Visibility Control using Revolving Polarizer

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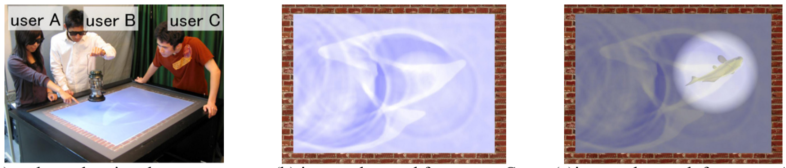

(a) a photo showing three users playing with an application.
(b) image observed from user C
(c)image observed from user A and B

Figure 1: An example of entertainment application.

Abstract

We propose a novel display technique that presents information with different visibility to multiple users. The system projects information on a screen through a revolving linear polarizer in front of the projector, and it shows information through another polarizer in front of the user's viewpoint. The brightness of the observed information is reduced according to the relative angle of the polarization axes between the two polarizers, thereby allowing applications to provide information at different arbitrary levels of brightness for each user by controlling the angle of the revolving polarizer. By measuring the brightness values of an implemented prototype, we demonstrate that the proposed method is effective. We then describe several example applications showing the benefit of the technique: concealment and classification of information for specific users. In addition, we describe an example of an entertainment application and a tangible polarizer on display.

1. Introduction

People engaged in communication/collaboration often meet at a physical location to talk and play. In more than a few cases, they use large displays like projected screens or plasma displays to share information effectively. Such displays sometimes appear on the wall [7, 28], but recently, display table systems have also become popular [2, 14, 20, 24]. Moreover, many techniques and interfaces have been proposed to support group work using such display systems.

When several users work or play together in a co-located face-to-face setting using a shared display, it is often necessary for users to conceal parts of their individual information from some users while at the same time sharing that information with other users [3]. However, information on a conventional large display is visible to the public and presented to all users in the same way. Although some systems and techniques have been proposed to try to adequately deal with personal information in a public space, there are still limitations to the proposed solutions [8, 11, 13]. Limitations include, for example, restrictions of available display area, difficulties experienced by the users in understanding the relationship between different pieces of information, restrictions against users moving their viewpoints freely, and so on. In addition, these systems can deal with only binary visibilities: visible or invisible. If a display can change visibility continuously by controlling brightness, it can be used for other purposes like classification of digital contents.

In this paper, we propose a novel display technique that provides different levels of visibility of digital content to different users who share the same display, by controlling the brightness of the projected information. To achieve this, we use a revolving linear polarizer in front of the projector. Although the polarization is popular and used on digital tables (e.g., [15]), they are not for the controls of the information visibilities to different users. Figure 1 shows an example of entertainment applications on a tabletop display utilizing the proposed method. In this scenario, the image observed by each user is different. Users A and B, who are wearing polarized glasses can see fish underwater but user C, who is not wearing any glasses, can see only the surface of water. We first describe how our system works and how it solves the problems mentioned above. Then, we describe the principle of the proposed method, followed by an assessment of the practicality of the proposed method by measuring brightness on an implemented prototype. Finally, we describe example applications adopting the method to highlight its benefits.

2. Related work

This section discusses requirement of the visibility control on shared displays by introducing previous work.

2.1 Sharing a large display with several users

In light of the increasing demand for using large displays in group activities, there is much literature devoted to devices for collaboration [2, 14, 20, 24], systems incorporating large displays [7, 23, 28], design

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guidelines [4, 17], visualization techniques[27], and so on.

When we hold discussions using digital content visible on a display, this information can be categorized into public information or private information. Public information is what may be observed by all participants; on the contrary, private information is what should be observed by only one or a subset of the users. Consequently, private information cannot be displayed on shared large displays because it is equally revealed to all of the users viewing the display.

To deal with the need to simultaneously show both public and private information, some systems use small personal displays like PDAs for private information and large displays for public information [13, 16, 22]. Such systems allow users to interact with information and transfer it seamlessly between connected displays; however, it is sometimes quite difficult for the users to comprehend the relationship between the information items across the displays [29]. Moreover, if a user wants to share his/her private information with particular users, he/she has to explicitly send or move this information to them. Even though the interaction mechanism involved might be intuitive to the user, the action can disrupt the spatial relationships between information pieces and thus inhibit collaboration. Therefore, it is important to show both public and private information simultaneously without having to spatially move them around. One way to accomplish this is to show both information simultaneously on the same display surface and permit each user to individually control the visibility of the information.

