Touch Detection Method for Non-Display Surface Using Multiple Shadows of Finger

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***Abstract*— Our objective is to create a system that enables users to interact with surrounding surfaces by using touch interactions. In this work, we propose a touch detection method that utilizes the shadows of a finger for use with a system featuring an infrared (IR) camera and two IR lights. Since the shape of a finger's shadow varies depending on the distance between the surface and the finger, the system can recognize a touch by detecting this phenomenon. Evaluations showed that a touch can be detected with high accuracy over an entire large (80 inches wide) operating surface.**

Keywords*— *Interactive surfaces and tabletops; interaction with small or large displays; novel user interfaces and interaction

I. Introduction

Tablet PCs and smartphones are used throughout the world, and touch interactions are commonly used for such devices. Various display devices such as head-mounted displays (HMDs) and projectors have also been developed to help users visualize information on surrounding surfaces. Since touch interactions have become the new norm, a system that allows users to manipulate information on surrounding surfaces with touch interactions is required.

Touch detection on various surrounding surfaces (walls, desks, screens, etc.) is the key underlying technology in the development of such a system. However, these surrounding surfaces are not always flat. For example, there might be outlets in a wall or magnets on a desk. In general, there are many surfaces where protrusions are present and/or objects are placed. In this research, we aim to detect touch operation with high accuracy without the need for any sensors on the surfaces.

II. Related Work

There have been many studies on enabling touch interaction on surrounding surfaces. Roeber et al. [9] proposed a system that uses a line laser. The line laser emits light parallel to the surface and the system detects a touch by recognizing the reflected light diffused from the touching finger. Today, many optical touch panels utilizing a similar algorithm are widely used. However, this system has some constraints primarily that the surface must be flat and the sensors must be settled stably on the surface.

To overcome these constraints, some researchers have proposed touch detection methods using 3D cameras (e.g., Kinect) [5, 6, 7, 8, 11], while others tried using a stereo camera [4]. Most of these systems capture the 3D geometry of a surface beforehand and detect touch by recognizing the distance between the surface and the approaching finger. Some researchers have also used the information from a color camera to prevent a system from detecting the touch of other approaching objects.

Even though we can easily detect touch interaction between a finger and various surfaces with 3D cameras, there are some disadvantages. For example, low accuracy of depth estimation with 3D cameras may cause mis-detection of a touch. Additionally, such a system requires a relatively large space due to the narrow field of view (FOV) of a 3D camera. In principle, the gap between a finger and a surface cannot be detected by a camera, so a touch is more likely to be mis-detected.

In light of the above, we propose a new touch detection method that uses the shadows of a finger and developed a prototype touch detection system. The shapes of a finger's shadow vary depending on the distance between the finger and a surface, and our system uses this variance to detect a touch, as shown in Fig. 1. The system can also detect a touch on a non-flat surface or surface with protruding objects because shadows can be observed even on those surfaces. Additionally, the system can operate in a wide operation area by using a wide-angle lens.

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Wilson [10] proposed a system that consists of an IR camera and an IR light to detect a touch by using the shape of a finger's shadow. However, the shape of a finger's shadow can dramatically change depending on the positional relationship between a camera and the finger or on the posture of the finger to the surface. This makes it difficult to precisely detect touch with only one side shadow.

In contrast, our prototype system uses two IR lights and detects a touch by recognizing both side shadows of a finger. Using two IR lights makes it easy to detect the distance between the finger and the surface, similar to a stereo vision measurement.

III. PROPOSED METHOD AND PROTOTYPE SYSTEM

A. *Basic principle*

In the proposed method, we use a camera to capture shadows made with two lights and the touch of a fingertip is detected by recognizing the change in shape of both side shadows. Fig. 1 shows how the shape of the shadows changes in a camera image with our proposed method. For example, when a fingertip is far from a surface, the distance between the shadow's tips is distant. In this way, the distance between the finger and the surface can be directly observed by noting the change of the shape of the shadow. The procedure of touch detection in the proposed method is as follows.

1) Extract shadow area on the basis of difference in luminance from background.

2) Trace the contours of the shadow area.

3) Extract features such as position of shadow's tip from shadow contour.

4) Detect a touch if extracted features meet the condition (e.g., if the tips of both side shadow are close to each other).

