Functional Fabric Pattern—Examining the Case of Pressure Detection and Localization

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***Abstract*—This paper proposes a method for modifying the functionality of conductive fabric by using different weaves on the same materials. After introducing the method, this paper demonstrates its effectiveness using an example involving fabric pressure sensors. The fabric pressure sensors in this paper can alter the electrical properties of a given fabric—while using the same material in both the warp and weft directions—by changing the weaving technique at certain locations within the fabric. Conventional fabric pressure sensors require separate, location-specific outputs; every increase in the number of detection locations requires an increase in the number of detector circuit input cables. However, our fabric pressure sensors can detect location and external force via just three input–output cables.**

***Index Terms*—Conductive fabric, flexible sensors, manufactured textile products.**

I. Introduction

E-TEXTILES, which integrate electronic circuits with textile products (fabrics), are now being practically applied as input interfaces for biosignal measurements and electronic devices. In addition to being bendable and washable, like normal textiles, e-textiles for use on or near the human body, such as clothes and bedding among others, can also detect biosignals and behavioral input. Given their capabilities, e-textiles have the potential to play significant roles as terminal devices in the context of the Internet of Things (IoT).

Most e-textiles achieve electrical functionality by either: 1) addition of electrodes to the fabric ([1]–[7], as described in Section II-A); or 2) replacement of certain warp and weft yarns with electrical wires ([8]–[17], as described in Section II-B.) This paper proposes a new concept: 3) *modifying the electrical functionality by changing the fabric-weaving techniques*. This novel conceptual approach not only makes it possible to avoid bringing skin in contact with metallic electrodes but also eliminates the need for large numbers of input–output cables.

What would happen if electrically conductive wires were used as yarns in a fabric? It would be possible to choose whether to bring each wire to the surface—over the crosswise yarn—or to hide it below the surface—under the crosswise yarn—at each grid point. This means that the same materials, using the same power source, could *produce different electrical properties depending on the crossing patterns*. Our method, which is based on this supposition, involves designing fabric patterns with capacitance levels that change in accordance with the pressurization position. We show that capacitance can be designed by partially changing the weave in a three-layered conductive fabric. Each layer includes conductive yarns with an insulating coating. In the first layer, different numbers of conductive yarns appear on the top, depending on the location. In the second and third layers, the weave does not change at any position. When the fabric is pressed, the distance between the layers becomes shorter, thereby the electrostatic capacitance. The capacitance generated between the second and third layers changes based on the external applied force independent of the pressed location. The capacitance between the first and second layers depends on both the external force and the pressed location. Thus, together, the two observed capacitances indicate the strength of the applied force and the location where it is applied. We confirm that the amount of change in capacitance varies according to differences in the weaving pattern.

The remainder of this paper is organized as follows. Section II provides an overview of related research. Section III explains the process underlying detecting positions based on the weaving technique. Section IV describes the implementation method in further detail, and Section V presents the results of a prototype experiment. Section VI concludes this paper with a general summary.

II. Related Work

In this section, we introduce previous methods related to e-textiles used to add functions to fabrics with metallic electrodes. We also describe the methods to replace yarns with

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conductive wires in fabric and overview the work on designing woven patterns for general textiles.

A. E-Textiles With Metallic Electrodes

E-textiles functionalized by metallic electrodes are famous as new IoT devices. Lee *et al.* [1] proposed pressure sensors that used Kevlar fiber coated with polymer. The sensors are based on sewing coated yarns into clothes or gloves, which detect pressure in multiple locations. The pressure is estimated from the fluctuation of the capacitance of the conductive yarns. Six-legged robot and drones incorporating such pressure sensors were operated using pressure detection.

Liu *et al.* [2] proposed a bedsheet that obtains pressure distribution by combining cloth with uniformly arranged conductive wires. The bedsheet uses two pieces of cloth, one with 128 conductive wires oriented horizontally and other with 64 conductive wires oriented vertically. When these two pieces of cloth are placed together and an external force is applied, the pressure distribution is obtained from the changes in electric resistance between the orthogonal conductive wires. In the same manner, several works have been conducted to acquire pressure distribution by crossing conductive wires. Baldoli *et al.* [3] obtained pressure distribution for application to leg-compression therapy. Xu *et al.* [4] proposed a sitting mat for analyzing the pressure distribution of the human body in a seated posture. Fabric that can sense and measure pressure is used not only to measure physical quantities but also to measure human–computer interaction.

