the whole surface of the hologram plane with the parallel beam from a projector, the LF is reconstructed and modulated by the projected image.



(a) (b)

Figure 4. (a) The optical system for recording the holographic screen. (b) The full-color vHOE is fabricated by stacking R, G, and B holograms.

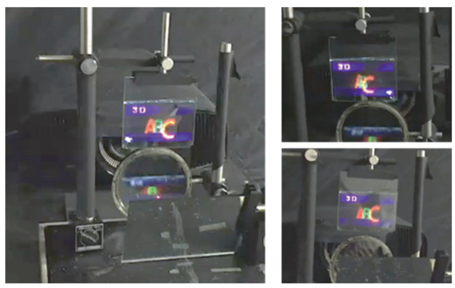


Figure 5. The reconstructed images observed from different directions confirming FP reproduction.

3.2 Registration between the projector and the holographic screen

For the LF reconstruction as shown in fig. 3 (d), the registration between the projected image and the holographic screen is necessary. When using a 4K-resolution projector, an image in 32×32 pixels is projected in an element, and one pixel corresponds to 1/32 ≅ 31 μm, and high-accuracy alignment is required. Since the mechanical alignment is not easy in the projector and screen, we applied an image-based registration technique [11,12]. By projecting some test patterns and capturing the reconstructed images with a camera, the parameters for image registration between the projector and the screen are acquired. Then the image for the projector is pre-distorted to compensate for the geometrical alignment error. Fig. 5 shows the reconstructed image after the registration when using a 4K-resolution projector (Sony VPL-VW500ES) [12]. The reproduction of FP and full-color images on a transparent screen can be confirmed in fig. 5.

3.3 Integration of a see-through holographic light-field display and a 2D display

One of the features of the HLFD is that the screen is transparent, and the reconstructed 3D image can be overlaid on a background real scene. Then the LF image can also overlay on a conventional 2D monitor. 3D images are attractive and suitable for an advanced human-computer interface, but floating 3D images are not stable and unsuitable for presenting detailed information, such as long descriptions and detailed maps. By using the HLFD, the LF display on a transparent screen allows integration of the LF 3D display and a conventional 2D display, such as LCD or OLED display, as shown in figs. 2 (a) and 6. The detailed information is presented on a high-resolution 2D display, and an aerial 3D image for the user interface is reproduced by the LF display. Fig. 7 shows some examples of overlaying a 3D image on a 2D LCD. The visibility of 2D and 3D texts depends on the size of the characters, as shown in fig. 7 (a) and (b), which show the importance of designing the contents for 2D and 3D displays considering the visibility. Fig. 7 (c) shows the example demonstration of the 2D/3D hybrid display. The information about the menu is shown on a 2D display, and the arrow signs for menu selection are shown in midair. Then a user chooses a menu by touching one of the arrows in the air.

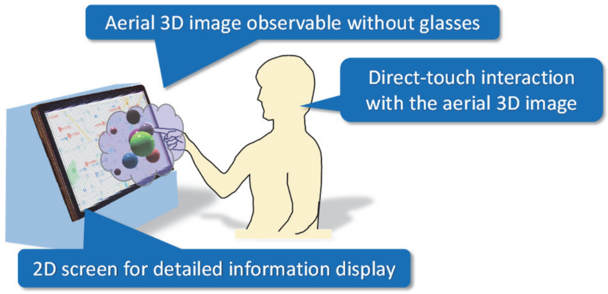


Figure 6. The concept of a 2D/3D hybrid display.

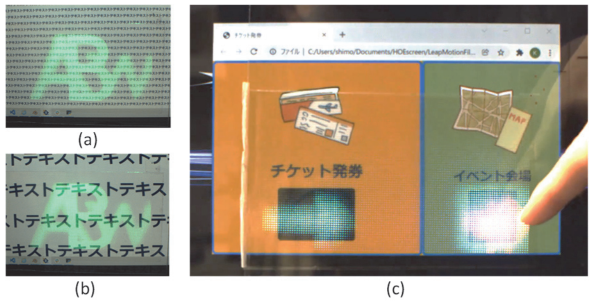


Figure 7. The examples of 2D/3D hybrid display.

