Making Graphical Information Visible in Real Shadows on Interactive Tabletops

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Abstract—We introduce a shadow-based interface for interactive tabletops. The proposed interface allows a user to browse graphical information by casting the shadow of his/her body, such as a hand, on a tabletop surface. Central to our technique is a new optical design that utilizes polarization in addition to the additive nature of light so that the desired graphical information is displayed only in a shadow area on a tabletop surface. In other words, our technique conceals the graphical information on surfaces other than the shadow area, such as the surface of the occluder and non-shadow areas on the tabletop surface. We combine the proposed shadow-based interface with a multi-touch detection technique to realize a novel interaction technique for interactive tabletops. We implemented a prototype system and conducted two proof-of-concept experiments along with a quantitative evaluation to assess the feasibility of the proposed optical design. Finally, we showed several implemented application systems of the proposed shadow-based interface.

Index Terms—Interactive tabletops, Shadow-based interface, Computational display

1 Introduction

FOLLOWING the pioneering works of [1], [2], [3], [4], [5], research and development of interactive tabletops has been changing cooperative working environments. Aimed at realizing intuitive interaction with interactive tabletop systems, previous studies employed gesture or multi-touch user interfaces rather than the traditional mouse and keyboard. However, the sensing techniques for such interfaces suffer from false recognition and delay. Consequently, providing secure collaborative workplaces where users can safely input and browse private information such as PIN codes using interactive tabletops remains difficult.

Another problem occurs when installing interactive tabletops in our daily residential spaces such as a kitchen, dining room, or study room. In particular, graphical information frequently appears inappropriately on the tabletop because inevitably the user's hands or fingers unintentionally touch the tabletop surface or make a predefined gesture during routine activities such as cooking on a kitchen table. Such unintentional visual disturbance bothers the user. However, installing interactive tabletops in residential spaces opens up potential applications such as reading digital recipes on a kitchen table while cooking, checking weather forecasts on a dining table before or after a meal, and web browsing on a study desk.

To solve these problems, we divide the interaction scheme into two independent layers: one for processing the user's input, such as touch or gesture, and the other for displaying graphical information. As a result, even in the case where there is false recognition and delay or where an unintentional touch/gesture is recognized, the interactive tabletop system will not display the resultant graphical information as long as the user does not activate the second layer. This means the second layer must be independent from the touch and gesture inputs. At the same time, the manipulation of the second layer should be easy and intuitive because it is an additional task for a user.

For the second layer interface, we focus on utilizing the shadow-based interface proposed by Minomo *et al.* [6], which completely relies on optical phenomena and does not require any computational processing, making it independent from touch/gesture input. Their system allows users to view graphical information by casting shadows with their bodies on a floor. This is achieved with two overlapping projectors: one projects the original image while the other projects its complementary image. The projected images that are overlaid on the floor become uniform gray owing to the additive nature of light. The shadow-based interface is easy because the user only has to cast a shadow on the surface, and is intuitive because shadows are natural extensions of one's body and part of the body schema [7].

In this paper, we introduce a shadow-based interface for interactive tabletops, which solves the issues regarding the gesture/multi-touch interfaces. In particular, the proposed interface allows a user to browse graphical information by casting a shadow with a body part, such as a hand, on a tabletop surface (Fig. 1). However, a straightforward extension of the previously proposed principle [6] does not fit interactive tabletop systems. In particular, projected images on an occluder (*i.e.*, a user's hand) are visible to the user in interactive tabletop systems because the

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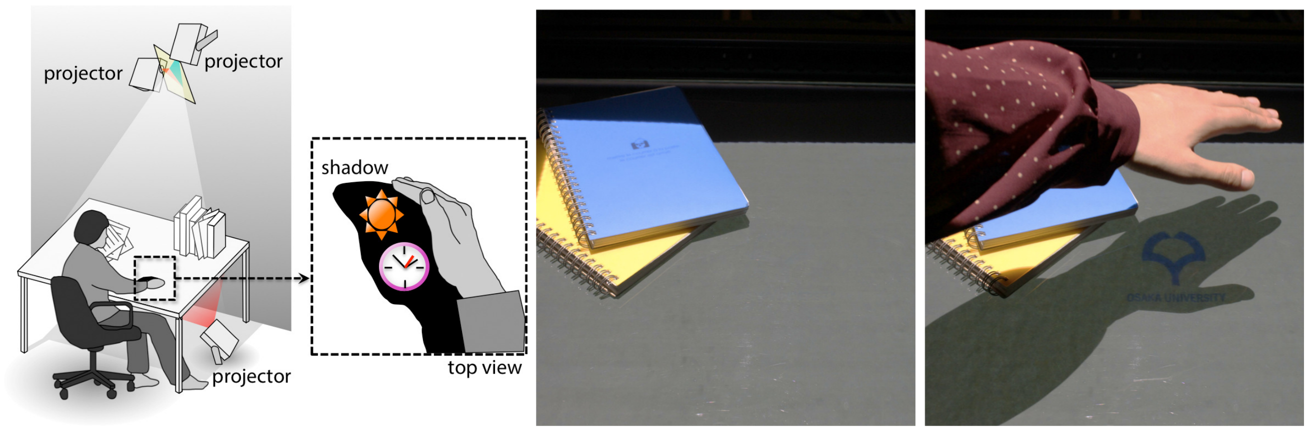


(a) (b) (c)

Fig. 1. Proposed shadow-based interface where a user can browse graphical information by casting his/her shadow on a tabletop: (a) a conceptual illustration, (b) the tabletop surface of a prototype system when no shadow is cast, (c) the same surface when a shadow is cast by a hand (the logo of a local university becomes visible in the shadow area).

distance between the user's eyes and the occluder is short. Therefore, such undesirable visual disturbances need to be removed. Central to our technique is a new optical design that utilizes polarization in addition to the additive nature of light to ensure that the desired graphical information is displayed exclusively in shadow areas on a tabletop surface, and concealed in non-shadow areas. Because the proposed technique only relies on the optical phenomenon and does not rely on any shape extraction processes, hidden graphical information appears in the shadow areas of any complex shapes. We show that the proposed interface can easily be combined with a multi-touch detection technique.

