A Thin Stretchable Interface for Tangential Force Measurement

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ABSTRACT

We have developed a simple skin-like user interface that can be easily attached to curved as well as flat surfaces and used to measure tangential force generated by pinching and dragging interactions. The interface consists of several photoreflectors that consist of an IR LED and a phototransistor and elastic fabric such as stocking and rubber membrane. The sensing method used is based on our observation that photoreflectors can be used to measure the ratio of expansion and contraction of a stocking using the changes in transmissivity of IR light passing through the stocking. Since a stocking is thin, stretchable, and nearly transparent, it can be easily attached to various types of objects such as mobile devices, robots, and different parts of the body as well as to various types of conventional pressure sensors without altering the original shape of the object. It can also present natural haptic feedback in accordance with the amount of force exerted. A system using several such sensors can determine the direction of a two-dimensional force. A variety of example applications illustrated the utility of this sensing system.

Author Keywords

Soft User Interface; Tangential Force Input; Transmissivity Measurement; Multiple Sensors;

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms

Measurement, Design

INTRODUCTION

People have long made use of their skin to communicate intentions and emotions to each other via touching. For instance, people can express affection for children by caressing their head and anger by sharply pinching their cheek. The integration of this property of skin into objects in our daily life or into a smart home environment would enable the implementation of a computer system that could detect user behavior and change the environment accordingly. For example, the user of a robot with sensor-augmented skin could indicate his or her intentions and emotions directly and naturally to a robot through touch interaction. Thus, the objective of this research is to integrate the property of skin into existing objects and thereby enable more natural communication with computer systems.

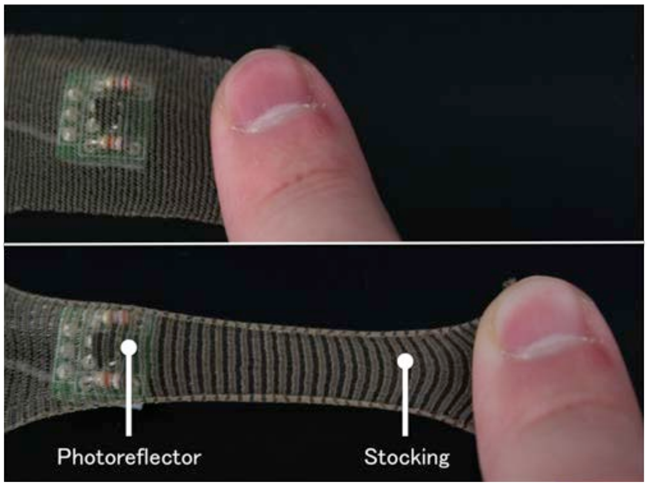

Figure 1: Proposed stretchable sensor measures tangential forces applied to elastic fabric.

There have been several attempts to create artificial skin for use in sense-touch interaction systems, especially in the field of robotics [13, 15]. Many researchers have focused on developing sensors that can detect touch (binary sensing) or measure touch pressure (force in the normal direction) as well as identify the touch points. Interaction via skin involves not only touching and pressing but also pinching, pulling, releasing, twisting, and caressing, thereby creating different tangential forces.

In this paper, we present a simple skin-like user interface that can be easily attached to curved as well as flat surfaces

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and that can measure tangential forces applied to the surface (Figure 1). The interface consists of several photoreflectors that consist of an IR LED and a phototransistor and elastic fabric such as stocking and rubber membrane. Because a stocking is a stretchable material, it can afford physical interactions such as pinching, pulling, releasing, caressing, and squashing and present natural haptic feedback on the basis of the amount of force applied. We found that photoreflectors can be used to measure the ratio of expansion and contraction of the stocking using the changes in transmissivity of IR light passing through the stocking. This is the key sensing technique used in this research. Since a stocking is thin, flexible, and semi-transparent, it can be attached to various types of objects such as mobile phones, robots, and different parts of the body as well as to various types of conventional pressure sensors, thereby enhancing and providing richer touch interaction. A system using several photoreflectors can determine the direction of a two-dimensional force. We have prototyped a variety of example applications to illustrate the utility of this sensing system.

Our sensor has several advantages over existing technologies. First, the components (stocking and photoreflectors) are commodity products and very inexpensive (less than $1 each). Because the configuration does not require any complex circuitry, users can easily duplicate the system on their own. Second, because a stocking is thin and flexible, it can be attached to various types of objects without changing their original shape and can be used to create powerful and economical ambient sensor environments. Finally, a stocking gives natural haptic feedback in accordance with the amount of force applied. Also, the softness and durability of the sensor can be controlled by using a stocking with a different denier[1] value or by adding another stocking. This can result in more comfortable interfaces.