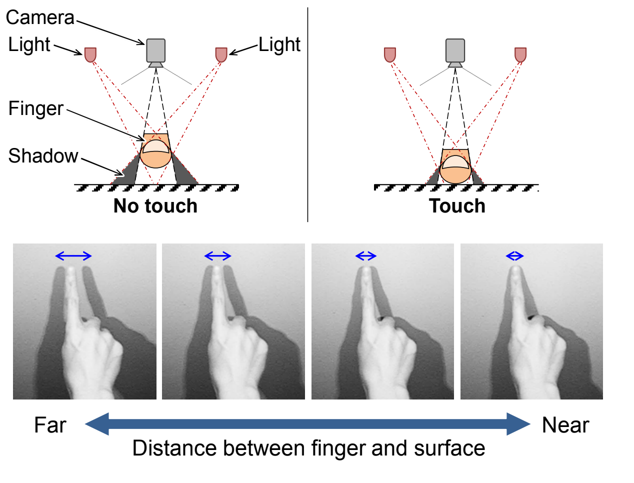

Fig. 1. Shapes of a finger's shadow vary depending on distance between surface and finger.

B. *Our targets*

In this research, we defined the touch to be detected as "a state in which the finger is less than 5 mm away from the entire 80-inches-wide operating surface" and set the target value of the touch detection accuracy at 90% or more for one frame of camera imaging. The reason for the target value is as follows.

First, in order to set a target for touch detection accuracy, we measured the distance between the finger and the surface during the actual touch operation. Fig.2 shows the environment and results of this measurement. The size of the touch target was 7 mm × 7 mm. This size is derived from the smallest object defined in "Guidelines for targeting" [1, 2, 3]. We arranged 9 objects in a grid at equal intervals of 2 mm on the surface, and the touch target was placed at the center of the objects. In this measurement we chose a double tap as a suitable operation, since when the double tap operation is performed, the finger touches the surface once, leaves the surface, and then touches the surface again. If the touch detection accuracy of our system undergoes the distance between the finger of the surface when finger is leaving the surface, our system can recognize a double tap operation and thus the user can operate the system in a natural manner. We configured two situations as a surface: a desk and a wall. Also, we configured two conditions for the hand posture, that is whether a part of the hand is placed on the surface or not. Ten subjects are participated in this measurement and they performed a double tap operation three times in each situation. We used a high frame rate camera for capturing the movement of the fingertip. As a result of this measurement, the average distance was 14.6 mm and the minimum was 5 mm. From this result, we set a target for touch detection accuracy as less than 5 mm.

Next, the width of 80 inches was chosen because when a person stands in the center of a surface, that is roughly the limit to where he or she can reach from end to end without changing the standing position. This is actually the size typically used for whiteboards and large displays.

Finally, since our proposed system operates continuously, the touch detection accuracy of 90% in one frame, which means a mis-detection rate of 10% or less in one frame, leads to a mis-detection rate of just 1% or less in two successive frames. Therefore, by introducing interpolation for touch detection, touch detection accuracy can be improved up to 99% or more.

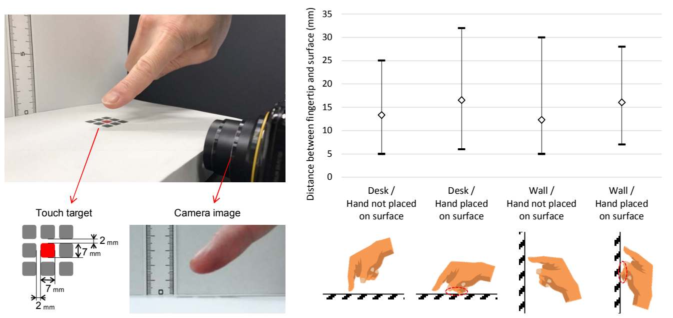

Fig. 2. Measurement of the distance between surface and fingertip during double tap operation.

C. *Hardware*

The configuration of our prototype system is shown in Fig. 3. The system consists of an IR camera and two IR lights, and the camera captures the shadows of a finger generated by the IR lights. The resolution of the camera is 1920 × 1080 pixels and it runs at 30 fps. Since we use a wide-angle lens with 120-degree FOV, the system can detect touch over a wide area.