To summarize, this paper makes the following contributions:

- We introduce a shadow-based interface for an interactive tabletop system, in which a user can browse graphical information by casting the shadow of his/her body on the tabletop surface.
- We describe a new optical design utilizing both the additive nature of light and polarization in order to ensure that graphical information is displayed only in the shadow area on the tabletop surface.
- We combine the proposed shadow-based interface with a multi-touch detection technique to realize a novel, two-layered interaction technique for interactive tabletops.

2 Related Work

Most previous studies on interactive tabletops have employed multi-touch [4], [5], [8], [9] or gesture [1], [3] interfaces. For multi-touch interfaces, researchers propose various measurement techniques; for example, one measures capacitance [5], while another measures heat [8]. Currently, owing to its higher scalability, a camera-based multi-touch sensing method using frustrated total internal reflection (FTIR) is widely applied in application systems [9]. For gesture interfaces, most researchers apply camera-based approaches [1], [3].

As described in the previous section, because a tabletop is inherently a public space and above-mentioned sensing techniques inevitably suffer from false recognition and delay, it is difficult to provide a secure collaborative workplace using interactive tabletops [10], [11]. In addition, when installing them in common residential spaces [1], [3], [12], users' unintentional touch/gestures sometimes trigger graphical information to appear on the tabletop. Therefore, we propose a shadow-based interface to control the emergence of graphical information, in which a user can browse graphics by casting a shadow on the surface.

By leveraging the intuitive nature of shadows, researchers have been employing shadow-based interfaces for the manipulation of digital information on large displays located approximately 10 feet away from users (10-foot user interface) [13], [14]. The shadow maintains proximity, whereas perspective enables interaction at a distance. Molyneaux *et al.* also propose a shadow-based interface for their handheld projector system [15]. Although interactive tabletops comprise large displays, little research has been conducted on the development of shadow-based interfaces for them.

In this paper, we introduce the shadow-based interface by Minomo *et al.* [6] to an interactive tabletop system. The reason we focus on this previous study is that it employs real shadows rather than virtual shadows, which are synthesized by detecting the silhouettes of users from images captured by cameras. People have a stronger affinity to their real shadows than virtual shadows, because a virtual shadow is

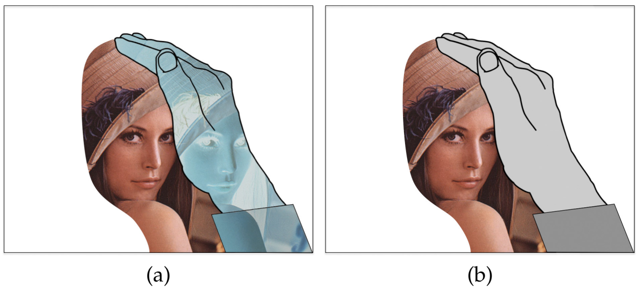


Fig. 2. A technical problem with a shadow-based interface in the context of an interactive tabletop. The original image (*i.e.*, Lenna) is intentionally visible in a shadow area, while (a) the complementary image is inconveniently evident on the occluder (*i.e.*, the hand) when the previous method [6] is extended to an interactive tabletop without any modifications. On the other hand, (b) our proposed technique can conceal it.

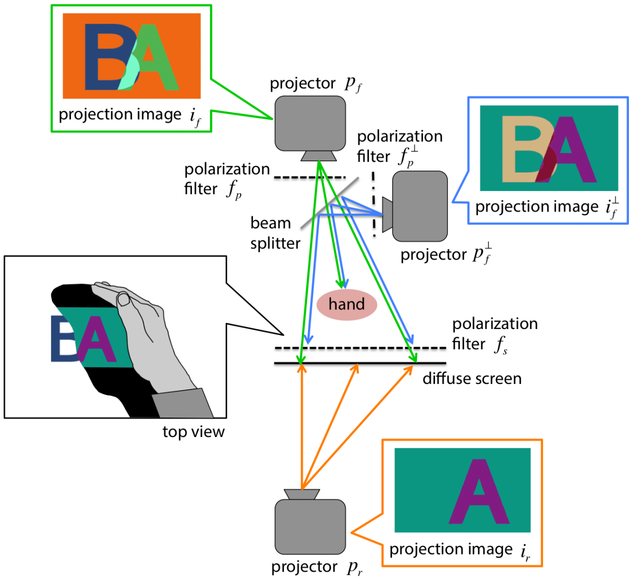


Fig. 3. Optical configuration of the proposed principle.

a discretized image with a relatively low resolution and suffers delay owing to data transfer and image processing [16]. As described above, we apply the technique by Minomo *et al.* with some substantial modifications because it projects the complementary image onto the surface of an occluder, as shown in Fig. 2(a). Therefore, we propose to utilize polarization to cancel this effect for our user scenario where users are close to occluders (Fig. 2(b)).