RELATED WORK

Our work builds upon four distinct areas of prior research that are covered in turn in this section. The first is the augmentation of the sensing area on near-surfaces; the second is tangential force sensing; the third is stretchable sensors and thin deformable displays.

Augmenting Sensing Area on Near-surfaces

There have been several attempts to develop thin skin-like sensors that can be attached to non-planar surfaces and that can detect touch and measure pressure. Lumelsky proposed the concept of “sensitive skin,” i.e., the covering of a large area and using a flexible array of sensors with data processing capabilities [11]. The entire surface of a machine or even a part of the human body can be covered. Commercial pressure, position, and bend sensors that are based on the resistance changes of a metal material can be very thin and can be used to augment the sensing area on objects in our daily lives or in the environment. Shimojo et al. developed a thin and flexible sheet-type sensor that can measure two-dimensional pressure and can be used to cover three-dimensional objects. This tactile sensor consists of pressure-conductive rubber with stitched electrical wires [17]. Hoshi et al. constructed a sheet-type sensor that can capture 3D shapes as well as shape deformation in real time by using distributed triaxial accelerometers and triaxial magnetometers [8]. In the field of robotics, several sensors have been proposed for sensing touch interaction on a robot covered with soft skin [13]. Ohmura et al. developed a conformable tactile sensor skin composed of photoreflectors covered with urethane foam [15]. Our method differs from these in that it can measure tangential forces.

Tangential Force Sensing

Strain gauges are commonly used to measure the tangential force on hard objects. Herot and Weinzapfel presented an interface that can measure, via strain gauges, the force vector applied to a screen [7]. Since the voltage change in the gauges is small, an operational amplifier must be used, resulting in complex circuitry. Also, strain gauges are rigid instruments. Since it requires solid attachment to the material, the material’s property changes. Our technique allows us to customize the sensor’s position and material shape to the target objects or environment because it only requires sensor allocation and cover with stocking.

Heo and Lee modified this interface so that it can measure the tangential forces of gestures applied to the screen of a mobile phone [5]. By combining the normal force with position sensing, this system enables users to use five force gestures. However, because the system components are made of hard materials, they may not produce the expected interactions. Moreover, they are unable to provide haptic feedback.

Several camera-based methods have been proposed for measuring tangential forces applied to soft materials. Kamiyama et al. developed the Gelforce sensor, which enables the measurement of six-degrees of freedom motions by capturing the deformation of color markers embedded in elastic material [10]. Yamane et al. placed many physical bumps on a plate and estimated the tangential forces from images captured with a CCD camera by measuring the mechanical changes in the bumps [22]. While these camera-based methods work well in a limited environment, such as a tabletop, a certain amount of space is required between the material and sensor because a camera is used to track the shape deformation or movement of soft material.

Kadowaki et al. proposed using a phototransistor and multiple IR LEDs to measure a variety of interactions such as push, pinch, and rub [9]. The idea is to measure the gap

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[1] Denier is a unit of measure for the linear mass density of fibers. It is defined as the mass in grams per 9,000 meters.

between the top of the silicone material with a phototransistor and its bottom with multiple IR LEDs. However, since phototransistors and IR LEDs have a certain thickness, it is difficult to attach them to object surfaces.

There are several attempts to measure slipping movement on a soft surface by using same optical sensor as that user in an optical mouse [1, 3]. These methods measure the material’s relative translational displacement, which leads to cumulative errors. Our sensing method measures the absolute stretch of material, thus it is not prone to such errors. In addition, our method can measure the stretch even if there is no translational move (e.g. measure the stretch of stocking at the center).

Stretchable Sensor and Thin Deformable Display

Slyper et al. proposed using analogue magnetic distance sensors to construct stretchable sensors for measuring the structural changes of silicone [18]. Perner-Wilson and Buechley described a method in which the resistance value of conductive wires knitted into cloth changes with the stretching motion [16].

There have been several attempts to develop thin deformable displays, especially in the media arts field. The “Khronos Projector” is an interactive art installation using a flexible and deformable projector screen [2]. The audience can interact with the screen using physical and dynamic actions, such as pushing. The deformation of the screen is captured using a CCD camera. Heo and Bank developed similar interactive art installations based on Kinect sensing [6]. Miaw presented a high-speed optical motion-capture method that can measure three-dimensional motion, orientation, and incident illumination at tagged points in a scene [12].

