Sensor Applications

An Embroidery Touch Sensor with Layered Structure of Conductive and Non-Conductive Threads

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Manuscript received June 7, 2017; revised June 21, 2017; accepted July 6, 2017. Date of publication July 12, 2017; date of current version July 12, 2017.

Abstract—Textile-based touch sensing methods for ubiquitous and wearable interfaces employ multiple independent or specific shaped electrodes, leading to limitations on three aspects: design freedom of electrode shape, durability, and simple production. We introduce the creation approach of an embroidery touch sensor by adding embroidery using non-conductive threads on top of an electrode made of conductive threads. Changes of stitch densities of the non-conductive thread embroidery lead to differences in electrical properties, which can be useful to distinguish which part of the embroidery is touched. Our method enables the creation of touch-sensitive embroidery with high design freedom of electrode shape and durability in a simple process.

Index Terms—Touch sensing, electronic textile (e-textile), fabric, embroidery.

I. INTRODUCTION

Textile touch sensors are the most common approach to achieving ubiquitous and wearable interfaces on fabric. Previous research provides a variety of touch-sensing methods by sewing conductive threads in specific structures while maintaining the flexibility and durability of the fabric sensor [1]–[4]. These approaches achieve different touch-sensing capabilities, but further research is needed to overcome three major limitations. Firstly, the complexity reduction in circuit design is critical for durability. To achieve touch-sensitive capabilities in multiple locations, developers may use separate electrodes, which is not desirable as it increases the complexity of a circuit design because fabric and circuit connections increase. While an electrode in a linear structure with specific patterns (e.g., a meander curve) may address this issue, this approach has a limitation concerning the shape of the electrode. The shape has to be representable with a single stroke. Thus, an electrode to be designed cannot have a branched structure. Although multi-layered fabrics (e.g., Separating touch electrodes and wiring) can overcome this limitation, this would lead to higher costs in production. To simplify the overall structure of embroidery, it is also desirable to place all electrodes and wiring in one fabric layer (i.e., placing all of them on the surface of a fabric). Otherwise, an additional process for circuit design and implementation across fabric layers would be necessary, hampers a quick production of touch-sensitive embroidery. Therefore, existing methods are limited in any of the three aspects of electrode shape design flexibility, durability, and simple production.

The parameters of fabric sensor creation are not only the shape and arrangement of the electrodes, but also the structure of textiles created by overlapping and interlacing threads. Especially, embroidery allows precise control of thread interlacement by adjusting manufacturing parameters (e.g., stitch density amd stitch length) using a computerized embroidery machine. This change in interlacement causes a change in electrical properties. Therefore, several previous research has begun to account for embroidery manufacturing parameters in the sensor design [5], [6].

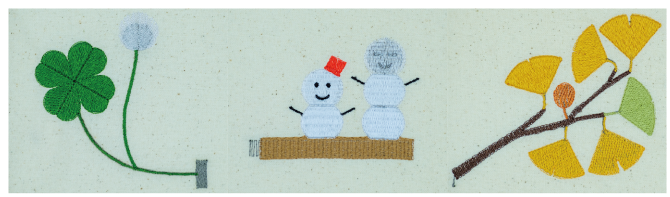

Fig. 1: Examples of touch-sensitive embroideries using our approach: (a) a clover, (b) a snowman, and (c) a ginkgo branch. Our approach adds a non-conductive thread embroidery over an electrode made of conductive threads. By controlling the stitching densities of the upper layer embroidery, developers can achieve different electrical properties at each part of the embroidery. In this manner, it can differentiate touch locations.