Note that the concept and first implementation were presented as a poster [17]. Here, we extend this work in several aspects such as generalizing the optical configuration, adding multi-touch sensing technology, and evaluating the image quality of the system.

3 Shadow-Based Interface for Interactive Tabletops

This section describes the principle of our shadow-based interface for an interactive tabletop. First, we explain the proposed optical configuration. Then, we explain how to combine the proposed interactive tabletop system with a multi-touch interface. Finally, we introduce an efficient and precise image correction technique.

3.1 Optical Configuration

We propose a shadow-based interface for an interactive tabletop by which two images can be displayed on the tabletop surface: one in a shadow area ("A" in Fig. 3) and the other in a non-shadow area ("B" in Fig. 3). Note that we can change the image in the non-shadow area to a uniform gray so that graphical information appears only in the shadow area. The system comprises three DLP projectors (p_r, p_f, and $p_f^\perp$), a screen, three polarization filters, and a beam splitter. p_r represents the rear projector, and p_f and $p_f^\perp$ represent the front projectors.

To display the target appearances in the shadow and non-shadow areas, we use two projectors p_r and p_f. Suppose the target appearances in the shadow and non-shadow areas are represented as i_s and i_{ns}, respectively. The sum of the original image i_r and the compensation image i_f, which are projected from p_r and p_f, respectively, can be computed as follows based on the additive nature of light:

$$i_r = i_s, \tag{1}$$

$$i_f = i_{ns} - i_r. \tag{2}$$

Users can view the hidden original image i_r by blocking the light from the front projector p_f. However, at the same time, the compensation image i_f appears on the occluder. Therefore, we use a second front projector $p_f^\perp$ to project the complementary image of the compensation image onto the occluder so that a uniform gray image i_{ug} appears on the occluder. The two front projectors p_f and $p_f^\perp$ share their optical axes by means of a beam splitter. Thus, we compute $i_f^\perp$ (projected from $p_f^\perp$) using the following equation:

$$i_f^\perp = i_{ug} - i_f. \tag{3}$$

When i_f and $i_f^\perp$ are overlaid on the occluder, the resultant image will be a uniform gray and will not disturb the users' activities.

However, the displayed image in the non-shadow area now becomes $i_{ns} + i_f^\perp$. Therefore, we apply polarization filters so that $i_f^\perp$, which is projected from $p_f^\perp$, does not reach the screen. Three polarization filters, f_p, $f_p^\perp$ and f_s, are placed in front of p_f and $p_f^\perp$ and on the screen, respectively. The directions of f_p and f_s are parallel, while that of $f_p^\perp$ is orthogonal to the other two. As a result, the polarized projection image $i_f^\perp$ does not reach the screen because it is blocked by

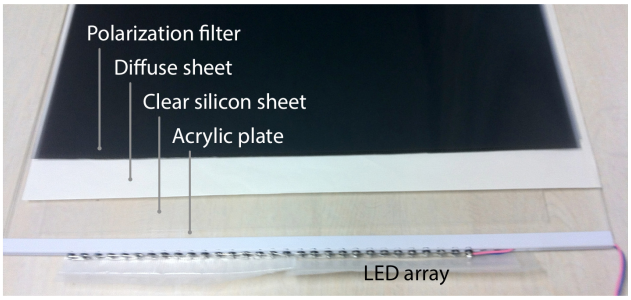


Fig. 4. Tabletop surface combining the proposed shadow-based interface and the FTIR-based multi-touch interface.

the filter, and the displayed image in the non-shadow area becomes i_{ns}.

Consequently, the original image i_r appears only in the shadow area, while the sum of the original and compensation images appears only in the non-shadow area of the screen. Moreover, a uniform gray image appears on the occluder surface.

We can apply this principle when the target appearance in the non-shadow area i_{ns} is set as uniform gray. As a result, the original image i_r appears only in the shadow area and a uniform gray image appears in other areas of the tabletop surface.

3.2 Combining Multitouch Interface

We can integrate the proposed shadow-based interface with a FTIR-based multi-touch interface [9]. An FTIR-based touch sensing system consists of a transparent acrylic plate, an array of infrared (IR) LEDs, and an IR camera. IR light emitted from the LEDs to the acrylic plate from its side strikes the top and bottom surfaces of the plate at a near-parallel angle owing to total internal reflection. When a finger touches the plate, the light at the touched area reflects downward and passes through the acrylic plate, and consequently the IR camera captures the light. Therefore, the touched area can be detected as the bright area in the camera-captured image.

To combine the FTIR-based multi-touch interface, we propose a new tabletop surface configuration consisting of a polarization filter, a diffuse sheet as a projection screen, a clear silicon sheet, an acrylic plate, and an IR LED array, as shown in Fig. 4. Note that the silicon sheet is used to increase the sensitivity of touch sensing. The proposed tabletop surface can be used for both multi-touch sensing and the proposed shadow-based interface. We place an IR camera behind the surface to detect users' touch areas.

3.3 Image Correction Technique

Projected images from each projector must be corrected in terms of color and geometry. Because of the different color spaces among the projectors and the different optical devices (*e.g.*, beam splitter and polarization filters) in the optical path of each projector, we need to match the color spaces of the projectors so that the target images i_s, i_{ns}, and i_{ug} are accurately reproduced on the screen and occluders. Furthermore, the geometric registration of the projected images must be precisely implemented, because the distance between a user's viewpoint and the screen is usually very short in interactive tabletops, and thus the user is sensitive to errors in the geometric registration of overlaid images.