When dealing with many different kinds of information objects (e.g., icons), it is necessary to classify them into several groups to make tasks easier and more comfortable. In the case of group work involving multiple users, classification is often made, for example, by using a public canvas and private toolboxes. All of these objects are classified by their positions, orientations or colors, which are determined according to their owners or the kind of tasks performed [10, 18]. However, if each of the multiple users has a different classification task, the situation becomes complex. In this case, a kind of dynamic filter that passes/cuts particular parts of information according to the users' individual demands would help their work. Therefore, we consider a classification method in which particular objects can be observed by only one, or a subset, of the users in a shared space.

2.2 Dynamic visibility controlling displays

Here, we review systems in which visibility of information is controlled for each participant sharing a display.

Lumisight Table is a square tabletop display that can show different information to the users sitting on each side of the table [11]. The display surface consists of several special films on which the information projected from a certain direction can be observed only from specific directions. Four projectors directed to each side, located inside the table, project four different images to four individual users. Parallax barriers, normally used in stereoscopic displays, are used to show different pixels of the same surface depending on the user's viewpoint. They can be used for the display surfaces that show different information to different users too [19]. These systems, however, impose the limitation that users cannot freely move their viewing position. If their viewing positions move, they see other users' information.

Hua et al. [6] proposed a collaborative system in which the users can freely move their head positions and observe individual information. In their system, a projector mounted on each user's head projects information to the retro-reflective surface on which the light is reflected only in the direction of the light source. This allows each user to observe only information from the projector on their head. However, this requires placing somewhat heavy hardware on the user's head, which must also be wired for power supply. Even if using small projectors like pico-projectors [12], they are still obstacles. SharedWell provides both public and private information with users moving around the table [8]. It consists of a normal display and a display mask that has a hole at its center. Each user observes a part of the display through the hole and uses that part as his/her private area. The overlapping sections of two or more private areas are used as the shared public areas. Although the users easily understand the relation between public and private information, they have to be in close proximity to create the public area, and as a result, they cannot collaborate over a large space.

There are systems that provide two different types of information to users separately, regardless of their viewpoints. Some systems display two images, one for each user in a time-sequential manner on the display [1, 21]; these system show images to one user who wears synchronized LCD shutter glasses, and show other images to the other user. It is difficult to adapt more then three users because of the flicker, and these show both images to the other users who do not wear the glasses. Yerazunis et al. [30] used a masked image and a private image that is displayed in time-sequential manner. The users wearing the LCD glasses observe the private image and the users without glasses observe the masked image. However, the system cannot flexibly control visibility; for example, it cannot change a certain user's private image to another user's private image. Besides, LCD glasses need synchronization signals which can be blocked when gesturing.

3. Multi-level visibility control system

This section describes outlines of our proposing system's benefits.

Our review highlights two main challenges in designing dynamic visibility control – the ability to control information visibility to multiple users simultaneously on the same surface without limiting the viewpoints' movements, and allowing the visibility control of each part of the information to be performed independently in order to show both public and private information. Moreover, if the visibility is controlled continuously, we can visualize the classification of information (for example as public and private) by assigning a different visibility to each part of information. In addition, statuses of the visibilities are desired to be known and changed intuitively by the users so that the users can easily control the visibility of the information. For example, they can select to show or hide certain information for the other users.

To overcome these challenges in a collaborative tabletop setting, we developed a tabletop system which allows multiple users to observe digital contents on the tabletop surface by varying the levels of brightness to control what they see. Figure 2 shows the implementation of the system. The digital contents on the tabletop projected projector 1 are polarized by a polarizer, labeled *projector-polarizer*, located in front of the projector. The users wearing polarizer glasses, labeled *eye-polarizer*, observe the digital contents with the brightness depending on the relative polarizing angle between the projector-polarizer and eye-polarizer. Therefore, by standing at different locations around the tabletop, each of the multiple users observes the same content with different brightness. If the observed brightness for a certain user is low enough, the content is invisible to him/her, but visible by the other users at different locations. In addition, the system can control the observed brightness by revolving the projector-polarizer. Here we assume that the projector does not have inherent polarization, such as e.g., DMD projectors, not LCDs.