Wicaksono *et al.* [5] proposed a keyboard composed of multiple layers of different fabrics, such as knitwear and mesh, to detect touch, pressure, and stretching of the fabric. Peshock *et al.* [6] proposed a wearable input glove that can input alphanumeric characters by attaching 15 magnetic patches and conductive cloth to the glove. Molla *et al.* [7] sewed conductive yarns to efficiently connect electronic components attached to a cloth and to a power supply. An application involving a display made of light emitting diodes (LEDs) arranged on the fabric was previously shown by them.

B. E-Textiles Composed of Conductive Yarns

Creating functional textiles by replacing part of the warps and wefts of the woven fabric with conductive yarns have also been proposed. By weaving highly parallelized conductive fibers [8] or conductive elastomer [9] in a grid of warps and wefts, the capacity may be changed according to the pressure applied at each grid point. When pressure is applied, the distance between the conductive materials changes. The position and the pressure exerted by the human body is estimated based on the capacitance. One advantage of these sensors is their flexibility and large size. The sensors have been applied to a keyboard that can be folded [10] and a bedsheet with 88 $\times$ 45 detection points [11].

Sensing devices composed of conductive fibers were introduced in a survey of textile-based wearable electronics [12]. By intersecting carbon fibers and aluminum fibers in a grid pattern, the bend and twist of a plane can be detected, based on the resistance value [13]. Poupyrev *et al.* [14] have sewn conductive yarns coated with isolating fibers into fabric to operate electronic devices such as smartphones. The operating principle of the proposed fabric is similar to that of projection-type capacitance touch panels. By connecting conductive warps and wefts to an integrated circuit (IC) that detects the change in capacitance, the fabric detects the position touched by the user wearing the fabric. By covering the entire fabric rather than individual fibers with reduced graphene, it is possible to sense both the force and the position of applied pressure [15]. The electrode can also be realized by printing a conductive material onto the fabric [16]. By observing changes in the capacitance of multiple sensors around the wrist joint, the degree of bending of the wrist can be estimated [17]. Both the works described above utilize a uniform weave on a single plane and have not used the idea of changing weave patterns within the fabric locally.

C. Design of Nonconductive Textiles

While e-textiles are evolving, the more general field of textiles has also been exploring the generation of fabric patterns that can preserve the design of an original image. While exploring this issue, we proposed that the technique used to increase the exposure of warp and weft yarns at specific positions could be converted in such a manner as to spatially vary the electrical characteristics of e-textiles. Our idea was inspired in part by the proposed method in Igarashi *et al.* [18] to control the intersection of yarns to faithfully reproduce tones of an arbitrary image. Their method of controlling the warps and wefts of fabric is applicable for controlling electrical properties of e-textiles.

The overall concept presented here centers on the structure of the fabric. Every fabric is a combination of warp (vertical) and weft (horizontal) yarns. If warp and weft strands are dyed with different colors, designers can weave them into an aesthetic pattern by crossing the yarns over and under each other at different locations and in different patterns. The overall color of the fabric aligns with the color of the yarn that appears more frequently on the surface; when warp yarns tend to go over weft yarns, the composite fabric color will gradually approach the color of the warp. Then, to create a visual pattern, a designer simply needs to adjust the warp–weft exposure ratios in certain locations.

All the fabrics used in existing e-textiles use only basic plain weave, and there is no discussion of how fabric is woven. In our approach, we change the weaving structure from region to region in order to design a fabric with different regions possessing different electrical characteristics. In the next section, we present an example of fabric pressure sensors with different electrical characteristics for each location.