Minomo *et al.* [6] use a special piece of equipment, *i.e.*, a spectroradiometer, to calibrate the system. The calibration is performed at a low spatial resolution and is not efficient owing to manual operation. In this paper, we propose an image correction technique in which we use a standard RGB camera placed above and directed toward the screen to realize fully automatic, quick, and per-pixel correction.

We apply a gray code pattern projection technique for geometric registration. In particular, we obtain the pixel correspondence between the camera and each projector in the system by projecting gray code patterns onto the tabletop surface. These correspondences are used to precisely align projected images from different projectors on the tabletop surface.

The goal of the color correction technique is to compute the input images for the projectors p_r, p_f, and $p_f^{\perp}$ such that the displayed images i_r, i_f, and $i_f^{\perp}$ become the desired images, and consequently the overlaid results become the same as the target images i_s, i_{ns}, and i_{ug}, respectively. We apply one of the color correction techniques investigated in the research fields of projection-based mixed reality and projector-camera systems as summarized in [18], *i.e.*, the color correction technique proposed in [19], which compensates the color differences among the projectors on a per-pixel basis using the camera.

The calibrations of geometric registration and color correction techniques are fully automatic and faster than those in previous studies because the calibrations are performed simply by capturing several projected patterns, which takes approximately 15 s. This image correction technique is also more precise than in previous studies in terms of spatial resolution, because it performs on a per-pixel basis.

Consequently, input colors sent to projectors to display the desired images i_r, i_f, and $i_f^{\perp}$ are generated as follows. First, the desired images are computed by Eqs. 1, 2, and 3 from the target images i_s, i_{ns}, and i_{ug}, respectively. Then, we generate the input colors sent to each projector by applying the color correction technique.

4 EXPERIMENTS

This section shows an implemented prototype system and its proof-of-concept experiment. We also show

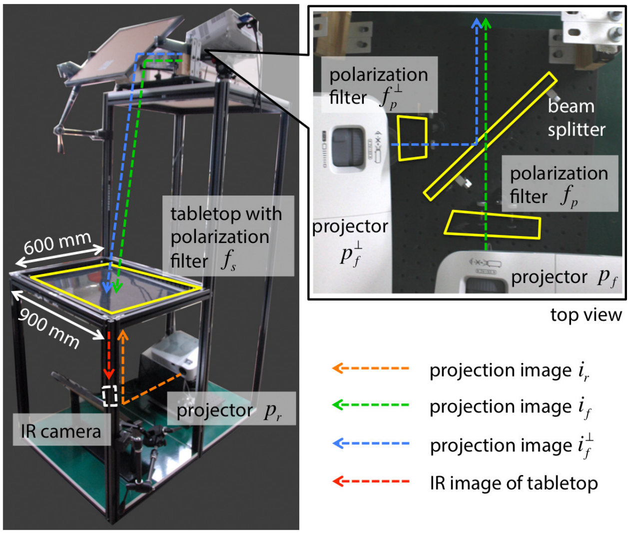


Fig. 5. Prototype system.

a quantitative experiment to evaluate the proposed optical configuration.

4.1 Prototype System

We implemented a system consisting of three DLP projectors (NEC, NP110, 2200 ANSI Lumen, 800×600 pixels), an IR camera (Point Grey Research, Chameleon, 1296×964 pixels, with an IR pass filter), a beam splitter, and three polarization filters, as shown in Fig. 5. The tabletop surface was implemented as shown in Fig. 4. The IR camera was placed behind the surface for multi-touch detection. An additional visible camera (Point Grey Research, Chameleon) was used for the calibration of our image correction techniques described in Secion 3.3. The visible camera was removed from the system after the calibration.

4.2 Proof-of-concept Experiment

We conducted a proof-of-concept experiment using the prototype system. First, we set the target image for non-shadow areas i_{ns} as uniform gray. Figure 6 shows the results when a sheet of paper casts a shadow on the tabletop surface. Figure 6(a) shows the target image for the shadow area i_s, which has various colors and complex textures. Figures 6(b), (c), and (d) show the input images to projectors p_r, p_f, and $p_f^{\perp}$, respectively, which were computed with the proposed technique. From the projection result shown in Figs. 6(e) and (f), we verified that a uniform gray image was displayed in the non-shadow area, while the target image i_s was displayed in the shadow area. We also confirmed that textured images were not displayed on the occluder. However, when we turned off the projector $p_f^{\perp}$ such that only i_r and i_f were projected, graphical information projected from the projector p_f was visible on the occluder, as shown in Fig. 6(g).

TABLE 1
Relation between MOS and human perception

MOS	Description
– 100	imperceptible
– 80	perceptible, but not annoying
– 60	slightly annoying
– 40	annoying
0 – 20	very annoying

Next, we set a set of card faces as the target image for the shadow area i_s and the backs of cards as the target image for the non-shadow area i_{ns}, as shown in Figs. 7(a) and (b), respectively. Figures 7(c), (d), and (e) show the input images to the projectors p_r, p_f, and $p_f^{\perp}$, respectively. Note that these figures are not the projected results. Figure 7(f) shows the projection result when a user's hand casts a shadow. As a result, we confirmed that the backs of cards appeared in the non-shadow area and the card faces appeared in the shadow area, while no textures appeared on the surface of the user's hand.