PHOTOREFLECTIVITY-BASED RATIO OF EXPANSION AND CONTRACTION MEASUREMENT

Principle

Photoreflectors are generally used to measure the distance between objects. We propose using them to measure the ratio of expansion and contraction of stretchable materials. When a material is stretched (i.e., when a stocking is pulled), the amount of emitted IR light passing through the material changes. This phenomenon is illustrated in Figure 2.

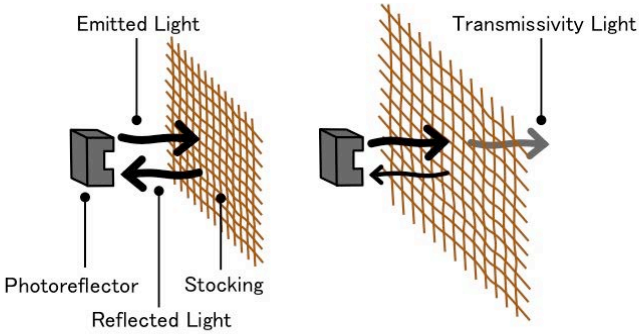

Figure 2: Photoreflector detects ratio of expansion and contraction of stocking on basis of transmissivity changes of IR light passing through the stocking.

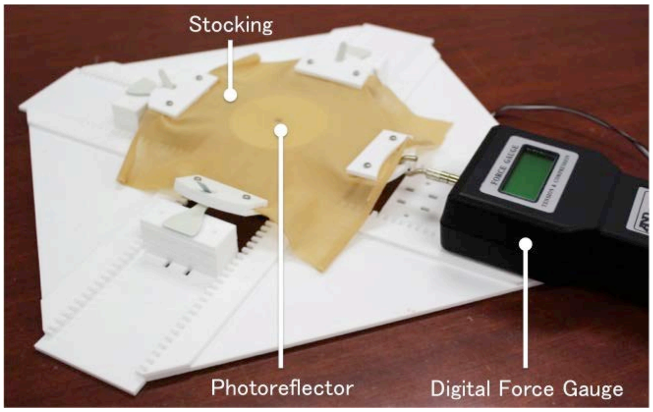

Figure 3: Experimental tool for pulling stocking in a step-by-step manner. Digital force gauge measures pulling force.

Relationship between Photoreflectivity and Ratio of Expansion and Contraction of Stocking

We conducted an experiment to investigate the relationship between photoreflectivity and the ratio of expansion and contraction of a stretchable material. A 20 denier stocking was spread over the center of an experimental tool (Figure 3) and held in place by clamps on three sides. The fourth side of the material was connected to a force gauge (A&D Company, Limited; AD-4932A-50N; resolution: 0.01N). The tool pulled the material in a step-by-step manner. A KODENSHI SG-105 photoreflector was located under the material at the center of the tool.

To check for the effect of hysteresis, we released the material in a step-by-step manner after pulling it until the pulling force was 6N (the maximum force with which 20 denier stocking can be pulled with it being torn apart). The photoreflector measurements were recorded using an Atmel ATmega328 microcontroller. The photoreflector was included in the voltage-divider circuit so that the measured output voltage would be inversely proportional to the light reflected on the sensor.

Experiment Procedure

1. Place 20 denier stocking on experimental tool.
2. Adjust initial force to 0.2N by pulling stocking.
3. Record photoreflector output at 1Hz for 10s.
4. Pull stocking in steps of 2mm.
5. Repeat steps 3 and 4 until force reaches 6N.
6. Release stocking by 2mm.
7. Record photoreflector output at 1Hz for 10s.
8. Repeat steps 6 and 7 until force reaches 0.2N.

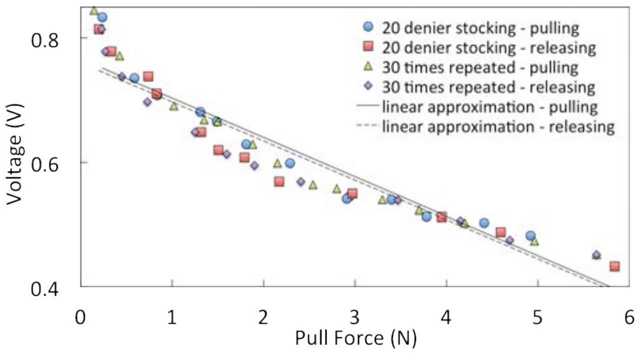

Figure 4: Average measured voltage against pulling force for 20 denier stocking.