III. Functional Weave

A. Structure of Fabric and Its Capacitance

As shown in Fig. 1, warps and wefts intersect to form a woven fabric. Fig. 1 shows plain weave, which is the most basic woven structure. This structure has the maximum number of intersections per unit area of the various weave structures. The dotted line in the figure outlines one of the intersections of the warp and

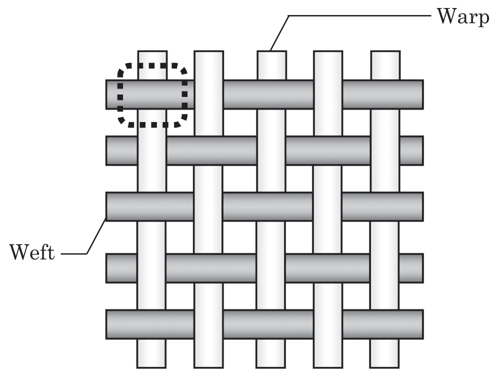


Fig. 1. Structure of plain weave.

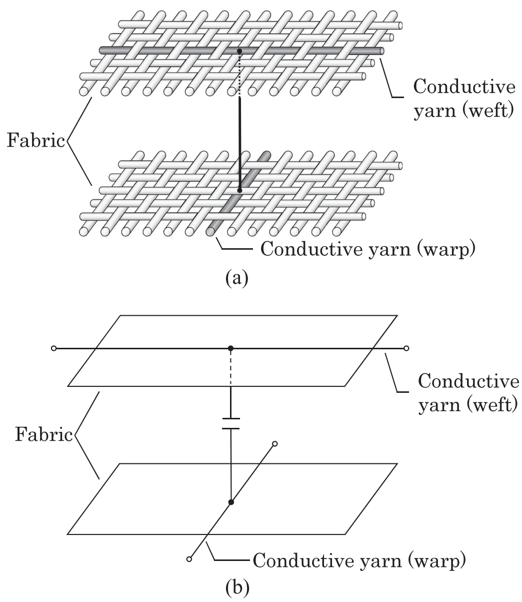


Fig. 2. Capacitor between two fabrics. (a) Relationship of conductive yarn. (b) Equivalent circuit.

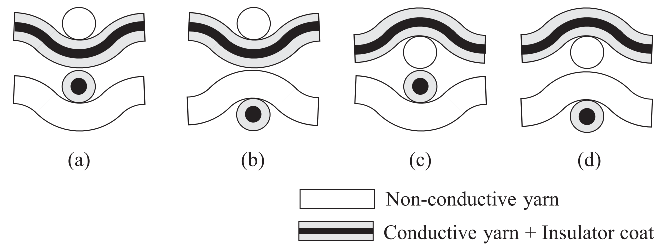


Fig. 3. Under–over relationships of conductive yarns and their separation distances.

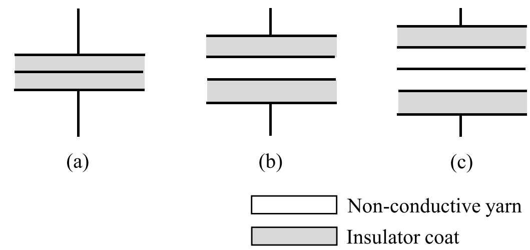


Fig. 4. Structures of capacitance corresponding to the weaves in Fig. 3. (a) N-N. (b) N-F, F-N. (c) F-F.

the weft. The fabric can be regarded as an object in which intersecting points are arranged in a planar manner. Here, consider two fabrics: 1) a woven fabric in which the warp is a conductive yarn; and 2) a woven fabric in which the weft is a conductive yarn, stacked as shown in Fig. 2(a). If each conductive yarn is insulated with a coating, then electrostatic capacitance will be generated between the conductive yarns. By controlling whether the warp and weft are under or over the counter weft and warp, respectively, the electrostatic capacitance can be changed. This is the essential conceptualization used in this paper.