We can realize more elaborate visibility control by using projector 2 projecting non-polarized content. The content projected from projector 2 is observed by all users whether or not they wear polarized glasses with same brightness regardless of their direction around the display. Combination of the contents from the two projectors produces various representations of information. For example, the content projected from the projector 2 can be used as public information while the content from the projector 1 can be used as private information. Also, if content from the projector 1 covers and conceals content from the projector 2, the content from projector 2 is concealed against the users without glasses. Only users wearing polarized glasses and stand at appropriate directions can observe the content from the projector 2 because the brightness of the content from the projector 1 is adequately reduced. By combining these controls, we can assign different visibilities such as public for all users, hidden from

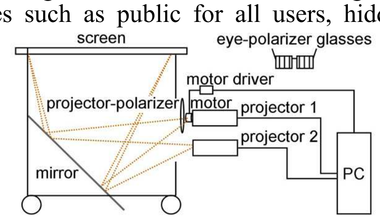


Figure 2: Design of implemented system.

certain glassed users, or shown only for certain glassed users to each part of the display independently.

Moreover, the brightness of the content can be continuously controlled so that the system can show the content from the projector 1 with any brightness to specific users wearing the glasses. Therefore, for example, if content from projector 1 is reduced to one tenth, while content from projector 2 is reduced to half at a certain user's eye-polarizer, they are recognized as darker and brighter parts. This can be used as a classification of information which only specific users can observe.

This system overcomes the most of the challenges mentioned above. However, users have no way to know the direction of the polarization and have no means to control it intuitively. As an example overcoming this, we can introduce tangible objects on the table to control the direction of the polarization by hand.

4. Visibility control using revolving polarizer

In this section, we describe physical principle of the visibility control using the revolving polarizer used in our system and experiment to confirm its feasibility. Then its availabilities are discussed.

4.1 Principle

Figure 3 shows the principle behind visibility control using revolving polarizers. A projector casts information through the projector-polarizer to a screen that does not break the polarization. The projector-polarizer is attached to a rotating motor that turns around an axis parallel to the direction of the cast light. The gratings on the screen and the polarizers in Figure 3 represent the polarizing axes for explanation (These are invisible in reality). If a user observes the projected information through the eye-polarizer, the brightness of the observed information is reduced according to the relative angle θ between the polarization axes of the eye-polarizer and the projected information.

According to Malus' law when a perfect polarizer is placed in a polarized beam of light, the intensity, I, of the light that passes through is given by

$$I = I_0 \cos^2 \theta \qquad (1)$$

where I_0 is the initial intensity, and θ is the angle between the light's initial axis of polarization and the axis of the polarizer [9]. The above equation governs the reduction of the brightness of the projected information at the projector-polarizer and the eye-polarizer in Figure 3.

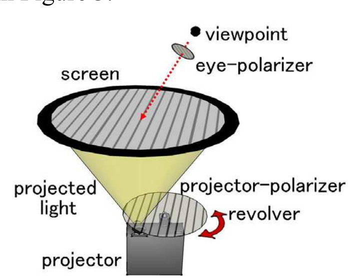


Figure 3: Principle.

4.2 Measurement of brightness

If perfect polarizers are used, the property of the system is expected to completely follow the equation (1). However, in a practical situation, real polarizers are not perfect and the transmission is not exactly zero even if the two axes of polarizers are orthogonal due to effects of refraction, birefringence, and so on. Therefore, it is necessary to measure the brightness property of the actual system.

To measure the brightness property of the system, we measured brightness when a white uniform circle was projected at the center of the screen from projector 1 and then calculated the ratio of reduction after the light passed through the eye-polarizer under the following two conditions:

1. At all observing directions around the table while the polarizing axis of the white circle is constant by fixing the projector-polarizer
2. At a fixed observing direction, while the polarizing axis of the white circle is changed by revolving the projector-polarizer

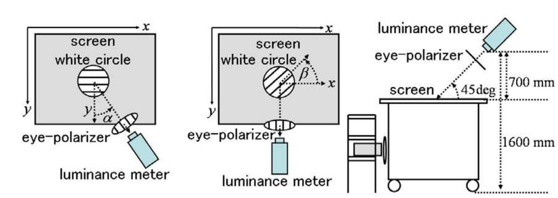
The observing direction represents the direction from the center of the white circle to the position of the luminance meter. Figure 4(a) shows the arrangement of the apparatus in condition 1. Here, only the projector 1 in Figure 2 is used for the measurement. The polarization axis of the white circle is always parallel to the x axis and the polarization axis of the eye-polarizer is always vertical. We define α as the relative angle between the y axis and the observing direction.