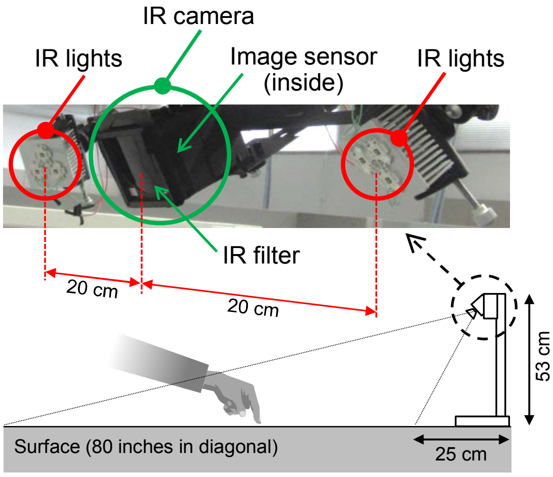

Fig. 3. Configuration of prototype system. Operation area is 80 inches in diagonal.

D. Touch detection

Here, we describe a technique for detecting a touch by recognizing the extracted shadow. Depending on its position on the operating surface, the shape of the shadow and the distance between a shadow's tips will vary dynamically, so our system has to accurately determine the touch corresponding to this difference. Fig. 4 shows the shadow when the fingertip is 10 mm away from the surface and touching at a position far from the camera on the surface. We found by comparing these two images that it is difficult to detect a touch from a single feature, since the change of the shape of a shadow is small, especially at a position far from the camera. Therefore, in the proposed system, touch detection is performed by combining multiple features extracted from the shadow to improve accuracy. There are three approaches for detecting shadow change, as follows.

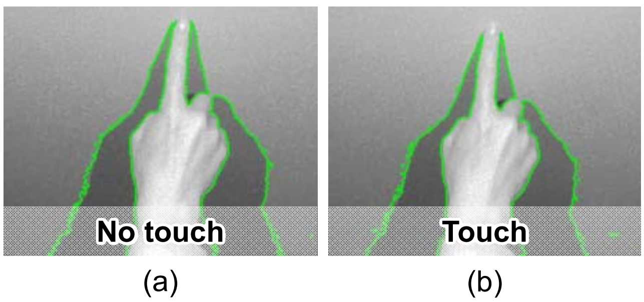

Fig. 4. Shadow change on the operation surface at a position far from the camera.

Distance between a shadow's tips (feature A): As explained above, shadows are formed on both sides of a finger on the surface, and when a finger approaches the surface, the distance between the shadow's tips becomes short. Therefore, if the distance between the shadow's tips is closer than a predetermined value, the system recognizes that the fingertip is touching the intermediate position between the tips. We designate this as feature A.

Sharpness of shadow tip (feature B): The angle of the shadow's tip is measured, and a touch is detected if the angle is sharper than a predetermined value. We designate this as feature B. In Fig. 4(a), which shows a fingertip 10 mm away from the surface, the shadow's tip curves around the fingertip and has a rounded shape. In contrast, when the fingertip is touching, as shown in Fig. 4(b), the shape of the shadow's tip is sharper than that in (a). In feature B, the system recognizes a touch on the basis of the sharpness of a shadow's tips.

Position shift between shadow's tips (feature C): On the outer side of the surface, the two IR lights illuminate the finger from almost the same direction as the finger, and thus the shadow changes a little differently from features A and B. Fig. 5 shows a state of touching at the position on the right outer side of the two IR lights. In Fig. 5(a), when the fingertip hovers 10 mm above the surface, the heights of the tip positions of the left and right shadows are almost the same. In contrast, in Fig. 5(b), when the fingertip is touching the surface, there is a difference in the height of the tip positions of the left and right shadows.

This phenomenon occurs because the finger reflects light emitted from the IR light and illuminates the surface. Since both IR lights are irradiating from the left side of the finger, the amount of light reflected by the finger increases. In Fig. 5(c), the pixel whose luminance largely rises compared to the background image is shown colored in yellow, and we find that the luminance has increased on the left side of the finger. In this area, the shadow becomes thin due to the increase in luminance, almost to the point that it becomes invisible. As a result, the tip position of the shadow is lowered on the left side of the finger.

Therefore, on the outer side of the surface, if the difference between the tip positions of the left and right shadows is larger than a predetermined value, the system recognizes that the fingertip is touching. This is defined as feature C.

