The "Everywhere Switch" using a Projector and Camera

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Abstract: We propose a virtual remote control interface called the "Everywhere Switch" as an alternative to multiple remote controllers for many computerized home appliances. The interface consists of a group of virtual touch buttons projected near the user from a projector affixed to a pan-tilt mount just below the living-room ceiling. Methods to implement our system, including methods to search for a place to project the virtual touch buttons, to extract finger and shadow regions on the virtual button area and determine their ratio, and to detect touch operations, are described. We evaluated the precisions of the foreground extraction (finger or its shadow) and the segmentation of the finger and its shadow under three different brightness conditions (dim, semi-bright, and bright). The foreground extraction showed an F value of more than 0.97, and the finger/shadow segmentation showed an F value of about 0.8 in all tested brightness conditions.

1 INTRODUCTION

Modern living spaces contain many devices that can be operated by remote control, such as televisions, air conditioners, and audio equipment. However, there are hardware issues inherent to remote controllers, such as limited battery life, deterioration of operation feel as a result of abrasion, and usage issues, such as losing the controller and having to keep it near at hand. To resolve these issues, operation of home electronics by other means has been proposed, such as by hand gesture (Shimada et al., 2013), smartphone (LG Electronics, 2013), and wearable terminal (Logbar, 2014). However, it is difficult to recognize complex operations from hand gestures, and security issues make it undesirable to allow unrestricted operation by a third party's smartphone or wearable terminal.

As an alternative to such systems, we propose a system that uses a projector to display a virtual interface and a camera to recognize gestures by the user, mainly fingertip movements near or on the interface.

With respect to this virtual interface, several input methods, including **pointing** (Borkowski et al., 2004; Borkowski et al., 2006; Goto et al., 2010; Kim et al., 2010) and **touch** (Homma et al., 2014; Dung et al., 2013) have been proposed. Here, **pointing** is a situation of a finger (or something like a stick) to dwell at some virtual interface widget, and the system will recognize it as the user's intention of selection of the widget if the situation continues for a fixed period of time. **Touch** is an action for a finger or something to contact with a virtual interface widget such as a button. The system should recognize the user's intention of its selection.

Since touch feels more akin to using a real button and has higher usability than pointing, we employ touch input in the proposed system.

Methods that rely on a depth camera have been proposed for recognizing touch operation by the user (Jiang et al., 2012). However, since sufficient accuracy cannot be expected from a depth camera in our assumed environmental conditions, we employ a normal optical camera for touch detection.

In this paper, the "Everywhere Switch," which projects a virtual remote control touch button and recognizes touch operation of the button by a single camera installed beside the projector, is proposed. In addition, various necessary functions are proposed and evaluated.

2 PROPOSED SYSTEM

Figure 1 shows the configuration of the Everywhere Switch system. The projector and the camera are affixed to a pan-tilt mount to allow projection onto an arbitrary location like the Steerable Camera-Projector in (Borkowski et al., 2004). In our system,

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the distance from the projector to the projection plane is assumed to be about 400 cm.

Figure 2 shows the processing sequence of the system with this configuration. Within this sequence, there are two important functions. The first is the search for a suitable area in the room near the user on which to project the virtual button. For this, an area detected as having a light color and a flat surface is selected as the projection area. The second is the determination of whether the virtual button, which is displayed by the projector, has been touched. This function can be further divided into the following three subfunctions: a) separating the foreground (e.g., a hand and its shadow) above the virtual button from the background (i.e., the projection plane on which the button light is projected); b) further separating the foreground into a finger region and a shadow region, and determining the moment of touch operation from the ratio of the region areas; and c) confirming whether the touching part is a fingertip.

The implementation method for each function is described below.

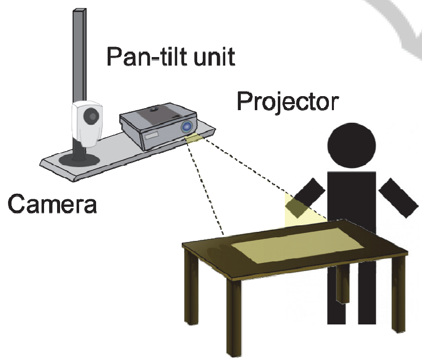


Figure 1: Configuration of the Everywhere Switch.