4. 3D TOUCH DETECTION

4.1 Touch detection using color

Since a real image is formed in an FP LF display, the reproduced light is scattered by the fingertip if a user touches the aerial image. Then the color image sensor captures the user's finger that scatters the light forming the 3D real image as shown in fig. 2 (a) [3]. If the user touches a yellow object, the fingertip becomes yellow. By detecting the color of the fingertip, the system can recognize which button the user touches. The color of user interface objects, e.g., buttons, needs to be designed such that different buttons can be distinguished by their colors. The demonstration shown in fig. 2 (b) is implemented only using the color detected by the camera. This method for touch detection is simple, and the computational cost is low, although the detection of complicated finger motion and touch detection without showing a button are not possible.

4.2 Finger motion recognition using a color camera

For the detection of more complicated finger motion, we also use the coordinates of the fingertip irradiated by the LF, as shown in fig. 8 (a) [7]. In this case, the camera is placed at the top of the display, and the finger motion in the xz-plane can be detected by the captured image. Note that the holographic screen is set in the xy-plane, and the z-axis is the depth direction. Nevertheless, the motion in the y-axis cannot be detected by the coordinates in the captured image. We design a user interface object with color encoding for detecting finger motion in the vertical direction, as shown in fig. 8 (b). The object is composed of two colors; the top and bottom halves are different colors (purple and green in this example). If the finger is moving toward the upper direction, the detected color changes from green to purple, and if moving toward the lower direction the color becomes purple to green. Figs. 10 (a, b) demonstrate this type of motion detection.

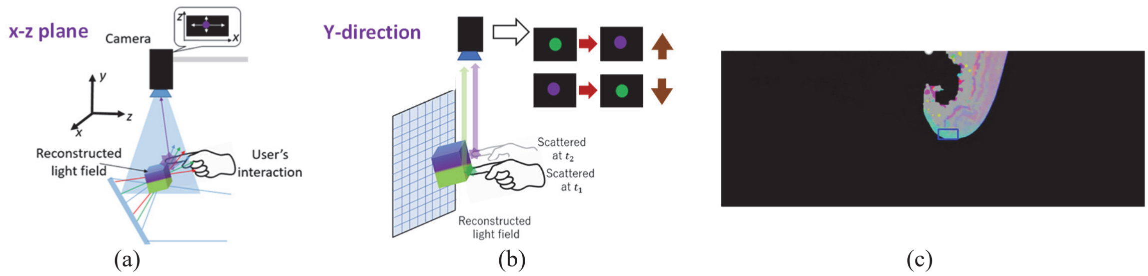


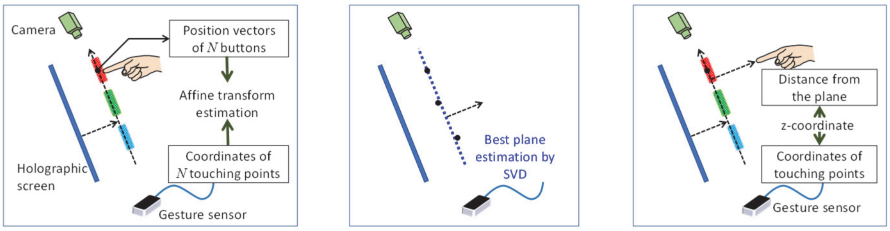
Figure 8. (a) The detection of finger motion in the xz-plane using the coordinates in the captured image. (b) The finger motion detection in the y-direction. (c) An example of the captured image after color normalization. The detected fingertip is marked by a rectangle and the color in the rectangle is used as the color of the button the fingertip is touching.

4.3 Registration of 3D touch with a gesture sensor

Recently, advanced gesture-sensing devices have been commercially available, which are useful for 3D user interfaces. However, an issue that must be solved for 3D-touch sensing is the registration between the image contents reproduced by the LF display and the spatial coordinates detected by the gesture sensor. Direct-3D-touch interface becomes possible only if the 3D image content and the user's gesture are spatially aligned. There was a report in which spatial registration was implemented in the 3D user interface system using an HPO LF display [13]. It required laborious manual geometrical measurements for registration. Moreover, even if achieving registration, a vertical alignment error appears depending on the user's vertical position due to the nature of HPO. This work proposes an automated method for the spatial alignment between the coordinates of the 3D display and the gesture sensor.