Result
Figure 4 plots the sensor value (i.e., the voltage) against the pulling force. The voltage decreased with the force created by pulling, and it increased as the force was reduced by releasing. The effect of hysteresis is evident from 1.3N to 2.8N in the figure. We also plotted the data that was recorded when the stocking was pulled and released at 30 times. We approximated these data by linear.

Other Materials
We also tested other materials in a similar setting. The value of the sensor for a 70 denier stocking decreased linearly from 2N to 11N. The stretch of a thin rubber material used for exercise can also be measured with this sensing method.

IMPLEMENTATION

User Interactions

People interact with skin-like surfaces in various ways. Our sensing method can currently measure three basic interactions (Figure 5). The measurements are made using values obtained from sensors placed on each side of the material. By dragging fingers on the surface, the user can create a tangential force in any direction (Figure 5a). The user can also use pinch-in (Figure 5b) and pinch-out (Figure 5c) gestures. On the basis of changes to the temporal axis, the system can differentiate among a flicking gesture, a double-flick gesture, and so on.

Sensor Module

We constructed a prototype sensor module that can be easily attached to everyday objects and the environment (Figure 6). It consists of photoreflectors, a microcontroller, a Li-Po battery (3.7V, 50mA) and a Bluetooth or ZigBee module (we prototyped both types). Both types of module have a diameter of 35mm, a thickness of 4mm and a weight of 20g. The case is made of laser-cut acrylic. The module requires no physical connection since it is equipped with a wireless communication module and battery. The AT-mega328 microcontroller has a 10-bit A/D converter, so the photoreflector outputs a value of 0 to 1023. It is connected to the Bluetooth or ZigBee module. Since an ID number can be assigned to each wireless module, multiple sensor modules can be used at the same time.

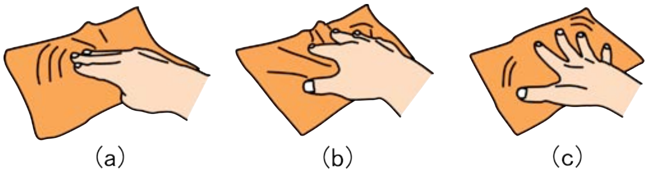
(a) (b) (c)

Figure 5: Basic interactions with stretchable surface: (a) dragging, (b) pinch-in, (c) pinch-out.

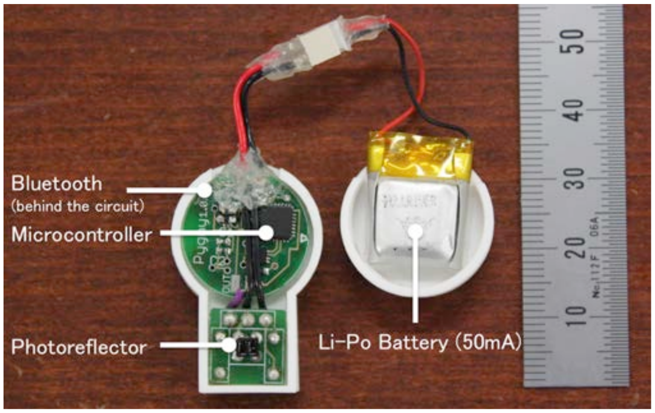

Figure 6: Main components of sensor module.

Calculation of Two-dimensional Tangential Force

A dragging interaction is measured by calculating a vector based on the value for each photoreflectors and calibrated sensor location. This calculation is based on the method used to detect the barycenter of multi-mass points. The system detects 1) the direction and 2) the force level of the user's dragging interaction using the following formula.

$$\mathbf{a} = ((\sum_{i=1}^{n} p_i x_i)/M - x_d, (\sum_{i=1}^{n} p_i y_i)/M - y_d) \qquad (1)$$

$$M = \sum_{i=1}^{n} p_i \quad , \qquad (2)$$

where $\mathbf{a}$ is the vector for dragging, n is the number of sensor modules, p_i is the photoreflector value for sensor module i, and x_i and y_i represent the x-y coordinates of sensor i. The user specifies the location of the sensors at installation. The default x-y position (when the user is not touching the sensor) is given by x_d and y_d. M is the total value for all the photoreflectors and is used to detect pinch-in and pinch-out gestures. We measured the accuracy of vector direction. The angular range was about ± 4.6 degree compared to real angle. Right now, since the characteristic of the elastic fabrics is not considered in the formula, the system detects these interactions roughly.