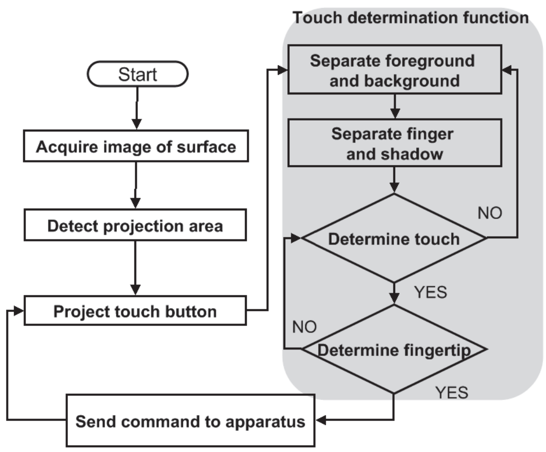


Figure 2: Processing sequence for the system.

2.1 Projection Area Selection

It is preferable that the projection plane be a flat lightly colored surface so that the user can clearly recognize the projected virtual touch button and that the camera can observe the shadow cast by the finger blocking the projector light in touch detection, as described below. Furthermore, in the assumed method of system use, it is necessary that the projection point be within reach of the user's hand.

In the system proposed in (Borkowski et al., 2004), several projection surfaces in the room are pre-registered, and the user selects one of them for the Steerable Camera-Projector to project. However, the area or position of suitable surfaces for projection may change if objects in the room are moved. Therefore, our system finds a projection surface on demand.

For our system to detect a projection area that satisfies the above conditions, it first recognizes the user’s invocation gesture and acquires an image of the vicinity from the camera. The image input from the camera is divided into predetermined small rectangular blocks, and the variance of RGB values in the blocks is calculated. Each block with variance below a threshold and brightness above a threshold is marked as a candidate for a flat area suitable for

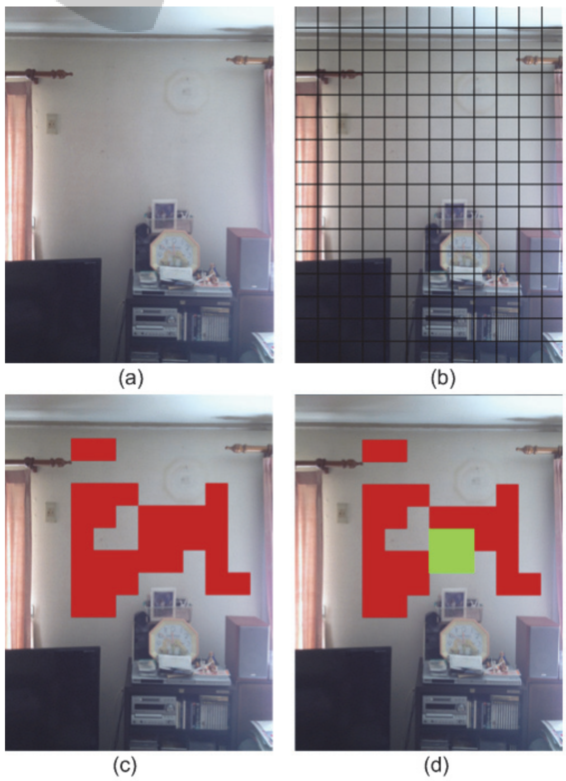


Figure 3: Example of the projection area selection.

projection.

Next, candidate blocks of similar colors are combined such that they are as close as possible to the point where the gesture was detected in order to secure an area with a size and shape corresponding to the projected button. Figure 3 shows an example of the processing sequence. In Figure 3, (a) shows the image input from the camera, (b) shows the image divided into blocks, (c) shows the candidate blocks indicated in red, and (d) shows the region selected as the projection area by combining candidate blocks indicated in green. With respect to (d), the point at which the gesture was recognized is assumed to be the center of the image.

2.2 Touch Detection Function

In (Hartmann et. al, 2012), the tip of a hand or a finger is detected by foreground shape analysis after separating its shadow. Their system can estimate the height of the fingertip from the interaction surface by calculating 3D distance from the tip of the shadow on the surface. However, in order to pursue the precision of the distance estimation, the camera should be placed far from the light source (i.e. the projector), and its positional relation cannot be adopted in our system.