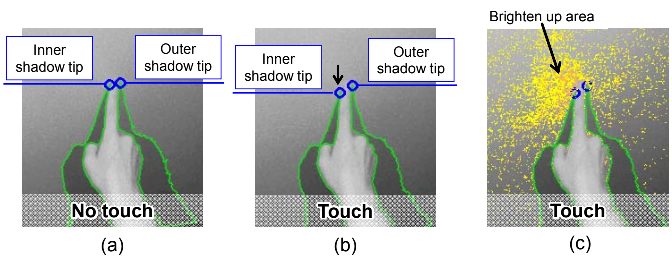

Fig. 5. Shadow change on outer side of the operation surface.

Touch detection is performed by combining features A, B, and C. In addition, depending on the position on the surface, the priority and parameters of each method are changed. Fig. 6 shows the algorithm of touch detection in the proposed method, including the processing described above.

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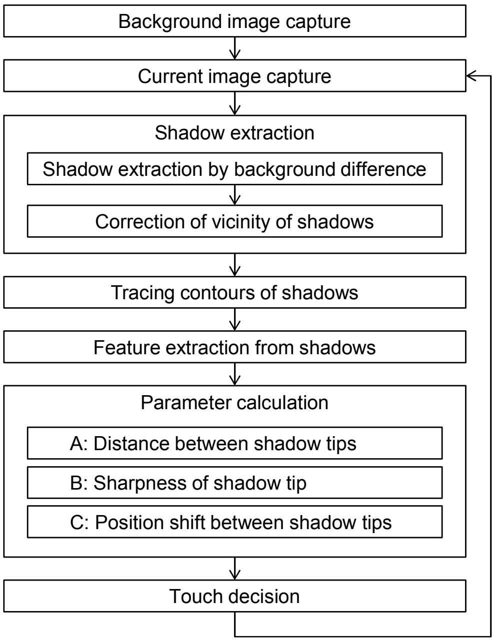

Fig. 6. Algorithm of touch detection in proposed method.

IV. EVALUATION

A. Touch operation verification

First, we verified the performance of the proposed method. In the verification, we mapped the detected touch coordinates to the coordinates of a PC application and projected a display image onto the surface.

Fig. 7 shows the verification of the touch operation on a surface having a sloped protrusion. In this verification, we used an application with multiple buttons that turn red when they are touched. Touch operation was performed on and around the protrusion, and it was confirmed that touch operation can be detected on all buttons.

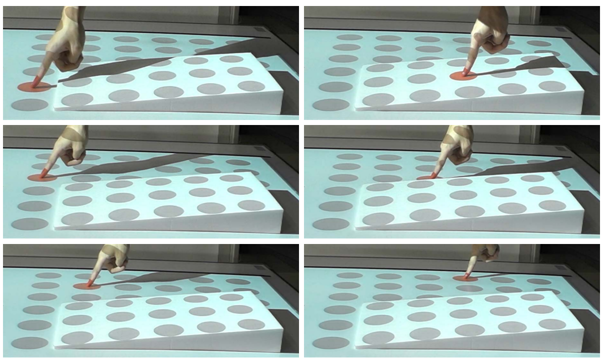

Fig. 7. Verification of touch operation on surface having a sloped protrusion.

Fig. 8 shows the verification of an operation with a drawing application. Here, users drew characters on a surface by touch operation. We confirmed that users could perform the operation even on sloped or hemispherical protrusions.

However, touch could not be detected on the periphery of protrusions, such as where the fingertip is hidden by protrusions in the camera image, or where a shadow of the protrusion is formed in the projector image. These areas roughly correspond to areas where the shadow is formed in the projected image in Fig. 8.

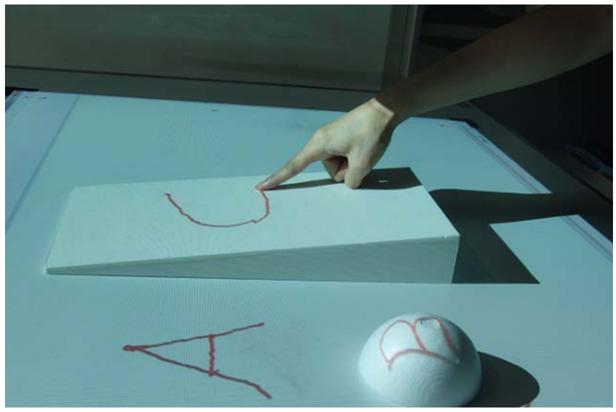

Fig. 8. Verification of touch operation using drawing application.