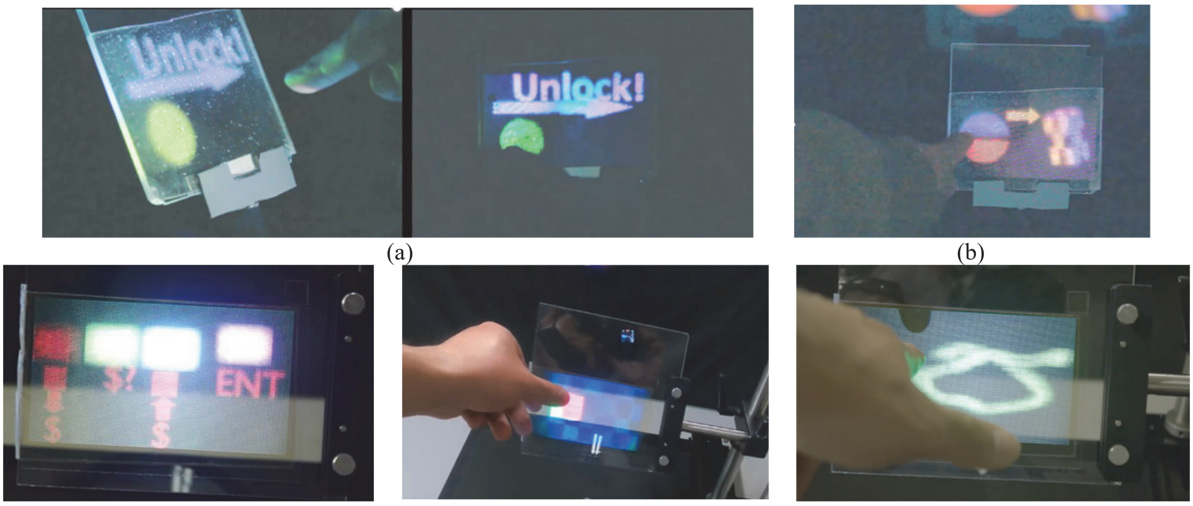
The proposed registration method [8] assumes that the system has some operation controlled by selecting some buttons or menus like the one shown in fig. 10 (c). Touching a button is detected by the color identification method explained in section 4.1. For example, when touching the red button, it is detected by the image captured by the camera, and the pair of the coordinates of the red button in the 3D display and the gesture sensor is obtained. Repeating the button selections that comprise the function of the system, then we have *N* pairs of position vectors in 3D display space and the coordinates detected by the gesture sensor, as shown in fig. 9 (a). As the accuracy of the touching coordinates in the *xy*-plane is fine while the *z*-axis is not, the *xy*-plane is estimated from *N*-pair measurements using singular value decomposition (SVD) [fig. 9 (b)]. Then finally, the *z*-coordinate is obtained as the distance from the *xy*-plane, as shown in fig. 9 (c). As a 3D user interface system mostly has a function operated by pushing some buttons, the spatial alignment can automatically be conducted during the normal system operation.

After the spatial alignment using this process, the gesture sensor data can be used for 3D-touch recognition. The limitation mentioned in sections 4.1 and 4.2 can be overcome by this method, which enables the implementation of more complicated operations. In our experiment, we used a Leap Motion controller, which is suitable for hand gesture recognition based on skeletal tracking.



(a) (b) (c)

Figure 9. The algorithm for finding the geometrical relationship between the 3D image reproduced by the LF display and the coordinates obtained by the gesture sensor.



(a) (b)

(c) (d) (e)

Figure 10. The demonstrations of 3D-touch user interface. (a) 3D swipe, side view and front view, (b) a rotating tetrahedron, (c) ATM-like menu used for the automatic alignment, (d) grabbing and moving a small cube, and (e) 3D free-drawing.

5. DEMONSTRATION

Some demonstrations of 3D-touch interaction are implemented with the proposed method. In addition to the colored buttons shown in fig. 2 (a), the aerial swipe is a simple and easy-to-use operation. As shown in fig. 10 (a), a green ball is floating, a user touches the ball to move toward the left, and then the system is unlocked. In fig. 10 (b), a tetrahedron is rotating on the right of the screen, and the user specifies the direction of the rotation. As the user moves the fingertip to up-down-left-right, the tetrahedron rotates in the specified direction.

Figure 10 (c) is a menu that mimics the automated teller machine (ATM), where a user selects a button from withdrawal, deposit, or balance. After the selection of the menu, the next screen is appeared for selecting the amount of money, etc., and accordingly, the system can acquire a sufficient number of coordinate data in a series of procedures for the algorithm shown in fig. 9. In the demonstration shown in fig. 10 (d), a user grabs a floating cube with the thumb and index fingers and moves the cube to the top-left part of the screen, where a waste box exists, and drops the cube to the box. It is like a game of tidying up the cubes. 3D free-drawing is also implemented as shown in fig. 10 (e). This enables drawing in 3D space with light paint emitted from fingertips.