4.3 Quantitative Evaluation

Because it is important in our technical contribution to cancel the graphical information projected on the occluder, we quantitatively evaluated how close the appearance on the occluder was to the target appearance i_{ns}, which was specifically a uniform gray. We used a high dynamic range visual difference predictor 2 (HDR-VDP-2) [20] for the evaluation. It predicts the perceptual visual difference as a mean opinion score (MOS) between two images. In this paper, MOS takes a value between 0 and 100, where 0 and 100 represent the lowest and highest ratings, respectively. The relation between the MOS value and human perception is determined in Table 1, with reference to [21]. MOS is a widely used subjective measure in the quality assessment of compressed images, which is normally acquired through a subjective experiment where human subjects rate image quality of a distorted image compared to its reference. The HDR-VDP-2 paper [20] shows that the MOS computed by HDR-VDP-2 can predict the subjective image quality more accurately than other metrics including conventional (PSNR) and state-of-the-art ones (MS-SSIM: multi-scale structural similarity index [22]). Because our system is finally used by a human user, it is reasonable to evaluate the image quality by taking into account the perceived image quality. Therefore we applied the MOS computed by HDR-VDP-2 for the evaluation.

The same target image used for the previous experiment (Fig. 6(a)) was used as the target image for the shadow area i_s in this experiment. We placed a sheet of paper above the tabletop surface as an occluder. We evaluated the difference between the uniform gray images and captured the appearance of the paper when p_f and $p_f^{\perp}$ projected images on it. We varied

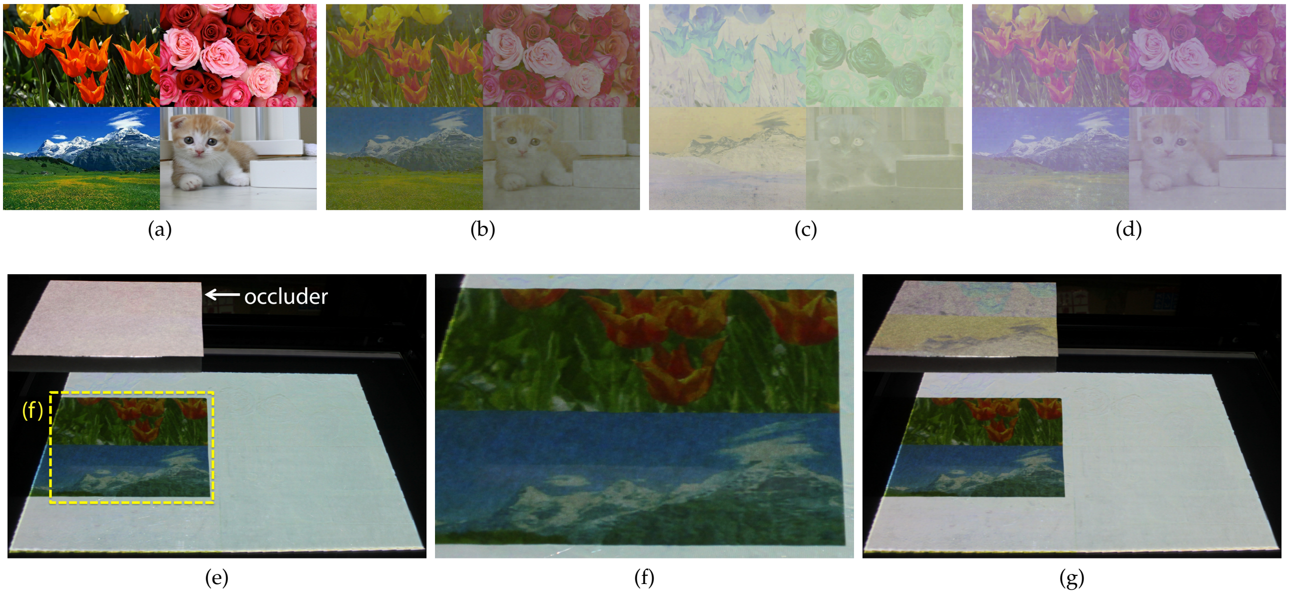


Fig. 6. Proof-of-concept experiment where the target appearance for non-shadow area i_{ns} was uniform gray: (a) the target appearance for shadow area i_s, (b)(c)(d) computed projection images for projectors p_r, p_f, and $p_f^{\perp}$, respectively, (e) projection result when a sheet of paper cast a shadow on the tabletop surface, (f) the magnified view of the shadow area, (g) projection result when $p_f^{\perp}$ was turned off (same as the previous technique [6]).