We measure the brightness of the center of the white circle using a luminance meter at a height of 700 mm from the display (1,600 mm from the ground) and *45 deg* from the center of the white circle upward (see Figure 4(c)). This position corresponds to the viewpoint of an average Japanese person standing on the longer side of the prototype.

We measure the ratio r of the observed brightness through the eye-polarizer to the observed brightness without the eye-polarizer every *15 deg* of α. If r is corresponded to the theory completely, r is given by

$$r = \cos^2(90 - \alpha) \tag{2}$$

Figure 4(b) shows the arrangement of the apparatus in condition 2. The observing direction is always parallel to the y axis, and the polarization axis of the eye-polarizer is always vertical. We define β as the relative angle between the x axis and the polarization axis of the white circle according to the projector-polarizer. The other configurations of the apparatus are the same as in condition 1 as shown in Figure 4(c). We measure the ratio r every *15 deg* of β.



(a) top view in condition 1 (b) top view in condition 2 (c) side view

Figure 4: Arrangement of apparatus for measurement.

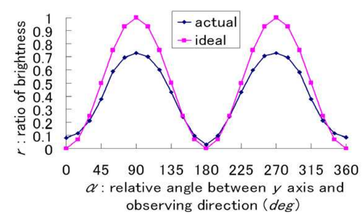
4.3 Result and discussion

Figure 5(a) shows the variations in r according to α under condition 1 and ideal variations derived from equation (1), while Figure 5(b) shows r according to β under condition 2. The result agrees with ideal values in shape, but not in magnitude. The local maximum and minimum values of r are not the ideal values of *1.0* and *0.0*. We assume that the eye-polarizer introduces some loss of r regardless of the polarization axes, and the polarization is broken slightly in the air and on the display surface although the material of the screen was carefully selected. This result means that when an application tries to conceal information from a certain user by preventing the light at the eye-polarizer, the information might be slightly revealed. However, in real cases disturbances like fluorescent lights or random reflections on the wall will conceal the dark information. Figure 6 shows the effect of a room lighting as the disturbance. We project an image shown in Figure 6(a) and take the screen's photos through the eye-polarizer in the situation where β equals *0 deg*. Figure 6(b)(c) are the photos in each case of the room lighting on and off.

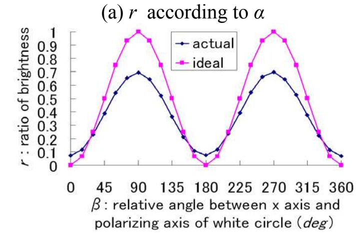
Weber's law says that the minimum intensity of brightness ΔI that a person can recognize in the disturbance intensity I is given by

$$\Delta I / I = k \quad (\text{k: constant}) \tag{3}$$

Therefore, the application can conceal the projected information if the brightness of information is reduced to less than kI in the disturbance I.



(a) r according to α



(b) r according to β

Figure 5: Result of measurement.

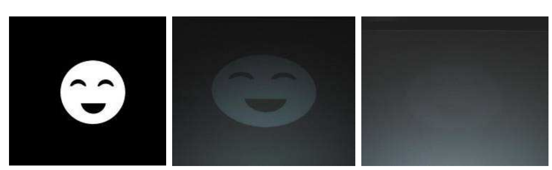

(a) projected image (b) user's view in darkness (c) user's view under light

Figure 6: Effect of disturbance.

5. Example representation

We now describe a suite of productivity and entertainment applications that can potentially benefit from such a tabletop system. The goal here is to highlight usage scenarios of such a system rather than build a complete system.

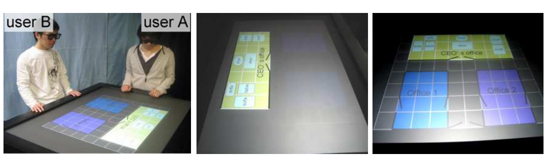
5.1. User-specific concealment of information

Studies of group collaboration have shown that often groups come together to discuss a group activity and then break apart to carry out individual tasks [25]. Our multi-level visibility control system can aide users in such situations.

Particularly, in large design projects where multiple users are working on different layers of a design project (for example, user A is designing the interiors of the CEOs office while user B is working on the design of the corridors on the same floor) it is often useful for users to work together on a shared surface so they can maintain awareness of others activities but at the same time it is also useful for both users to be able to focus on their segment of the activity without being disturbed by external factors.