As shown in Fig. 3, each intersection of the two fabrics can be classified into one of the four types. Note that the conductive yarns are coated with an insulating material. The thick black line represents conductive yarns, the gray section indicates the insulating coat, and the white indicates nonconductive yarns. Fig. 3(a) illustrates the weaving structure in which the distance between the conductive yarns is the smallest. The conductive yarns of the lower layer in Fig. 3(b) and those on the upper layer in Fig. 3(c) appear in the opposite direction with respect to the intersection point. Thus, the distance between the conductive yarns is increased. Fig. 3(d) depicts a weaving structure in which the conductive yarns appear in the opposite direction of the intersection, thereby resulting in the largest distance between the conductive yarns. Fig. 4 depicts these weave patterns as capacitors. The white part represents the nonconductive yarns, and the gray part indicates the insulator coat on the conductive yarns. The capacitor depicted in Fig. 4(a) is formed only by the insulator coating. As illustrated in Fig. 3(a), this configuration has the smallest distance between conducting yarns. The capacitor depicted in Fig. 4(c) is formed by the distance between the insulating coat and the two nonconductive yarns, in the configuration shown in Fig. 3(d), which has the largest distance between conducting yarns. In Fig. 3(b) and (c), the distance between the conductive yarns is the same. Two layers of insulator-coated yarn and one layer of nonconductive yarn separate the two electrodes of conductive yarns. Both are depicted in Fig. 4(b). The capacitor is formed by the insulating coat and one nonconductive yarn. The structure with the smallest distance is denoted by N–N (Near–Near), and the structure with the largest distance is denoted by F–F (Far–Far). The distances denoted as N–F (Near–Far) and F–N (Far–Near) are the same as previously described. The difference between them is that the conductive yarn is on the upper and lower sides, respectively. The capacitors shown in Fig. 4(a)–(c) are denoted as C_{nn}, C_{nf}, and C_{ff}, and these capacitances are represented by the following equations:

$$C_{\mathrm{nn}} = \varepsilon_{ri}\varepsilon_0 \frac{S}{2T_i} \tag{1}$$

$$C_{\mathrm{nf}} = \varepsilon_{ry}\varepsilon_{ri}\varepsilon_0 \frac{S}{2T_i\varepsilon_{ry} + T_y\varepsilon_{ri}} \tag{2}$$

$$C_{\mathrm{ff}} = \varepsilon_{ry}\varepsilon_{ri}\varepsilon_0 \frac{S}{2T_i\varepsilon_{ry} + 2T_y\varepsilon_{ri}} \tag{3}$$

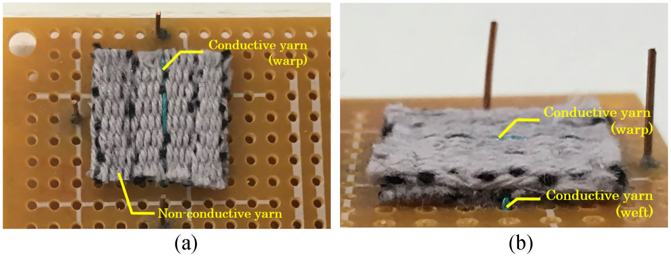


Fig. 5. Prototype fabric for examining the characteristics of a capacitor composed of conductive yarns. Two conductive yarns intersect perpendicularly at the center of the prototype fabric, and they are separated by nonconductive yarns. This results in one F–F type capacitor in the fabric, as shown in Figs. 2, 3(d), and 4(c). (a) Top view. (b) Side view.

where ε_0, ε_{ri}, and ε_{ry} are the relative permittivity of vacuum, the insulating coat, and the nonconductive yarn; T_i and T_y are the thicknesses of the insulator coat and the nonconductive yarn; and S is the surface area between conductive yarns. From (1)–(3), it is evident that $C_{\rm nn}$ has the largest capacitance under the same pressure.

Furthermore, if the fabric is pressed by applying an external force, the surface area increases and the spacing between the conductive yarns narrows; $C_{\rm nn}$, $C_{\rm nf}$, and $C_{\rm ff}$ then increase according to (1), (2), and (3), respectively. The amount of change in area and spacing when pressure is applied is not constant between the types of capacitors. Experimental differences in the capacitance values of the capacitors are examined in detail in the next section.

B. Characteristics of a Capacitor Composed of Conductive Yarns

In this section, we examine the practical relationship between the external applied force and the capacitance value, and how it varies with the crossing pattern (i.e., woven structure). While the theoretical relationship was discussed in the previous section, here it is investigated using prototype fabrics.