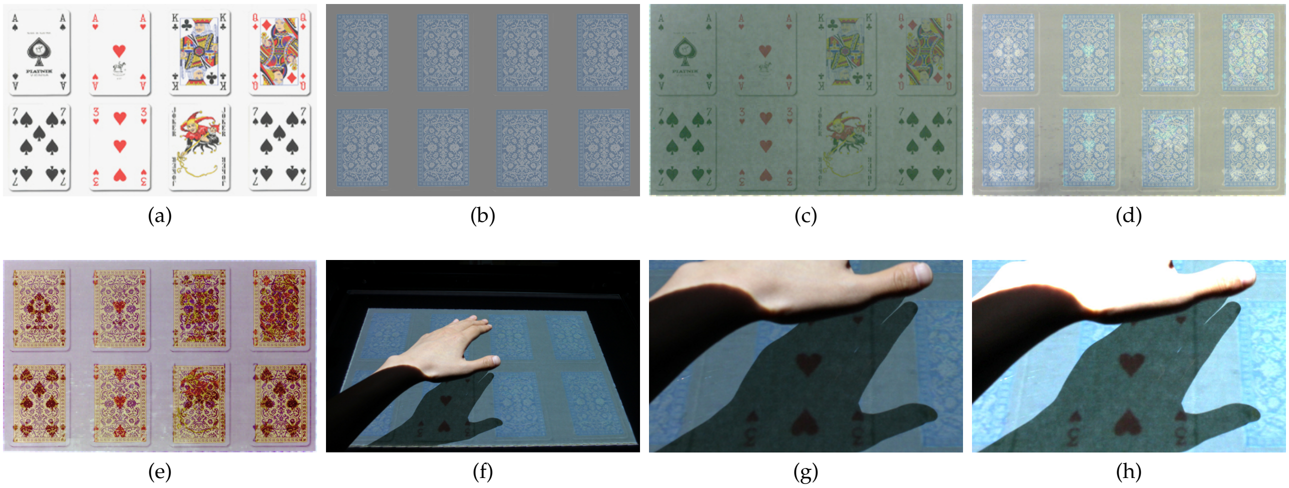


Fig. 7. Proof-of-concept experiment where the target appearance for non-shadow area i_{ns} was the backs of cards: (a)(b) the target appearances for shadow area i_s and for non-shadow area i_{ns}, respectively, (c)(d)(e) computed projection images for projectors p_r, p_f, and $p_f^{\perp}$, respectively, (f) projection result when a hand cast a shadow on the tabletop surface, (g) magnified view of (f), (h) same view with increased brightness.

the distance between the surface and the paper from 0.0 mm to 300.0 mm at 15.0 mm intervals. The result is shown in Fig. 8 and indicates that the MOS values were higher than 90 where the distance was shorter than 195 mm.

The geometric calibration of the system was done by projecting gray code patterns on the tabletop surface from each projector in the system. In addition, although we placed the front projectors p_f and $p_f^{\perp}$ so that they shared the same optical axis, it was generally not possible to perfectly align the axes. Therefore, the two images projected from the front projectors were precisely registered on the surface, but they were slightly misaligned above the surface. Furthermore, the amount of misalignment increased as the distance from the surface increased. Consequently, MOS values degraded as the distance increased. Through this experiment, we confirmed that the cancellation worked well as long as the distance was less than around 200 mm in the prototype system.

5 Applications

We implemented several applications on the prototype system.

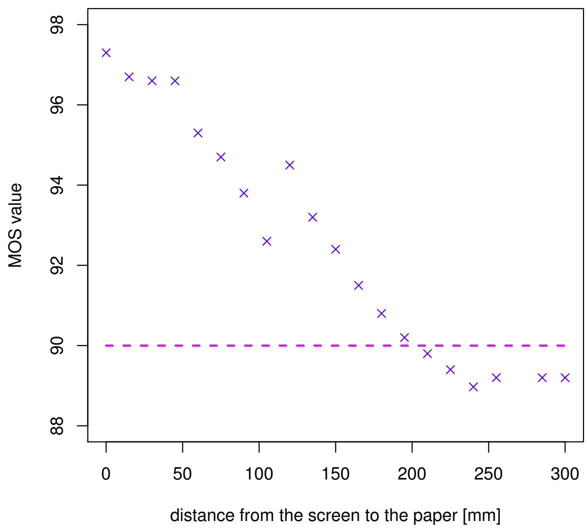
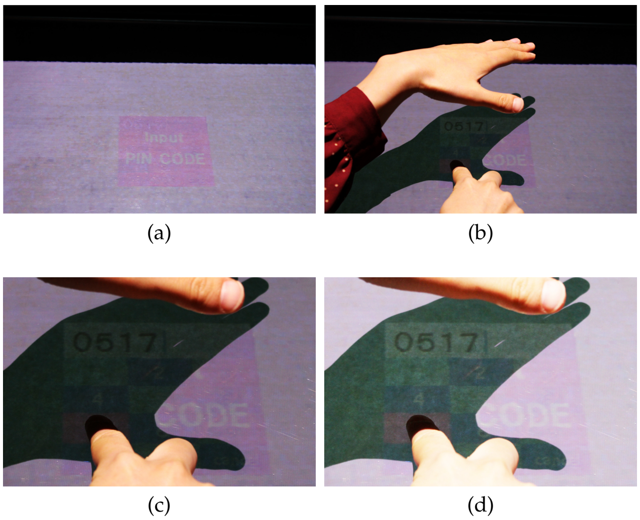


Fig. 8. HDR-VDP2 results with line that shows MOS equals 90.



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

Fig. 9. PIN code input application: (a) a rectangle on which “Input PIN code” was displayed indicated the place for a PIN input widget, (b) the user cast a shadow on the widget to see where the keys are and to input codes, (c) magnified view of (b), (d) same view with increased brightness.

5.1 Secure Interactive Tabletop for Cooperative Work

A tabletop in a meeting space is inherently public, and multi-touch and gesture sensing techniques inevitably suffer from false recognition and delay. Consequently, it is difficult to provide a secure collaborative workplace where users can safely input and browse private information such as PIN codes using current interactive tabletops.

We developed an application system in which users could securely input PIN codes by covering the PIN input widget displayed on the screen in the non-shadow area using his/her hand to cast a shadow in which input buttons appear. This hand shielding gesture naturally provided a visual barrier, and consequently prevented shoulder surfing. Because there was no delay or false recognition in displaying the input buttons, there was no possibility of their appearing at a different place on the screen. Even if the covering hand was removed from the surface by accident, the input button immediately disappeared without any delay because the hand was no longer casting a shadow.