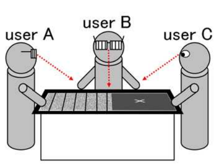
In the example above, the system can filter out information about the corridors to user A so he can focus on the CEO's office but at any moment if he wants to know how user B is choreographing the corridor spaces he can get an overview of the status of the design by removing his polarizer glasses.

Figure 7 illustrates this simple example of concealment. Two users standing along adjacent edges of the table wearing eye-polarizers look at the screen. Projector 2 only projects information that is relevant to user A. The entire floor plan is projected from projector 1 and has a polarizing axis which is parallel to the user B's eye-polarizer. As a result, user A only observes information projected from projector 2 (images from projector 1 are filtered out). Conversely,

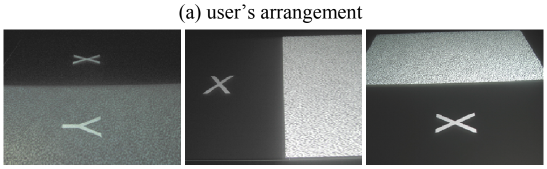


(a) overview (b) user A's view (c) user B's view

Figure 7: A typical example using prototype display.



(a) user's arrangement



(b) user A's view (c) user B's view (d) user C's view

Figure 8: Users' views in example using noise image.

user B observes all the content on the display. If the application turns the polarization axis of the projected information by *90 deg* by revolving the projector-polarizer, user A observes all information and user B observes only the corridor.

This control can be used in cases where a user wants extra information about parts of the shared space but projection of this extra information might disturb other users. So we can use the idea of the concealment to provide augmented information for a particular user. This could be the case of shared single display groupware applications where users are working on the same area but on different tasks.

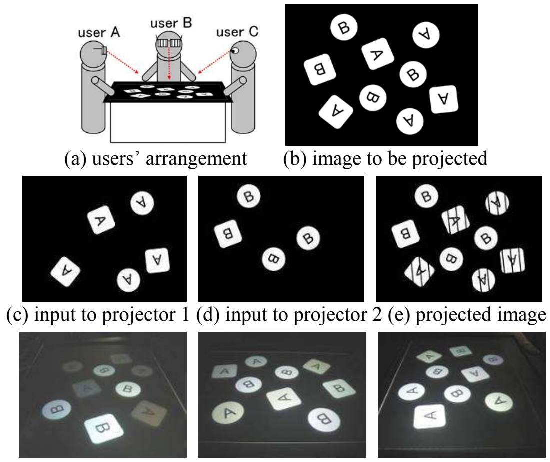
The above example can conceal information from only the users who wear the eye-polarizers. However, in some situations (as in a strategic negotiation tasks [29]) we might need to conceal information from users not wearing eye-polarizers. This can be achieved by projecting a polarized noise image on top of the non-polarized information. Figure 8 shows an example with 3 users, users A and B who wear the eye-polarizers and user C without the eye-polarizers look at the screen from different sides of the table. Projector 2 projects the main image, including two letters X and Y, while projector 1 projects a noise image that covers only the letter Y. When the polarization axis of the noise image is parallel user B's glasses as shown in Figure 8(a), the view of each user is as shown in Figures 8(b), (c) and (d). The letter X on which the noise image is not projected is observed by all users. User A observes the letter Y because the main image passes through his eye-polarizers while the noise image, whose polarization axis is perpendicular to the eye-polarizers, does not pass through. Conversely, user B does not observe it because the noise image passes through the eye-polarizers. User C, who does not wear the eye-polarizers, does not observe the letter Y regardless of the observing direction. If the application revolves the projector-polarizer by *90 deg*, user B observes the letter Y in addition to the letter X. User A and user C do not observe it. The letter X is observed by all users as before.

The application can control the projector-polarizer according to any input, for example, positional information of the user's viewpoint by attaching position sensors to the eye-polarizers. By this, the application can always show or filter out the information to a certain tracked user and others standing near the tracked user.

5.2. User-specific classification of information

The second example application is the user-specific classification of information. This shows a difference in brightness between information from one projector and that from the other projector to a specific observing direction by controlling the angle of the projector-polarizer.