Figure 7: Application to commercial pressure sensor array (left) and FuwaFuwa sensor (right).

Combination with Conventional Pressure Sensors

Since our sensor is thin and deformable, it can be easily combined with conventional touch sensors to enhance the interaction experience. We attached our skin-like surface sensor to two touch pressure sensors: a commercial pressure sensor that can be used to measure not only normal force pressure but also tangential forces (Figure 7, left), and a FuwaFuwa sensor [20], which can detect the shape deformation of cotton on the basis of the cotton's density as measured with a photoreflectors (Figure 7, right). Our sensor did not affect the cotton's softness property, and it expanded the variety of interactions, adding squashing and pulling in addition to interactions based on tangential forces. Also, we can combine our sensor with other soft sensor that is developed by Smith et al. [19].

EXAMPLE APPLICATIONS

Smart Phone – We developed two different types of attachments based on our nearly transparent sensor skin for use with touchscreen mobile phones. The first type is flat and enables the use of both touch and tangential force sensing. The location of a 3D object on the touchscreen is manipulated by normal touch and drag (Figure 8, left). If the user increases the touch pressure when dragging an object, the object rotates (Figure 8, right). Users can thus generate different types of gestures with only one finger. The other type is curved and supports pinching, dragging, and releasing gestures. With these gestures, users can play games with more complicated actions, like shooting at a target with an arrow (Figure 9). The arrow is controlled by dragging them from side to side and up and down and is launched by using a releasing gesture.

Robot – A user would likely feel more comfortable interacting with a robot with soft surfaces than one with hard surfaces [13, 21]. With this in mind, we developed a robotic toy that has soft surfaces and that affords the user physical interactions. The robot is covered with our sensor skin, and two photoreflectors are placed on the front surface of the robot. The robots eyes change direction when the robot is "pulled" using dragging gestures (Figure 10). The robot makes a rocking motion as well when the robot is "caressed" using pinch-in and pinch-out gestures.

Home Appliances – We covered a speaker with our sensor skin (Figure 11). Four photoreflectors were attached at the corners of the speaker (one at each corner), enabling it to detect touch interactions. In this prototype, the user can control the volume and track being played by dragging a finger across the skin up and down and from side to side. Tracks can be fast-forwarded by using a rotation gesture.

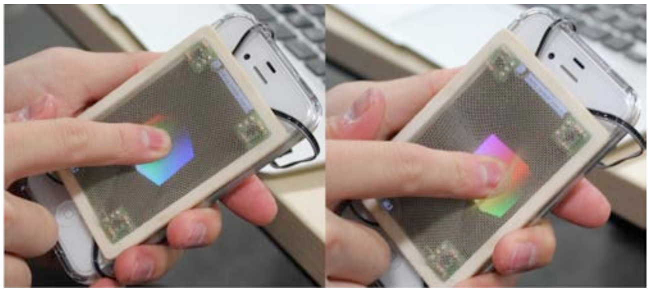

Figure 8: Location of computer graphics object is controlled using normal touch (left); object is rotated using hard touch (right).

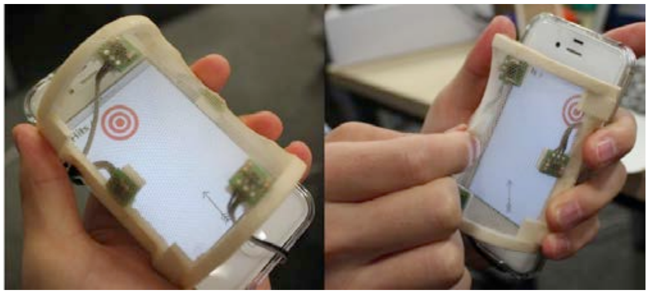

Figure 9: Target shooting game controlled using pinching, dragging, and releasing gestures on the curved type of attachment.

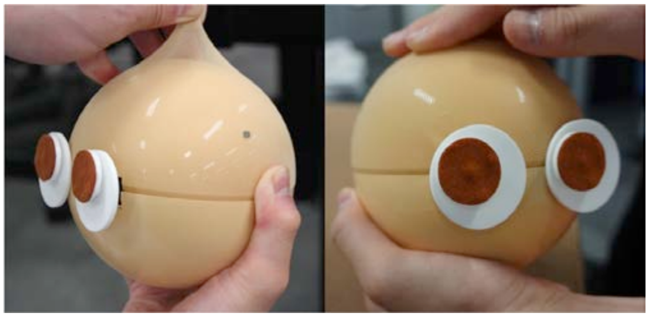

Figure 10: Direction of robot's eyes changes on basis of gestures.