Figure 9 shows snapshots of the application. When a user covered the PIN widget (Fig. 9(a)), the input buttons appeared in the shadow area (Figs. 9(b)(c) and (d)(e) with different exposure). From the figures, we confirmed that a user could input the PIN code “0517” using the input buttons that were visible only in the shadow area.

Private information hiding on interactive tabletops is an issue that has been investigated only in limited ways. Wu and Balakrishnan introduced the notion of public and private spaces for interactive tabletops [23]. According to their definition, users can manipulate objects in the public space and in their own personal spaces, but they cannot control objects that are in the personal spaces of other users. They suggest that a user’s hand gesture, by which the side of the hand is placed on the table, naturally acts as a barrier that blocks others from seeing the displayed information in the private space. However, in this work, users can view information displayed in others’ private spaces if they tried hard enough. On the other hand, our system provides a user with a private space in the shadow area, which the user can create immediately, and can make disappear completely by moving the occluder so that other users cannot view the information. Another approach to private information hiding applies a special optical element to the tabletop surface, which lets light from a certain direction pass through it and that from the other directions reflect on it [24]. Consequently, displayed information visible from a certain direction cannot be viewed from the other directions. In this system, although users do not need to explicitly block their private information by their hands, they cannot move around the table because the private information can be viewed from a fixed location.

5.2 Map Viewer

We implemented a map-viewer application in our system in which the map view was displayed in the non-shadow area of the tabletop surface and the satellite view was displayed in the shadow area. Users could switch between different types of information simply by casting a shadow, as shown in Fig. 10, without having or holding devices such as sheets of paper. Various

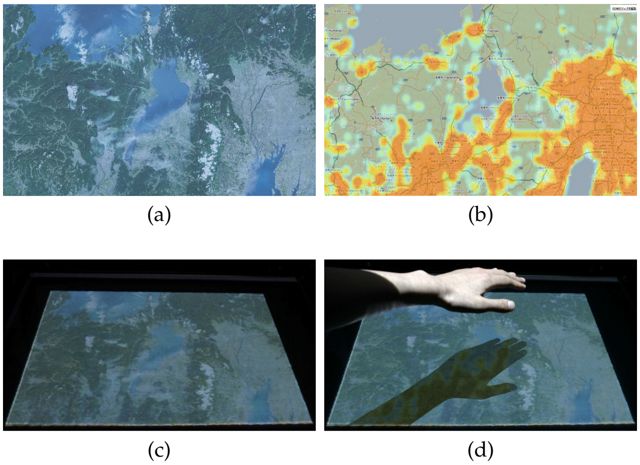


Fig. 10. Map-viewing application: (a)(b) the target appearances for the shadow area i_s (map with visualized radio wave condition) and for the non-shadow area i_{ns} (satellite view), respectively, (c)(d) the actual appearance of the tabletop surface when there was no shadow and when a user's hand cast a shadow, respectively.

image contents could be displayed in the application. For example, we could display an anatomical model whose organs and bones were displayed in the non-shadow and shadow areas, respectively.

Several researchers have proposed interactive tabletop systems that enable users to switch between different types of information using a handheld screen such as a sheet of paper above or on the tabletop surface. Pioneering work about the above tabletop input has been done by Ullmer and Ishii [25]. Their work allows users to view other types of map information than the one displayed on an interactive tabletop surface using a lens-shaped tangible object or a handheld secondary display. Kakehi *et al.* have proposed a special optical configuration for an interactive tabletop and realized a map-viewer application [26]; when a sheet of paper is placed on the tabletop surface, the user can see the satellite view of a map, while the map view is displayed in other areas of the tabletop surface. They have realized this system using the same optical element used in [24]. Izadi *et al.* proposed applying a switchable projection screen, which can be made diffuse or clear under electronic control, to interactive tabletops [27]. The screen can be continuously switched between these two states so quickly that the change is imperceptible to the human eye. It is then possible to rear-project what is perceived as a stable image onto the display surface, when the screen is in fact transparent for half the time. The clear periods may be used to project a second, different image through the display onto objects held above the surface. Cotting *et al.* have proposed a new mobile projection technique where a user can view different types of information on a large tabletop surface within the projected area of a handheld projector [28]. Compared to these previous works where users need to hold a tool for viewing different types of information, our proposal does not require users to hold any additional tools or devices.

6 Discussion

This section discuss the potential applications and limitations of the proposed approach.

6.1 Potential Application

An important contribution of this paper is realizing an interactive tabletop surface without using any recognition techniques, including computer vision. This approach enables a quick (almost no delay) response and does not cause any errors and misrecognitions. Consequently, it does not require any high performance computers, which are normally necessary to build a stable and feasible interactive tabletop system. Thanks to this, our approach is more suitable for map viewer-like applications than other lens-based visualization approaches (*e.g.*, [25]), particularly in a public environment where multiple users simultaneously interact with a large display surface. An example is a digital signage scenario, where a large wall surface is used to display the advertised product and multiple users can simultaneously explore different-layer information (*e.g.*, detailed explanation about the displayed product) at different locations on the surface. In such a case where the number of users is usually large, the conventional lens-based visualization approach needs to simultaneously measure the large number of input manipulations without errors in real-time. To meet this need, the system inevitably becomes costly, as it uses high performance computers and sensors. On the other hand, our approach does not require such expensive sensing equipment. The users of our system can explore the information visible in the shadow areas just by walking around in front of the surface, on which their shadows are naturally cast.