Two fabrics with different weaves are stacked as shown in Fig. 5(a) and (b). We arranged one conductive yarn with the insulating coat in the fabric composed of nonconductive yarns. One fabric is stacked on the other fabric, and rotated 90° on its horizontal axis. This results in one F–F type capacitor in the fabric, as illustrated in Figs. 2, 3(d), and 4(c). Cotton yarn is used as the nonconductive yarn, and AG-poss T1 is used as the conductive yarn. AG-poss T1 is a silver-plated nylon fiber coated with 12 μm of polyester. The outer diameter of the AG-poss T1 fiber is 512 μm, and it has low conductor resistance (5 $\Omega/10$ cm). This coating prevents electrical shock to the human body, even if a person touches the fabric. The two conductive yarns on the two fabrics are orthogonal. We apply an external force to the fabric, and then measure the change in capacitance of the capacitor between the conductive yarns.

As shown in Fig. 6, an external force is applied to the fabric using an RZ-10 digital force gauge. The corresponding electrostatic capacitance is measured using an inductance, capacitance, and resistance (LCR) meter ZM2371. The external force applied to the fabric ranged from 0 to 50 N, in increments of 5 N. The value of the capacitance obtained at each force was recorded. This operation was performed five times for each force, and the average value was adopted as the result. The conditions for capacitance measurement are presented in Table I.

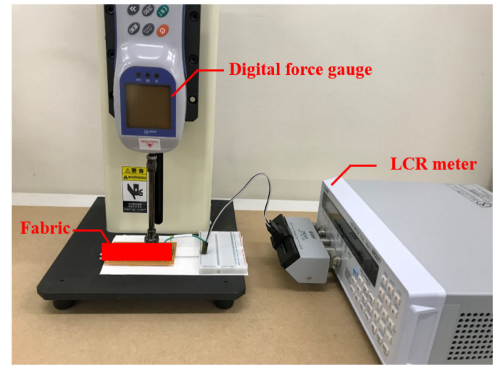


Fig. 6. Experimental environment for measuring capacitance.

TABLE I
CONDITIONS FOR MEASUREMENT OF CAPACITANCE

External force[N]	0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50
Area [cm^2]	1.5 × 1.5
Input voltage[V]	1
Input frequency [kHz]	100
Connection to LCR Meter	Four-terminal sensing

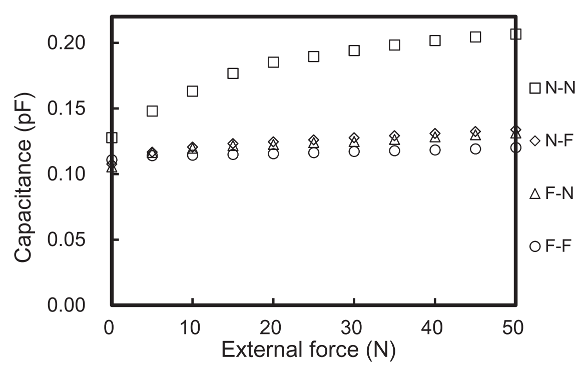


Fig. 7. Absolute values of capacitance for prototype fabrics.

The capacitance-measurement results are illustrated in Fig. 7. From Fig. 7, we can see that the smallest change in capacitance value for different external forces occurred in the F–F structure, which was about 0.11 pF with no external force. Application of 50 N external force increased capacitance to approximately 0.12 pF. The F–F structure corresponds to Figs. 2, 3(d), 4(c), and 5. In N–N, the conductive yarns are positioned on opposite sides compared to F–F; moreover, the capacitance value was 0.13 pF when no external force was applied and approximately 0.21 pF under an external force of 50 N. Fig. 4(b) and (2) indicate that the capacitors N–F and F–N share the same construction. As shown in Figs. 7 and 8, N–F and F–N showed almost the same change in capacitance from 0 to 50 N. The relative change from

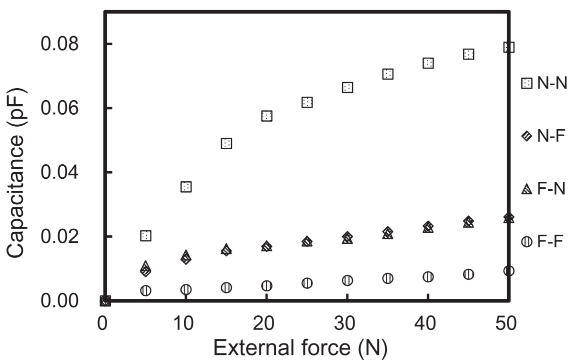


Fig. 8. Relative values of capacitance for prototype fabrics.

the state of 0 N is depicted in Fig. 8. The result confirms that we can treat N–F and F–N as being essentially the same capacitor. The relationship between the thicknesses of the insulator layers produced the differences in the capacitors, as described by (1)–(3) in Section III-A. The capacitance of N–N changed the most, increasing by 0.08 pF with an applied external force of 50 N, while the capacitance of F–F increased by only approximately 0.01 pF.