Figure 9(a) shows an example where two users wearing the eye-polarizers and one user without the eye-polarizers look at the screen. Figure 9(b) shows projected information consisting of circles and rounded



(a) users' arrangement (b) image to be projected

(c) input to projector 1 (d) input to projector 2 (e) projected image

(f) user A's view (g) user B's view (h) user C's view

Figure 9: User-specific classification of information.

squares, each marked with a letter. It is divided into two parts, where one part is projected from polarized projector 1 while the other is projected from non-polarized projector 2.

When the images shown in Figures 9(c) and (d) are projected from projector 1 and projector 2, respectively, the combined image shown in Figure 9(e) appears on the screen. Only the objects from projector 1 are polarized and the brightness of those is reduced to half. For convenience, in Figure 9(e), the grating represents the polarization axis depending on the projector-polarizer in front of projector 1. In this case, user A can observe all objects and recognizes the classification as the difference in brightness between the objects marked A and B as shown in Figure 9(f). The objects marked B are brighter than those marked A. This difference is caused by the light from projector 1 being significantly reduced at user A's eye-polarizers while the light from projector 2 being reduced to half. User B does not recognize this difference as shown in Figure 9(g) because the light from projector 1 passes through user B's eye-polarizers without reduction and the light from projector 2 is reduced to half. User C, who does not wear the eye-polarizers, does not recognize the above difference regardless of his/her viewpoint as shown in Figure 9(h), although the images from projector 1 are darker than those from projector 2. This is because the human perceives the difference logarithmically according to Weber-Fechner's Law so that the difference is perceived very small.

5.3. An entertainment application

Using the implemented system, we developed an entertainment application “Mysterious POND” as a practical application. It uses polarizer glasses attached with 3D position sensors and additionally a lantern with a 3D position sensor attached to it. Figure 1(a) shows a snap shot where three users are interacting with Mysterious POND. It displays a water surface of a pond with fish swimming underwater on the tabletop. User C who does not wear the glasses can only see the surface of the water as shown in Figure 1(b). On the other hand, user B, who wears the glasses with a lantern in his hand, can see the underwater scenery at the region under the lantern as shown in Figure 1(c). The user A wearing the glasses and standing near the user A can see underwater, too.

To realize this example, a part of the underwater illuminated by the lantern is projected from projector 2 (see Figure 2), while the water surface is projected from the projector 1 and hides the underwater. The projector-polarizer is controlled so that the lantern's owner can see the under water by filtering-out the image of water surface at his/her glasses. By this way, the lantern's owner can see underwater even if he moves around the display. Other users can see the underwater only by moving to near or the opposite side of the lantern owner. The users enjoy illuminating the underwater place to place with the lantern, passing the lantern to the other user, moving around the display, talking to each other, and so on. Meanwhile, the projector polarizer can revolve at an angular velocity greater than *360 deg/s* while users generally move less than *180 deg/s* around the table.

5.4. Tangible polarizers on the display

We can easily extend this idea to include tangible interface elements [5, 26] with polarizer screens so that users can directly control visibility of information under the tangible element. These tangible polarizers on the screen work as the alternatives of the projector-polarizer. In addition, the piece's orientation can serve as a cue of ownerships of the information underneath [10]. Figure 10(a) shows a snapshot where two users (users 1 and 2) standing on adjacent sides of the table are using three tangible polarizers (TPs). User A, observing the world map from the south, adjusts the rotation angles of two of the three TPs so that their insides are visible to her but invisible to the user B as shown in Figures 10(b) and (c). On the other hand, the user B, observing the same map from the west, adjusts the rotation angle of the other TP so that its inside is visible to him but invisible to the user A. In the example shown in the figure, positions and orientations of the TPs are detected by sensors and the users have to seek out treasures in a tabletop adaptation of the geocaching game. Only when the user puts a tangible polarizer on a particular position, the system reveals any treasure inside the TP.

The visibility control system using tangible polarizers can also be used in the example of a large design project outlined earlier. In this case both users can selectively filter out content in their region of focus.

(a) overview (b) user A's view (c) user B's view

Figure 10: Example to use tangible polarizers.

6. Discussions

In this section, we discuss potentials, problems, and prospects of the proposed technique.

6.1. Dealing with noise image

We demonstrate through the application that the noise image covering information can conceal it from the users without the eye-polarizers and only the users with the eye-polarizers looking at the screen from the specific range of the directions can observe it. However, the contrast ratio of the polarizer is not so high as shown in Figure 5. Therefore the concealment is built on the delicate controls of the brightness of each image. An idea making the concealment more robust is to use other types of noise images instead of using the random noise described in the previous section. For example, an image whose color is similar to the hidden information or an image that is the sum of random color images and negatives of the hidden information might be a better noise image. In addition, using brighter noise images or vignetted hidden information might be useful for improving the concealment.