For detecting a fingertip over or on a small interaction surface, the virtual widget, Borkowski et al. have proposed very simple and effective methods (Borkowski et al., 2004; Borkowski et al., 2006). Their metric for the touch detection is the ratio of foreground occupation in the camera view. If the ratio in the central region of the virtual widget is very high and that in its surrounding region is sufficiently low, the system recognizes a pointing. However, as the distance of the foreground from the widget is not estimated, false detection may occur when a tip of some thin-rod like object or its shadow happens to be observed over the central region of the widget in the camera view. Therefore, in our touch detection, we examine whether a user's finger (foreground) is close to the widget or not by the ratio of the foreground to its shadow.

In order to make foreground shadows observable, the camera is installed at a location slightly offset from the optical axis of the projector (e.g., 50 cm to the side in the setup described below) in the system.

When a finger enters the region of the virtual button projected by the projector, the finger and its shadow appear in the camera image as shown in Figure 4 (a). The shadow of this finger is large when the finger is not touching the projection plane and almost disappears when the finger touches the projection plane, as shown in Figure 4 (b).

In this system, touch detection based on the amount of this shadow is realized by the following three functions. The first function separates the background (button region) and the foreground (shadow and finger region). The second function further separates the foreground into a finger region and shadow region, and the third function determines whether a touch operation has been performed from the area ratio of the finger and shadow regions.

A certain degree of variation in environmental brightness must be tolerated because the hypothesized environment for the system is a living space such as a typical living room. Other projector-camera systems that use fluctuations in a shadow region similar to the one in the present study include a system that uses infrared LEDs to respond to fluctuations in environmental brightness (Dung et al., 2013) and a system that extracts the shadow region by altering the color of the projected light (Homma, 2014). However, special equipment in addition to the projector and camera is necessary for the infrared LED system (Dung et al., 2013). Furthermore, changing the button color temporarily by altering the projected light in order to separate the shadow region (Homma et al., 2014) can make the user perceive it mistakenly as a system response to a touch operation.

We propose a method for detecting touch operations in environments where brightness fluctuates that uses just an image input from a monocular camera and without alteration of the projected light. Our touch detection method consists of the following process, described in Sections 2.2.1–2.2.4.

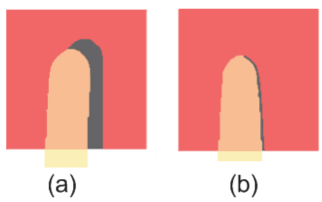


Figure 4: Example of the reduction in shadow consequent on a touch operation.

2.2.1 Separation of Foreground and Background

A background subtraction technique is used to separate the foreground (the region containing the hand, its shadow, etc.) from the background (the projection plane onto which the button light is projected). As detailed above, the method must be able to adapt to a certain degree of fluctuation in environmental brightness in a living space. However, typical techniques that use fixed threshold values to separate the background and foreground in the background subtraction technique cannot handle such fluctuation in brightness and cannot provide high separation performance.

To handle brightness fluctuation, we set the threshold used to separate the background and foreground by a discriminant analysis method (Otsu, 1972). Specifically, the difference in pixel value at each pixel location in the input image, which may be the foreground or background, is expressed as the distance from the prerecorded background pixel value in the RGB space, and discriminant analysis is applied to a histogram in which the horizontal axis (bins) is the distance and the vertical axis (frequency) is the number of pixels. The distance may be Euclidean or Manhattan. In our current implementation, we adopt Manhattan distance because of its low computation cost. A pixel whose distance is smaller (resp. larger) than the acquired threshold is determined to be the background (resp. foreground).

This discriminant analysis method assumes that the histogram is diphasic or has a certain degree of spread, and so it is not suitable if the foreground within the button region is too small or too large. Accordingly, in order to satisfy this condition, threshold determination and foreground separation by discriminant analysis are carried out in only when the variance of the histogram exceeds a certain level.

2.2.2 Separation of the Finger and Its Shadow

To obtain the area ratio of the finger region and the shadow region, the finger and shadow regions are separated. Accordingly, the threshold values for the histogram of just the foreground image separated as described in Section 2.2.1 may be found by further application of discriminant analysis. Here, it is also preferable that the histogram be bimodal or have a certain degree of spread, as in Section 2.2.1. It is therefore necessary to select feature values in order to form a histogram that satisfies this condition when a certain degree of area exists with finger and shadow regions in the button region.