The above results show that the amount of change in capacitance between the intersections of the conductive yarns changes on the basis of how the fabrics are stacked.

C. Pressure Detection and Location Estimation

In this section, we discuss the structure of the proposed fabric and the method for detecting the location of the pressure, and estimate the applied pressure.

The capacitance discussed in the previous section was generated by one intersection of a single warp yarn and a single weft yarn. Actual fabric consists of multiple conductive yarns in the warp and weft, and thus possesses multiple intersections. Multiple intersections can be represented as in Fig. 9(a) and (b); the capacitors of the fabrics are assumed to be arranged in parallel. Fig. 9(a) shows the conductive yarns of the upper layer that cross the conductive yarns of the lower layer when two fabrics are layered. Fig. 9(b) shows the capacitor constructed by the yarns in Fig. 9(a). We intend the amount of change in capacitance to be different for each region; therefore, we summed the combined capacitance at each intersection point of the fabrics. This composite capacitance is realized by electrically connecting the conductive yarns in each layer and making a planar electrode. We generate the plane by allowing the yarns to go around the fabric, as shown in Fig. 9. Other options include connecting each conductive yarn to one conductive material or directly connecting the yarns to each other, but these options require additional wiring. Therefore, we selected the option of allowing the yarns to go around the fabric. The capacitance C_{fab} between the fabric layers is ideally represented by the sum of the capacitors of each intersection. If we denote type $\in \{\text{nn}, \text{nf}, \text{ff}\}$, C_{fab} is represented by the following equation:

$$C_{\text{fab}} = \sum_{\text{type}} n_{\text{type}} C_{\text{type}} \tag{4}$$

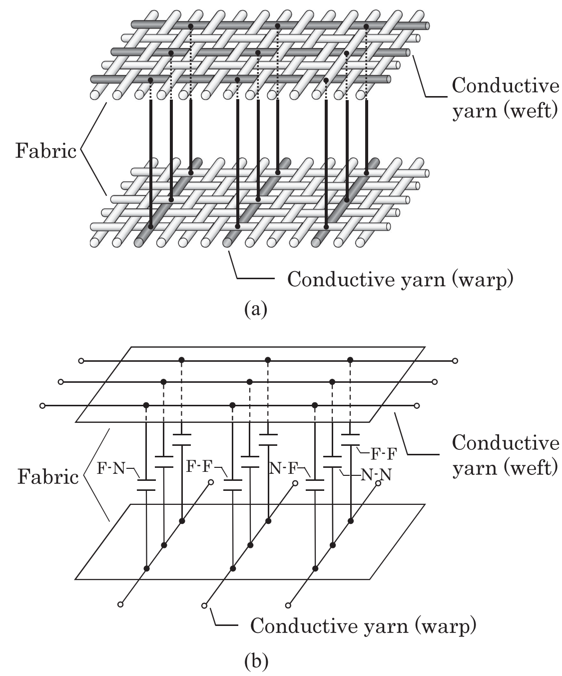


Fig. 9. Relationship of warps and wefts in two layers of fabric. In this figure, the combined capacitor is composed of six F–F type capacitors and one each of N–N, F–N, and N–F capacitors. According to (4), C_{fab} becomes C_{nn} + 2C_{nf} + 6 C_{ff}. (a) Relationship of conductive yarn. (b) Equivalent circuit.

where n_{type} is the number of C_{type} generated between fabric layers. Actual C_{fab} includes the error from parasitic capacitances. When the number of warps is represented by n_{warp} and the number of wefts by n_{weft}, the following equation is always satisfied:

$$\sum_{\text{type}} n_{\text{type}} = n_{\text{weft}} \cdot n_{\text{warp}}. \tag{5}$$

When an external force is applied to the fabric, the capacitance at each position increases. By arranging the same type of capacitors across the entire fabric, the amount of pressure can be estimated. By arranging different types of capacitors at different locations on the fabric, different changes in capacitance are obtained for the same amount of applied pressure. To estimate both pressure and position simultaneously, we propose a three-layer structure, as schematically depicted in Fig. 10(a) and (b).