Apart from avoiding shoulder surfers, there is another application field that requires private information viewing on an interactive surface, *i.e.*, interactive education applications using an electronic (or interactive) blackboard. Using an electronic blackboard in a classroom, a teacher can play multimedia educational materials interactively. However, although the teacher wants the students in class to focus on the materials, they tend to be distracted by the teacher's manipulation of the blackboard, *e.g.*, selecting the menu, pushing the play button by touching the displayed widgets, etc. To tackle this issue, previous researchers proposed a pie menu, or a widget that appears only in a part of the blackboard that the teacher can hide from the students with his or her body [29]. Thanks to this function, the teacher can manipulate the multimedia material without showing the manipulation to the

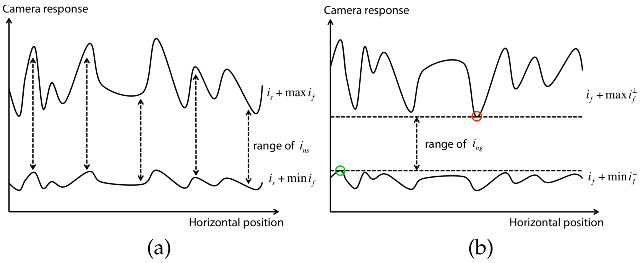


Fig. 11. Limited dynamic ranges of (a) i_{ns} and (b) i_{ug} (green and red circles represent the maximum of $i_f + \min i_f^{\perp}$ and the minimum of $i_f + \max i_f^{\perp}$, respectively).

students. However, because this system uses a touch recognition technique to detect the hiding gestures, it might fail in recognition and cause some delays. This results in an inappropriate situation where the students can see the widget accidentally. We can improve this scenario by applying our approach, by which the teacher views hidden widgets by casting a shadow to manipulate them. Because there is no delay and misrecognition in making the widget visible or invisible, the students would have no chance to see the widgets.

6.2 Limitation

6.2.1 Dynamic Range

Once the desired image is chosen, we compute the projection image using the image correction technique [19] described in Section 3.3. The desired image can be displayed by projecting the corrected image. In theory, the image correction technique provides a displayed result with the same colors of the desired image as long as the desired colors are within the color gamut of the projection system, which is determined by the projector's dynamic range, the reflectance of the projection surface, and environment light. A desired color outside the color gamut needs to be compressed or clipped. Normally, this operation narrows the contrast of the desired image. Considering the human visual system, previous researchers solved this issue using techniques (summarized in [18]) that modify the desired image so that the color gamut of the modified image is within the dynamic range of the projection system, and observers do not perceive the modification.

We use an HDR (high dynamic range) capturing technique in the current system, and assume that the reflections of the projected images do not saturate the camera's response (16 bit floating point value for each color channel) even when they project purely white images. However, the intensity ranges of i_{ns} (the target appearance in the non-shadow area) and i_{ug} (a uniform gray image) are limited as follows. From Eqs. 1 and 2, we can derive $i_{ns} = i_s + i_f$. Therefore, once i_s (the target appearance in the shadow area) is decided, the intensity range of i_{ns} is determined, which is from $i_s + \min i_f$ to $i_s + \max i_f$, where $\min i_f$ and $\max i_f$ represent purely black and purely white intensity values of i_f, respectively (Fig. 11(a)). In the same manner, the intensity range of i_{ug} can be determined once i_f is decided. Because i_{ug} is a uniform gray image over the projection area, every pixel in i_{ug} should take the same intensity value between the maximum of $i_f + \min i_f^{\perp}$ and the minimum of $i_f + \max i_f^{\perp}$, as shown in Fig. 11(b).

6.2.2 Ambient Illumination

The image correction technique applied in the current system considers the effect of ambient illumination (see [19] for details). Therefore, we can compensate for the effect and display the desired appearance on the tabletop surface under ambient illumination. However, a significantly bright ambient illumination leads to serious contrast degradation in the displayed results. In such cases, we can improve the image quality of the displayed images in such cases by applying one of the tone mapping techniques that are usually used for compressing an HDR image to fit the dynamic range of a normal LDR (low dynamic range) display, while preserving its perceptual impression (details are summarized in [30]). The investigation of the effect of significantly bright ambient illumination on displayed results and how tone mapping improves their image quality are issues we plan to tackle in our future work.

6.2.3 Fatigue

In the proposed system, a user would hold his or her arm above the surface to cast a shadow on the tabletop surface. Maintaining this posture for a long time inherently leads to a certain amount of fatigue. On the other hand, one could cast a shadow also by putting a part of the hand or arm on the surface for support. Such a posture seldom leads to fatigue. However, the area of the shadow thus created is relatively small. Therefore, it is preferable to design our interface so that graphical information should be small enough to view by casting a shadow with the latter posture.

7 Conclusion

We introduced a shadow-based interface for interactive tabletops. We explained the principle of the proposed interface, which allows a user to browse graphical information by casting the shadow of a body part, such as a hand, on a tabletop surface. The most important technical contribution in this study is that the proposed optical design utilizes polarization in addition to the additive nature of light in order to ensure that the desired graphical information is displayed only in the shadow area on a tabletop surface. We combined the proposed shadow-based interface with a multi-touch detection technique to realize a novel interaction technique for interactive tabletops. We implemented a prototype system and conducted two proof-of-concept experiments. In these, we confirmed that our technique successfully concealed the graphical information on surfaces other than the shadow area, such as the surface of the occluder and the non-shadow area on the tabletop surface. Through a quantitative evaluation, we confirmed that the cancellation worked well as long as the distance was less than around 200 mm in the prototype system. We also implemented several application systems and confirmed the high applicability of the proposed shadow-based interface.

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