6. USABILITY EVALUATION

6.1 Experimental setting

To experimentally confirm the significance of the 3D touch user interface developed in this study, we conducted an experiment to evaluate the user experience. In the experiment, we evaluated three systems as follows;

a) Registered system (R): A direct-3D-touch system (registered) in which the coordinates of the fingertip obtained from the gesture sensor are aligned with the coordinates of the 3D image on the LF display using the proposed method.

b) Unregistered system (UR): A general gesture interface system (unregistered) in which the gesture sensor and the LF display are not spatially registered, so the operation is performed in a space distant from the displayed image. During the operation, a white LF sphere indicating the average position of the index finger and thumb is displayed to assist the user.

c) Mismatched system (M): An erroneous direct-3D-touch system, in which random displacements were introduced to the aligned coordinates in the system a). The displacements were obtained from a uniform probability distribution, restricted to half the screen size (screen size: 120 x 67 mm) and 3 mm in the z-axis direction.

Subjects performed the following three tasks shown in fig. 11 and evaluated them by the task completion time (TCT) and a questionnaire shown in table 1 subjectively using a Likert scale;

1) Aerial swipe gesture: This gesture mimics the conventional 2D gesture of unlocking a smartphone screen, where a similar version is shown in fig. 10 (a). Moving the LF sphere to the edge of the screen, the color of the LF sphere changes. The user was requested to swipe the sphere five times before the unlock screen appeared.

2) Box sorting: The system generates three cubic boxes floating in front of the screen, and the user moves them to the upper right corner of the screen. When the boxes reach the goal, they shrink and are erased (simulating absorption). The task was to place the three boxes into the goal.

3) Circle tracing: The real image of the circle was presented in purple, and the trajectory of the user's fingertip was drawn in green. In this task, the user had to trace the 3D coordinates of the purple circle. If the coordinates of the green circle match the coordinates of the purple circle, the task is complete.

Thus, three tasks and three versions yielded nine scenarios for measuring the TCT and the user's subjective evaluation. For each version evaluation, subjects received a tutorial to perform the task using the registered version. They then rehearsed each task only once with the registered version. Subjects were then asked to perform randomly selected nine scenarios (task registration level) and repeated each scenario three times (27 scenarios were evaluated). A beep indicated the start of the test, at which point the TCT was measured. A beep was also played when the subject completed the task.

After the experiment, subjects were asked to complete a questionnaire regarding their subjective evaluation of each task and the system (see Table 1). Subjects rated their experience with the different implementations of the 3D GUI for both registered and unregistered versions on a scale from 0 (totally disagree) to 5 (totally agree). Note that the subjects were not told that there were three possible systems, and they were administered in random order.

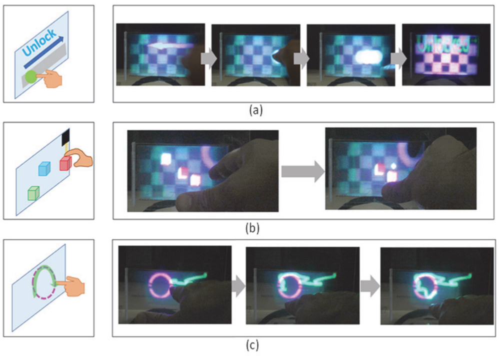


Figure 11. Three tasks used in the experiment. (a) Aerial swipe, (b) box sorting, and (c) circle drawing.

Table 1. The questionnaire used in the subjective evaluation

1. How would you grade the naturalness of the interaction for:	Registered interaction:	very unnatural	0 1 2 3 4 5	very natural
	Unregistered interaction:	very unnatural	0 1 2 3 4 5	very natural
2. How would you grade the difficulty of the interaction for:	Registered interaction:	very difficult	0 1 2 3 4 5	very easy
	Unregistered interaction:	very difficult	0 1 2 3 4 5	very easy
3. How would you grade the fatigue of the interaction for:	Registered interaction:	very exhausting	0 1 2 3 4 5	not exhausting
	Unregistered interaction:	very exhausting	0 1 2 3 4 5	not exhausting
4. How would you grade the novelty of the interaction for:	Registered interaction:	not novel	0 1 2 3 4 5	very novel
	Unregistered interaction:	not novel	0 1 2 3 4 5	very novel

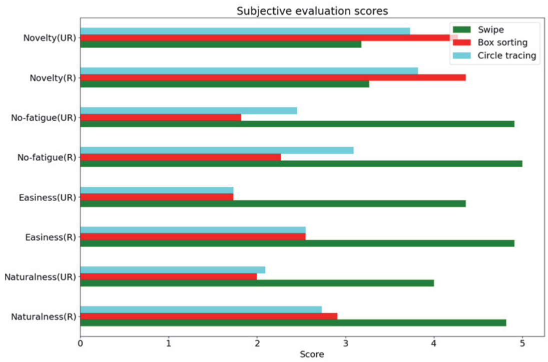


Figure 12. The result of subjective evaluation using the questionnaire shown in table 1.