Saturation S (S in HSV space) is a possible candidate for this feature value. Because saturation S is easily affected by environmental contrast, the feature values of V multiplied by S (expressed here as "SS"), and also V were considered for a total of three candidates. As a result of having considered the merits and demerits of these values in a preliminary experiment, we decided to switch between using SS in the case of low environmental brightness and V in the case of high environmental brightness. Figures 5–8 show example foreground histograms for each contrast environment with respect to these two feature values.

As it is difficult to directly measure environmental brightness from a camera input image alone, we decided to use the separation metric, employed in discriminant analysis, to perform switching between the two feature values (SS or V).

The separation metric is a value that represents the degree of separation among groupings and is defined by equation (1).

$$n_1 \cdot n_2 \cdot (\mu_1 - \mu_2)^2/(n_1 + n_2)^2 \quad (1)$$

Here, n_1 and n_2 are the number of pixels in each group, and μ_1 and μ_2 are the average value of each group. In other words, it represents how distinctly the histogram has been separated into two. The separation point that gives the maximum separation metric for the histogram is chosen as the threshold to divide the histogram into two groups.

If the maximum separation metric for SS histogram is greater (resp. smaller) than that of V histogram, the feature value SS (resp. V) is chosen to separate the finger region from its shadow region. In this way, the feature value can be selected that gives a more bimodal histogram suitable for separation.

Under conditions where a shadow region does not exist from the start during a touch operation, and under conditions where only shadow enters the button region and the foreground is just shadow, it is not suitable to attempt separation of finger and shadow by discriminant analysis in the first place. For this reason, the threshold is updated (recalculated) by the above method only when the variance of feature values SS and V for the foreground are at or above a certain value and the maximum value of the variance up to this point is in the process of being updated.

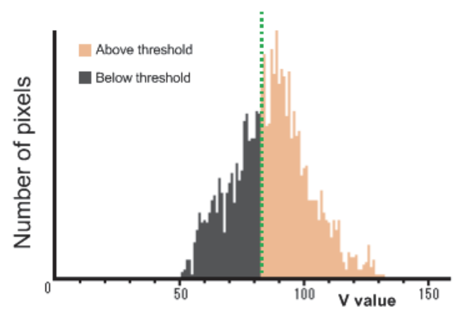


Figure 5: V histogram for low brightness.

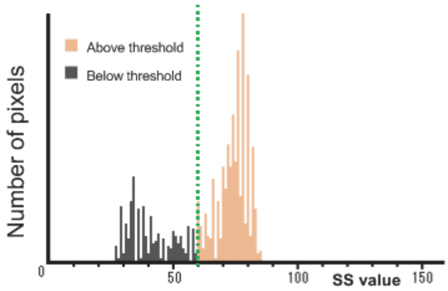


Figure 6: SS histogram for low brightness.

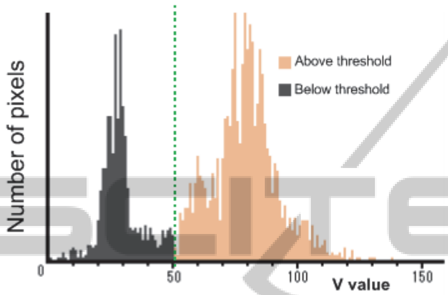


Figure 7: V histogram for high brightness.

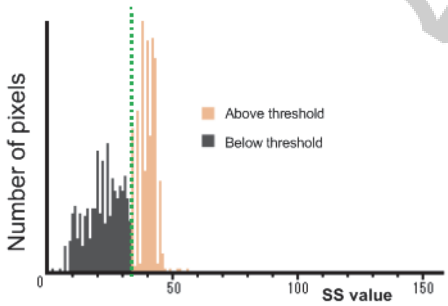


Figure 8: SS histogram for high brightness.

2.2.3 Touch Operation Detection

A touch operation is detected by observing the area ratio of the shadow region with respect to finger region over time. Here, two thresholds, a and b, are

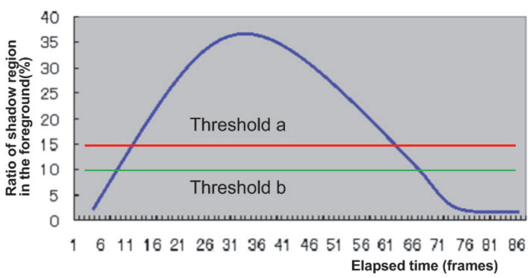


Figure 9: Relationship between shadow ratio over time and thresholds a and b until touch operation.

used (a > b). A touch operation is detected only when the ratio of shadow drops below threshold b after temporarily exceeding threshold a. This makes it possible to reduce false detection of touch operations due to noise. Figure 9 shows the relationship between thresholds a and b, and an example of the changing ratio of the shadow region from when the finger region enters the button region until the touch operation.