We present our work on an embroidery touch sensor design by changing the embroidery design parameters for each position. Our approach overlays an electrode made of conductive threads with embroidery using non-conductive threads. By employing different stitch densities for the non-conductive thread embroidery, the entire embroidery exhibits different electrical properties, and a system can exploit it for differentiating touch locations. In this manner, our approach has advantages from three perspectives: design flexibility, durability, and production. For the embroidery design perspective, the electrode shape of our method has a high degree of freedom, such as a branched structure, and there is no restriction on the position of the sensor connection. In addition, visual differences by

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Associate Editor: Alan Smithee.
Digital Object Identifier 10.1109/LSENS.2017.0000000

stitch density of non-conductive thread embroideries can be subtle though their electrical properties are different. These offer a unique capability in terms of the appearance design of embroideries. This gives designers further freedom in their touch-sensitive embroidery designs. For durability perspective, embroideries with our approach can achieve touch-sensing capabilities with a single connection between the embroidery electrode and the sensing circuit. For production perspective, our approach only involves the placement of electrodes and wiring on the surface of a fabric, which enables the creation of embroideries with a commercially-available embroidery sewing machine. Our method enables the creation of touch-sensitive embroidery with high design freedom of electrode shape and durability in a simple process (as shown in Figure 1).

II. RELATED WORK

Touch detection is a fundamental interactive capability of e-textiles. Touch detection approaches for e-textile from the perspective of electrode design, in general, are categorized into three approaches: using separate electrodes, using a matrix-structured electrode, and using a linear-structured electrode.

Using separate electrodes is a method of detecting touch position by arranging multiple electrodes that are completely isolated from each other [7]. This is the most straightforward approach, and developers can easily control where to sense by allocating independent electrodes. A main shortcoming of this approach is that it requires wiring and connections between each electrode and external sensing circuits, which increases the complexity of the overall circuit design and its durability. Moreover, it is challenging to increase the input resolution as embedding many wires in a high density would likely cause hardware deficiency (e.g., short circuits between conductive threads).

A matrix-structured electrode involves structures made of two layers: one consisting of electrode rows, while the other of electrode columns [3], [4], [8]. When a user touches the fabric, these two layers contact, causing resistive or capacitive changes. While this approach allows developers to create a large touch-sensitive area, it still suffers from similar issues as the approach of using separate electrodes.

A linear-structured electrode comprises a single-line electrode arranged in a meander curve [1], [2]. When a user touches the embroidery, the electrode detects the capacitance by using a current differential along the linear path electrode. A unique advantage of this approach is that it simplifies the hardware design, which also contributes to improved durability. However, its fundamental limitation is that the electrode design must be linear; thus, this approach cannot achieve designs with branches.

In summary, existing approaches for touch-sensitive embroidery using conductive thread have several design limitations, particularly in a narrow space or with branches. Therefore, overcoming these limitations would further improve the input expressiveness of touch-sensitive embroidery as well as bringing more flexibility to electrode designs.

III. TOUCH-SENSITIVE LAYERED EMBROIDERY CREATION METHOD

A. Principle

To address the limitations described in the previous section, our approach introduces an additional embroidery layer made of non-conductive thread over electrodes using conductive thread. By changing the stitch density of the upper-layer embroidery, the distance between the finger and the electrode made of conductive threads (the lower-layer embroidery). This difference in the distance leads to a change in capacitance. In this manner, designed electrodes provide different electrical responses and can differentiate user's contact positions.

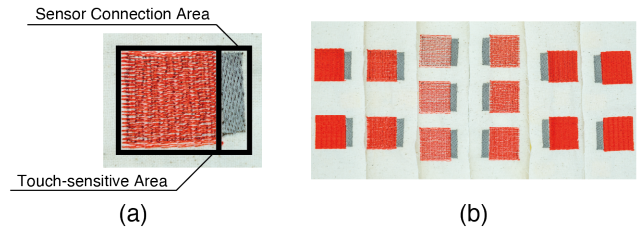

Fig. 2: The electrodes used for our preliminary evaluation. (a) Each electrode consists of two parts: the touch-sensitive part and sensor connection part. (b) We created 14 embroideries with different stitch densities.