On the other hand, the noise image does not completely disappear at the glasses even if the glasses have perpendicular polarizing axis to the noise image as shown in Figure 5. Therefore, it might not be easy for the observers having such glasses to observe low-contrast image. Difficulties to observe information varies according to the distance between the viewpoint and the information, the user's eyesight, and so on.

6.2. Managing brightness

When the relative angle of the polarizing axes between the projected image and the eye-polarizers is between *0 deg* and *90 deg*, the users observe relatively darker information. In such a situation, it is difficult for the users to recognize the parts of the information where the contrast of the image is insufficient. Therefore, as the contrast of projected information becomes lower, the area where the users can observe information becomes narrower. On the other hand, as the contrast becomes higher, the area where the users can observe information becomes larger. This allows the applications to control the size of the area where information is shown/concealed from the users with the eye-polarizers.

The concealment, however, can be defeated in some way. When the user tilts the eye-polarizer significantly or puts another polarizer between the screen and eye-polarizer, he can see the hidden information. If the system uses circular polarizer or shutter glasses whose visibility is independent from the position, the system can completely conceal the information, providing different visibilities for three types of the users (users with two different types of glasses and users without glasses) at same time. But our main goal is reducing the information clutter and the entertainment rather than the security which needs the perfect concealment. We believe the flexibility of the control is more important in these domains.

The user-specific classification showed the difference in the brightness between the pieces of information to only those users who need personal classifications. The parts observed as brighter or darker can be determined arbitrarily by switching the projector to which the parts are input. The observing direction in which a user with the eye-polarizers can recognize the classifications can also be arbitrarily controlled. For example, the application can control the observing direction to follow a user by using the 3D position sensor. However, revolving the projector-polarizer might unnecessarily show a difference to the users who do not need the classifications. In such cases, the application must control the projector-polarizer and the brightness of the projected information properly to prevent other users from recognizing the difference.

By using the classifications, a user can work while paying attention to only the brighter parts of information or can filter information in order to search for objects without attracting the attention of other users when some users are working together using shared objects. In addition, it can be used for simple indications. For example, when users play a game, the applications can easily assign handicaps by indicating better cards or suggesting the next step for only weaker players.

Contrary to flexibilities of our technique, there is a limitation that it provides same visibility to glassed users who face across the table or stand close direction (viewpoint's height and distance from the table are still free). Therefore, if an application needs to provide different visibilities to several users, it requires users to stand by avoiding these positions. For this purpose, reasonable positions are, for example, vertices of a triangle or a pentagon around the table.

6.3. Extensions

We can develop more advanced multi-level display systems by adopting extensions to the implementations described in this paper. With the recent release of pico-projectors [12] it is possible for the system to be composed of multiple projectors each with its own projector-polarizer controlled independently. This would allow the applications to assign each part of the screen as a private area for a certain user or show classifications that have certain levels of brightness. A liquid crystal panel has a potential to rotate the polarization axis of each pixel. Therefore a panel in front of a fixed polarizer might work as an alternative of many small revolving polarizers. More advanced systems could be built by using eye-polarizers that are coupled to independent revolvers.

Although we used 3D position sensors in our system, more conventional sensors like touch sensors around the table, pressure sensors on the ground, or camera based tracking systems are sufficient to determine the rotation angle of the polarizer.

As a more extended idea of tangible polarizers, we can install a motor to each of the TP to rotate the polarizer dynamically. Moreover, if the system equips a tangible object (a TP is an example) whose rotation is connected to the direction of the projector-polarizer, users can control the projector-polarizer intuitively by controlling the object directly with his/her hands.

7. Conclusion

In this paper, we proposed a novel technique that can provide different visibilities of information to different users who share a single display by using a revolving polarizer. We measured the brightness values of an implemented prototype based on the proposed technique and confirmed the effectiveness of the method. Then we described several applications on the tabletop display with the proposed technique. In the future, we are developing novel collaborative systems using the proposed technique and future work described in the previous section. Thus, we explore extended display techniques which can realize more complicated visibility control of the presented information. Display systems of this kind may change the dynamics of social collaboration [25]; therefore, investigating the behavior of users in the proposed system is an important issue.

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