2.2.4 Fingertip Detection

A lot of methods have been proposed to detect a fingertip on some interface area by a camera. However, having to wear a marker places a burden on the user and is a problem with such a method. Another method has been proposed that detects fingertip position by matching the fingertip with a circular template (Goto et al., 2010), but this has the problem of high computational cost.

The present system determines whether the finger that has entered the button region is a fingertip intended to perform a selection without using a marker or other attachable device. Specifically, the system determines whether the fingertip is above the button by analyzing the condition of finger region entry into the four sides enclosing the button with respect to the foreground at the instant when a touch operation is detected.

As described in 2.2, the methods proposed in (Borkowski et al., 2004) and (Borkowski et al., 2006) are effective for determining whether a fingertip is at the center of a widget by examining the ratio of foreground occupation in the central and the surrounding region. However, we make more detailed examination for accurate detection.

Figure 10 shows various patterns for the condition of finger entry into the button region. It can be seen that the fingertip is within the button region in the case where the finger crosses just one side of the button region (Figure 10a), and outside the button region in the case it crosses two opposing sides (Figure 10e), three sides (Figure 10f), or all four sides (Figure 10g) of the region. In the case the finger enters from two adjacent sides (Figure 10b, c, and d) the decision is made by the following two tests.

- If the vertex of the two sides entered is not in the finger region (Figure 10c), the fingertip is outside the button region.
- If the number of pixels within the triangle formed by the intersection of the finger region on each side and the vertex of the two sides (Figure 11) is

smaller than the number of pixels of the finger region within the button region (Figure 10b), then the fingertip is within the button region.

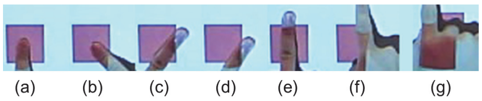


Figure 10: Patterns of hand entry into the button region.

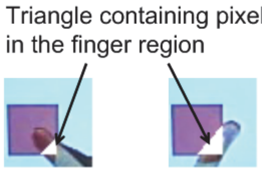


Figure 11: Triangles made by the intersection of the finger region with each side and the vertex of each side.

3 EVALUATION

As the precision of our touch detection depends on the foreground separation accuracy and shadow separation accuracy, we evaluated them under various conditions described below.

Table 1 shows the test settings used in all evaluations below. The camera was installed facing a screen 50 cm almost exactly to the right of the projector. The evaluation was performed under the following three environmental light conditions according to the brightness of the screen surface in the absence of projected light: dim (51 lx), semi-bright (263 lx), and bright (597 lx). The foreground separation result when a finger was separated by 3 cm from the projection plane above a button region projected in red and the shadow separation result produced at that time were evaluated using precision, recall, and F value. These values were calculated using the manually separated results for the foreground and background, or finger and shadow, as the true values. Figure 12 shows examples of manual foreground separation and shadow separation.

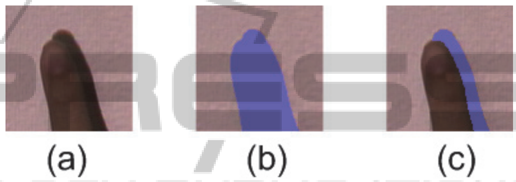
The foreground separation results for the case where the finger extended in a downward and down-rightward direction are shown in Table 2. Figure 13 shows examples of foreground separation by our method.

Similarly, the shadow separation results for the case where the finger extended in a downward direction are shown in Figure 14, and those for the case where the finger extended in a down-rightward direction are shown in Figure 15. The values on the top of the bar graph are the **F value**, and those in the bar graph are the **precision** (upper) and **recall** (lower) values. Figures 14 and 15 show the results of the foreground separation with a manually selected feature (V or SS) and manually adjusted thresholds for the separation.

In every case, the proposed method was found to exhibit good, stable separation, close to the results given by careful manual separation.

Table 1: Test setup.