B. Embroidery Implementation

We use a computerized sewing machine (Inovis NX2800DW, Brother Industries, Ltd.) to fabricate embroidery. The conductive thread we used for prototyping is Smart-X, Fujix, Inc., which is 100% nylon silver-coated thread. Its line resistance is approximately $250\,\Omega\,\mathrm{m}^{-1}$. The non-conductive thread is 100% polyester embroidery thread (Ultrapos embroidery thread, Brother Industries, Ltd.). The cloth is 100% cotton sheeting, and we use an adhesive core to prevent distortion of the embroidery due to shrinkage of the cloth. We designed the embroidery data using SHISHU-PRO-11 (Brother Industries, Ltd.).

To quantitatively examine the effect of the stitch density of the non-conductive thread embroidery, we fabricated touch-sensitive square-shaped embroidery (25 mm^2) with different stitch densities. The electrode made of the conductive thread is divided into two parts: the touch-sensitive area for interaction and the sensor connection area (Figure 2 (a)). The sewing pitch of the electrode is fixed at 4 mm for the touch-sensitive and sensor connection areas, respectively.

We then covered the electrode made of conductive thread by embroidering with non-conductive thread. We employed 14 different stitch densities (1.0, 1.5, 1.8, 2.0, 2.2, 2.5, 2.8, 3.0, 4.0, 6.0, 8.0, 10.0, 12.0, and 14.0 threads/mm) in our current preliminary exploration (Figure 2 (b)). To avoid damaging the electrode with the needle, the deviation (misalignment of stitches) of the non-conductive thread embroidery and its stitch length was set to 50% and 4 mm, respectively. In this manner, the needle would not strike where the conductive threads run. We also deliberately designed the touch-sensitive area to be slightly smaller than the non-conductive thread embroidery layer so that it does not protrude. While we did not perform formal evaluations, differences in stitch density are not distinguishable visually except for cases where the density becomes lower than 2.0 threads/mm. This brings another benefit in terms of embroidery appearance design.

C. Sensing Method

We use SFCS (Swept Frequency Capacitive Sensing) [9], a method of impedance measurement using signals of various frequencies, as a sensing technique. We followed the implementation by Honigman

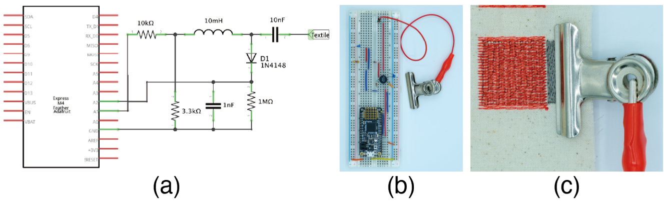

Fig. 3: (a) circuit schematic. (b) We implemented it on a breadboard. (c) Connection of electrodes and circuits by a clip.

et al. [10]. The microcontroller board employed is an Adafruit Feather M4 Express (Adafruit Industries) with an ATSAMD51J19A (Microchip Technology) and sweeps at 1980 frequencies in the range of 300 kHz to 27.5 kHz. We implemented it on a breadboard and connected the electrode to the circuit with a clip (Figure 3). We use random forests to infer which embroidery is contacted based on SFCS responses.

IV. EVALUATION

We conducted the experiment to evaluate what stitch densities are identifiable on touch sensing. This study protocol was approved by our IRB.

A. Data Collection Procedure

We recruited 11 participants (Male:5, Female:5, Other:1) aged between 19 to 24 years old (mean: 21.5, SD: 1.5). Participants used a palm rest to avoid touching another electrode embroidered on the same cloth. Participants touched each electrode ten times by moving only the index finger while keeping the hand on the palm rest, and we collected the SFCS responses. We instructed the participants on the intensity and angle of touching the electrode in order to collect accurate data. In this experiment, we used electrodes with 14 different stitch densities (shown in the Figure 2 (b)).