B. Evaluation of touch detection accuracy

Here, we discuss our evaluation of the touch detection accuracy of the proposed method. In the evaluation experiment, we captured two types of images: a fingertip touching the surface and a fingertip hovering 5 mm above the surface.

As shown in Fig. 9(a), touch detection accuracy was evaluated at 169 positions set at equal intervals in both the vertical and horizontal directions over the entire 80-inch operation area. The interval between the touch positions, decided with consideration for the size of the hand, was 8 cm in the vertical direction and 15 cm in the horizontal direction. The evaluation images were captured under various conditions:

— Touch position: 169 points (Fig. 9(a))

— Finger posture: Three ways (Fig. 9(b))

— Touch state: Two ways (touch, no touch: 5 mm)

Therefore, the number of evaluation images was 1014 (169 points × 3 postures × 2 states).

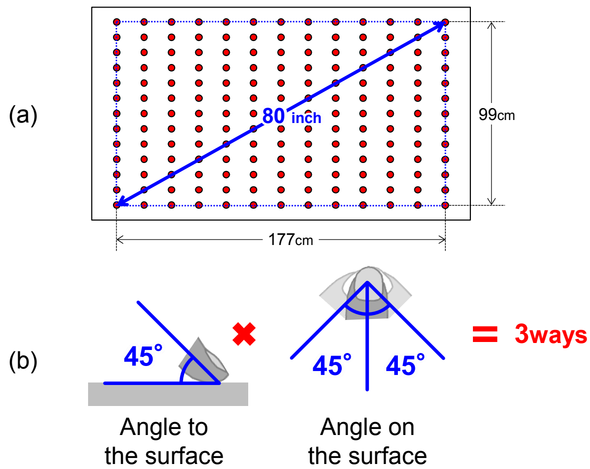

Fig. 9. Evaluation of touch detection accuracy.

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Table 1 lists the evaluation results of the touch detection accuracy. The true positive rate (touch image recognized as a touch) was 95.9%, the true negative rate was 95.5%, and the total detection accuracy was 96.1%.

In addition, the false positive rate was 4.53%, the false negative rate was 3.35%, the positive predictive value was 95.5%, and the negative predictive value was 96.6%. These results demonstrate that we achieved our target touch detection accuracy of 90% over the entire 80-inch operating surface.

TABLE I. RESULTS OF TOUCH DETECTION ACCURACY.

		True Condition		
		Condition positive	Condition Negative	
Predicted condition	Test outcome positive	True positive **490**	False negative **23**	Positive predictive value **95.5%**
	Test outcome negative	False positive **17**	True negative **484**	Negative predictive value **96.6%**
		Sensitivity **95.9%**	Specificity **95.5%**	

V. DISCUSSION

We found that in many images where false positives occurred, the posture of the finger was tilted. When the posture of the finger is tilted, the positions of the shadow's tips on both sides of the finger are largely displaced in the horizontal direction. For this reason, we assume that the distance between the shadow's tips did not meet the threshold prescribed in feature A.

Fig. 10. Positions where false positives occurred on the operation surface.

In addition, both false positives and false negatives occurred at positions far from the camera on the operation surface. In Fig. 10, positions where false positives occurred are indicated by blue dots. At a position far from the camera, the shadow change becomes smaller in the captured image, so erroneous detection tends to occur. Furthermore, since these positions are captured in the peripheral area in the image, there was a considerable effect on the recognition due to lens distortion. Also, many erroneous detections occurred, particularly on the right side of the surface. This was probably because the lighting was not uniform on the left and right sides of the surface.

VI. CONCLUSION

We proposed a touch detection method that utilizes the shadows of a finger and developed a prototype touch detection system with an IR camera and two IR lights that requires no sensors on a surface and can detect touch even on non-flat surfaces. We evaluated the accuracy of touch detection using 1014 evaluation images with our prototype system and found that the system can detect whether a finger is less than 5 mm from the surface with an accuracy of 96.1% over a large (80 inches wide) operating surface.

Future work will include improving the touch detection accuracy, performing evaluations on various surfaces, and addressing issues related to practical usage of the system.

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