Camera	Panasonic HDC-SD5
Projector	Optoma EP1691i
Camera-projector separation	50 cm
Distance to the projection plane	400 cm
Number of test subjects	7



(a) Original image
(b) Separation of foreground
(c) Separation of shadow

Figure 12: Original image and examples of manual separation.

Table 2: Evaluation results for foreground separation when a finger enters in the downward and down-rightward direction.

	F value [precision, recall] in three environmental light conditions		
Intrusion direction	Dim environment (51 lx)	Semi-bright environment (263 lx)	Bright environment (597 lx)
downward	0.97 [0.99, 0.98]	0.99 [0.99, 0.99]	0.98 [1.00, 0.97]
down-rightward	0.97 [0.99, 0.95]	0.98 [0.99, 0.97]	0.98 [0.99, 0.97]

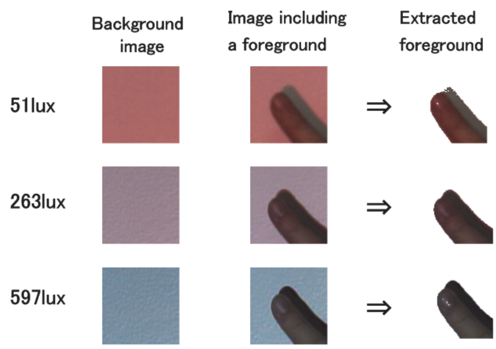


Figure 13: Examples of the foreground separation by our method.

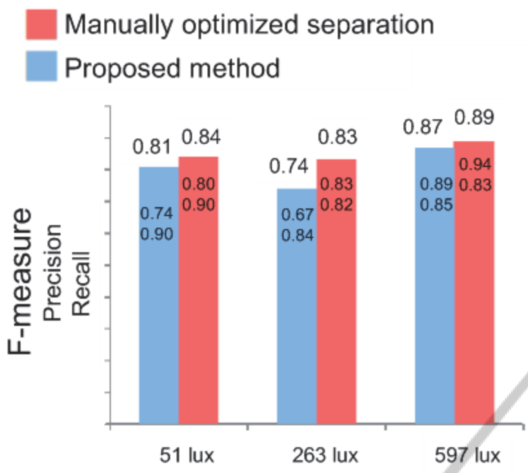


Figure 14: Evaluation results of shadow separation when a finger extends in a downward direction.

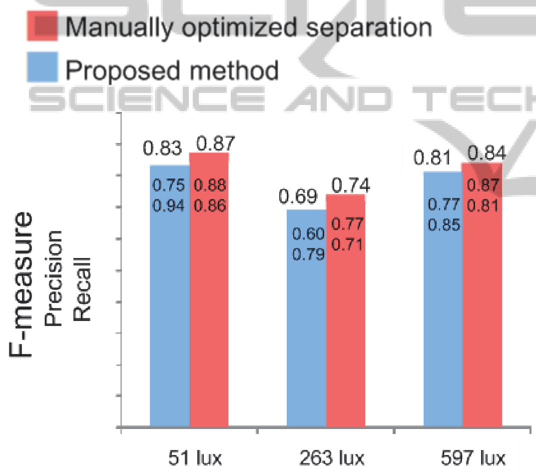


Figure 15: Evaluation results of shadow separation in cases where a finger extends in down and rightward.

4 SUMMARY AND FUTURE WORK

We have developed the Everywhere Switch, which uses a projector and camera to provide a remote control interface for multiple devices in living spaces. It consists of a group of virtual touch buttons projected near the user. We also implemented a set of methods to realize the Everywhere Switch. In particular, precisely detecting the user's button touch from the camera image is vital. We proposed a series of methods to search for a place to project the virtual touch buttons, to extract a finger and its shadow regions on the virtual button area and calculate their ratio, and a method of touch detection. Because extracting the finger and its shadow region is key for detecting a button touch, we evaluated the precision of the extraction under three different brightness conditions. The calculated accuracy shows that our methods work precisely and are robust to variations in environmental brightness.

In the future, we plan to install the proposed system in an actual living space or other real-world location, and will verify the effectiveness of the proposed system, including control functions and the effectiveness of the touch detection method proposed in this paper. The button is currently red or green, but tasks for future investigation include examining other available button colors and the effects of faint shadows produced by environmental light other than the shadow produced by the projector.

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