B. Results & Discussion

Figure 4 shows the average impedance of the embroidery at different stitch densities. The results suggest that the stitch density of the non-conductive thread embroidery influences the impedance of the overall touch-sensitive embroidery. In addition, the results show that the waveforms at stitch densities of 1.0, 1.5, and 1.8 threads/mm are significantly different from those at other stitch densities. This is because at these stitch densities, the finger directly touches the conductive threads due to the wide stitch spacing, whereas at stitch densities of 2.0 threads/mm or higher, the finger does not directly touch the conductive threads. Figure 6 shows the average of all participants' classification scores (macro-F1) through the stratified 3-fold cross-validation (k=3) using random forests. The accuracy improves as the number of stitch densities decreases. In particular, macro-F1 is 0.96 for classifying eight stitch densities, which is sufficient for identification. The accuracy depicted in Figure 6 represents the mean accuracy obtained through individual training and assessment for each participant in the study. Given the variation in pressing force among users, which influences sensing outcomes, there exists a potential for diminished accuracy if a universally trained model is employed. Therefore, by tuning the model for each user, we can expect accuracy levels similar to those found in the current results. Table 1 shows the number of stitch densities and their combinations for classification.

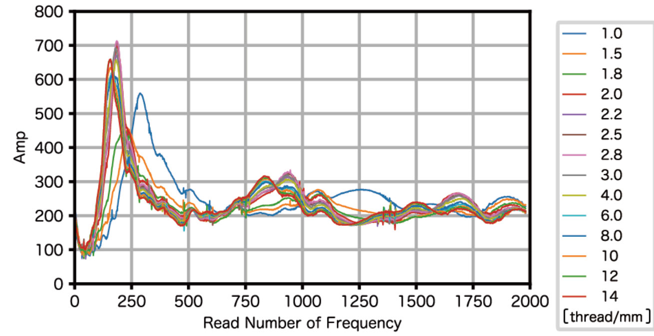

Fig. 4: Impedance during touch for each stitch density of non-conductive threads.

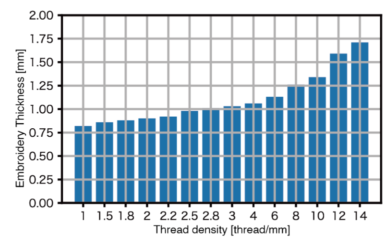

Fig. 5: Embroidery thickness for each stitch density.

Figure 5 shows the thickness of the non-conductive thread embroidery. The thickness of the non-conductive thread embroidery is one of the contributing factors to the impedance differences because the capacitance is inversely proportional to the thickness. The change of embroidery thickness causes the distance between an electrode and a finger to increase. This result, therefore, confirms electrical property changes by different stitch densities.

V. EXAMPLES OF TOUCH-SENSITIVE EMBROIDERY

A. Clover

Figure 7 (a) shows a touch-sensitive embroidery of a clover. This touch-sensitive embroidery can identify touches at six locations of the clover's four leaves, flower, and stem. The external sensing unit is connected to the lower right area where the conductive threads are exposed. It is difficult to detect touch positions on these kinds of shapes using existing methods because it has a branched structure. Using separate electrodes would result in five different wiring routes, which would increase the complexity of a circuit design. Our embroidery enables touch detection by using different stitch densities of non-conductive threads at each touch-sensitive part. The classification score (macro-F1) of recognizing the six touch locations is 0.866.

B. Snowmen

Figure 7 (b) shows a touch-sensitive embroidery of a snowman. This touch-sensitive embroidery can identify touches at six locations of five circles of the two snowmen and the ground. The sensor connection is at the lower left area (left edge of the ground). These two snowmen consist of a branched structure. The touch sensing capability could be achievable with a linear-structured electrode if we place the sensor connection point at the top of the higher snowman (e.g., starting from its top to the bottom, going through the ground, and going up to the top of the other snowman). However, this would

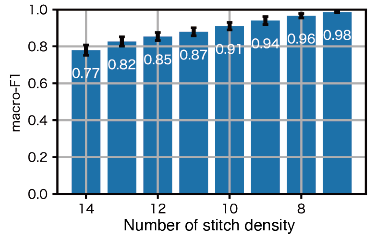

Fig. 6: Number of stitch densities and classification score.

Table 1: Combination of stitch density. Underlines show the stitch density removed when the number of classification targets is reduced by one.