Chairs – Tangential force interactions occur not only at one's finger tips but also at one's hind end. Postural imbalance affects one's ability to concentrate. There have been several attempts to encourage good postural balance by visualizing the user's own posture [4, 14]. Our sensor skin can be easily attached to an everyday chair and can measure the posture of a person sitting in it, especially slipping (Figure 12). A system combining a conventional pressure sensor with our sensor skin can measure the user's posture in five directions.

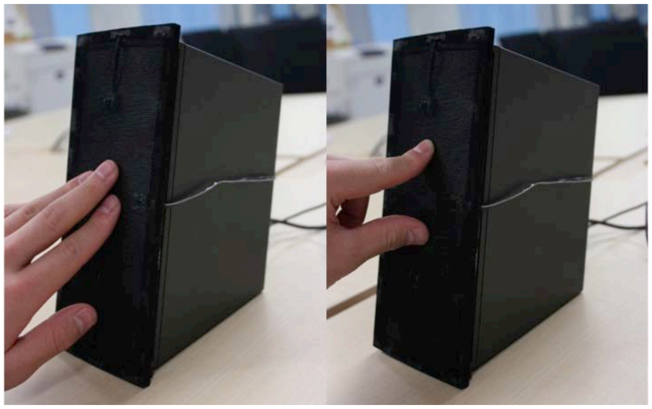

Figure 11: Volume, track-change, and fast-forward functions are controlled using finger dragging gestures.

Figure 12: System combining conventional sensor and skin sensor can detect posture of person sitting in a chair, especially slipping movement.

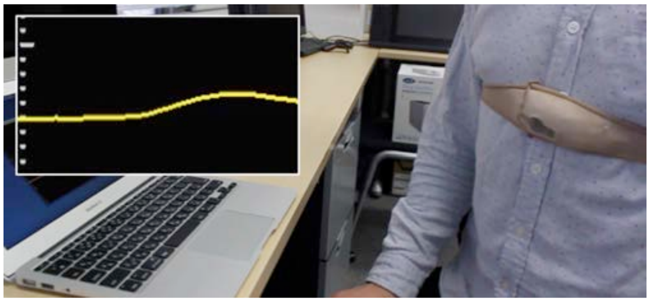

Figure 13: Breathing is captured by our method.

Human Body – Since a stocking is obviously a suitable covering for human skin, we prototyped an application that illustrates the utility of such an application. It is a simple breathing sensor that measures the stretch of a stocking bound around a person's chest (Figure 13). Its continuously detects the respiration rate and depth.

LIMITATION AND FUTURE WORK

Our skin-like sensor is a "proof-of-concept" implementation, so there are some limitations. The photoreflectors are affected by ambient light such as from an electric lamp or sunlight. We plan to implement a filtering system using light modulation that separates IR light emitted by the LEDs in the photoreflectors from ambient light. Photoreflectors also detects the user's hand or other objects if they enter the sensor's detection field. These problems do not occur when using a photo interrupter. However, since a photo interrupter is larger than a photoreflector, we need to establish a method for determining which one to use depending on the application.

Another problem is the durability of the stocking. The 20 denier stocking we mainly used in this research is torn apart when a force greater than 6N is applied. This problem can be overcome by using a stocking with a denier value appropriate for the target application. The color of the stocking affects the sensor value, we plan to generalize the relationship between stocking color and photoreflector sensor value.

As future practical applications, our method is suitable for wearable interface applications. Users can wear the material on the arm to detect interaction. Some of the intended applications are in the medical field: continuous human body monitoring such as muscle movement and body volume changes (edema). Also, it is possible to log dynamic body shape change (e.g. exercising, working, eating).

CONCLUSION

We have demonstrated a simple low-cost skin-like interface that can be easily attached to curved as well as flat surfaces and used to detect and measure tangential force interactions such as pinching and dragging. The sensor consists of photoreflectors and elastic fabric such as stocking and rubber membrane. The photoreflectors are used to measure the ratio of expansion and contraction of the stocking on the basis of changes in the transmissivity of IR light passing through the stocking. Since a stocking is thin, stretchable, and semi-transparent, it can be easily attached to various types of objects such as mobile devices, robots, and different parts of the body as well as to conventional pressure sensors. It presents natural haptic feedback in accordance with the amount of force exerted. Multiple photoreflectors could determine the direction of a two-dimensional force. Prototyping of a variety of example applications illustrated the utility of such a system.

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