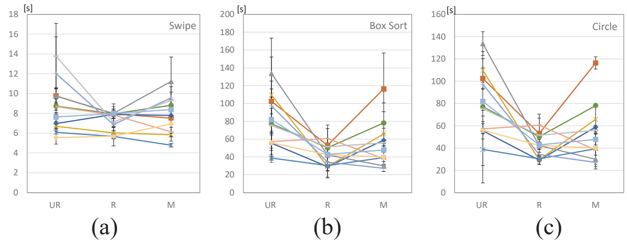


Figure 13. The TCT in the systems R, UR and M for the tasks (a) Aerial swipe, (b) box sorting, and (c) circle drawing.

Table 2. ANOVA result.

	$F(2, 10)$	p
Swipe	3.269	0.0591
Box sorting	9.006	0.0016**
Circle tracing	2.786	0.0856

Table 3. Multiple comparisons

Multiple comparisons after Bonferroni Correction		p
Box sorting	R - UR	0.0055**
	R - M	0.4289
	UR - M	0.1028

6.2 Results

The experiment was conducted by 11 subjects (8 males and 3 females). The results of the subjective evaluation are shown in fig. 12. Overall, it can be seen that the registered system (a) was rated higher. The swipe gesture was the easiest operation, and the rearrangement of boxes was the most novel task, but along with the tracing circle task, it was relatively difficult to perform.

The TCT for each system and each task is summarized in Fig. 13. The unregistered system (UR) has the highest TCT regardless of the task. The difference between the registered (R) and mismatch (M) systems is not very noticeable, but both UR and M systems had a large variation in TCT; the variation in the R system is small in all tasks.

To test the statistical significance of these results, a one-way repeated measures analysis of variance (ANOVA) was performed on 11 individuals (average of 3 observations). The results are shown in Table 2. The results showed that there was a statistically significant difference ($p<0.01$) in the system for the box sorting task ($F(2, 10) = 7.924$, $p = 0.0016$). Therefore, we performed multiple comparisons with Bonferroni correction, where the p-value is multiplied by 3 in this case. Paired T-test for multiple comparisons found that the mean value of TCT was significantly different between R and UR ($p = 0.0055$ after Bonferroni correction). There was no statistically significant difference between the other systems.

Although the experiment introduced here is limited, at the point that the quality of the implemented interface is not high and the number of subjects is not large, it is confirmed that the TCT in the registered system is relatively stable and short, while it becomes longer sometimes in the unregistered system and the system with the registration error. A statistically significant difference was found in the box sorting task. As it was shown that displaying the user's hand in the image is very effective when the image content and gesture are not aligned, comparison with such cases is an important topic for future research.

7. CONCLUSION

This paper introduces an LF 3D display that can reconstruct real and virtual images with the capability of a direct-3D-touch user interface. A user can touch and interact with the 3D image reproduced in midair, like 3D buttons, aerial swipe, grabbing or poking a floating image, and 3D free-drawing. The interactions by the user's hand are detected by the color of the fingertip irradiated by the LF, and the color detection can also be used for the spatial registration between the gesture sensor space and the 3D contents space. Then the application of the off-the-shelf gesture sensing device enables the recognition of more complex gestures by the proposed automated registration technique. Using the prototype system, it is expected to explore more attractive and intuitive interactions achieved by the direct-3D-touch, which mimics human-object interactions in the real world.

The prototype LF 3D display uses a projector and a holographic screen, which is transparent and attractive in AR applications. The 3D-touch capability can be used in other LF displays, particularly in the FP-reconstruction type. But the use of the vHOE screen allows the integration with a 2D display, i.e., a 2D/3D hybrid display, which will open up new possibilities for 3D visual interfaces. As the system does not require special wearing devices for observing 3D images and the intuitive interaction is usable without practice, it will be suitable for public terminals such as digital signages, digital kiosk displays, ATMs, and the user interface for an unmanned store, as the 3D-touch feature provides the ability to prevent contamination and infection.

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