Number	Combination of stitch density
14	1.0, 1.5, 1.8, 2.0, 2.2, 2.5, 2.8, 3.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0
13	1.0, 1.5, 1.8, 2.0, 2.2, 2.8, 3.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0
12	1.0, 1.5, 1.8, 2.2, 2.8, 3.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0
11	1.0, 1.5, 1.8, 2.2, 2.8, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0
10	1.0, 1.5, 1.8, 2.2, 2.8, 4.0, 6.0, 8.0, 10.0, 14.0
9	1.0, 1.5, 1.8, 2.2, 2.8, 4.0, 8.0, 10.0, 14.0
8	1.0, 1.5, 2.2, 2.8, 4.0, 8.0, 10.0, 14.0
7	1.0, 1.5, 2.2, 2.8, 8.0, 10.0, 14.0

degrade the appearance of the embroidery. But the sensor connection point in our embroidery can be placed anywhere, which creates an advantage in circuit and embroidery design. The classification score (macro-F1) of recognizing the six touch locations is 0.933.

C. Ginkgo branch

Figure 7 (c) shows a touch-sensitive embroidery of a ginkgo branch. This touch-sensitive embroidery can identify touches at 8 locations of 6 leaves, the ginkgo nut, and the branch itself. The sensor connection is at the lower left area (origin of the branch). This shape has many sub-branches that become too narrow to contain many wires or conductive threads. However, our method enables the detection of touch position by changing the stitch density of each leaf. Our technique does not detract from the appearance of the embroidery, because differences in stitch density are almost indistinguishable. In this example, we create embroideries with stitch densities higher than 2.5 thread/mm, and thus the appearance differences in the touch-sensitive parts are subtle. This example thus demonstrates unique freedom in embroidery design developers can enjoy with our method while maintaining touch sensing capabilities. The classification score (macro-F1) of recognizing the eight touch locations is 0.962.

VI. CONCLUSION AND FUTURE WORK

We introduce a touch-sensitive embroidery creation method that utilizes capacitive changes caused by overlaid non-conductive thread embroidery. This creates different electrical properties by controlling the stitch densities of the upper layer embroidery, enabling touch differentiation. In this paper, we explain the principle of the technique and report touch classification performance results. We also demonstrate three examples of touch-sensitive embroideries as examples of our sensor creation methods.

Our future work includes computational design methods of an embroidery touch sensor as well as further investigations to increase input expressiveness (e.g., differentiating the pressure of a contact).

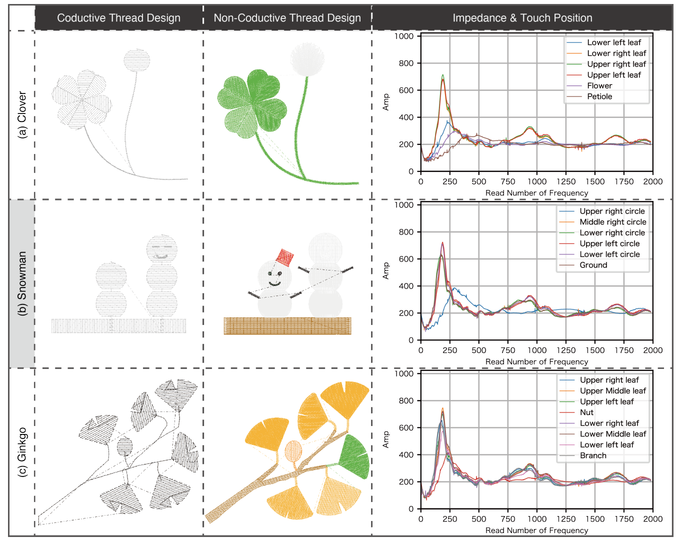

Fig. 7: Three examples of touch-sensitive embroidery.

ACKNOWLEDGMENT

This research is part of the results of Value Exchange Engineering, a joint research project between Mercari, Inc. and the RIISE. PEARL YACHT CORPORATION also provided advice on the fabrication of the embroidery.

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