Each plane in Fig. 10(a) represents one layer of fabric. The solid lines in the planes indicate that the conductive yarns appear on the top, and the dotted line shows that the nonconductive yarns appear at the back. We call these the first layer, second layer, and third layer from top to bottom, as represented in Fig. 10(a). In the fabric, multiple conductive yarns are short-circuited at the ends. Assume that the conductive yarns are coated with nonconductive fibers; therefore, the conductive yarns in the different layers do not short-circuit one another. Because the conductive yarn of the second layer perpendicularly intersects the conductive yarns of the other layers, the intersections of the conductive yarns between the first and second

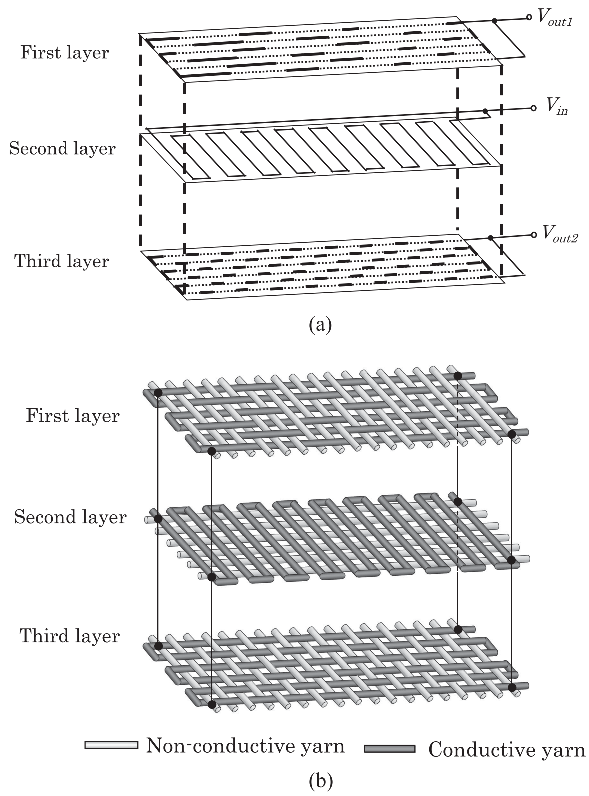


Fig. 10. Structure of the proposed fabric for pressure detection and localization.

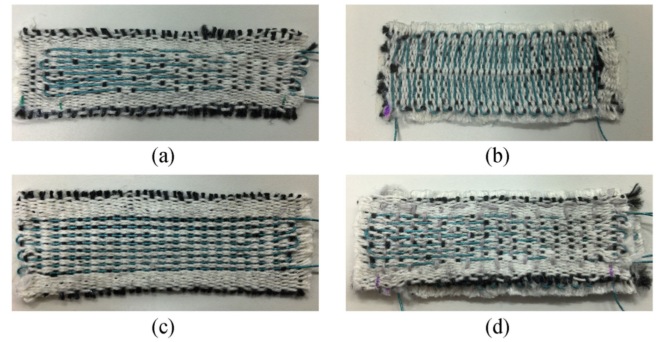


Fig. 11. Prototype fabrics. (a) First layer. (b) Second layer. (c) Third layer. (d) Stacked fabrics.

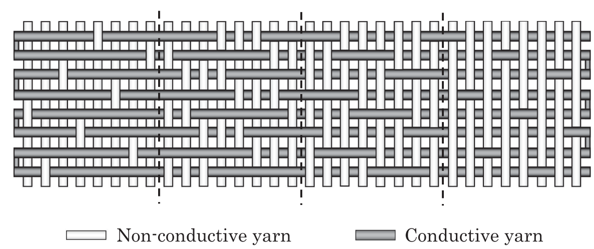


Fig. 12. Relationship of warps and wefts in the first layer.

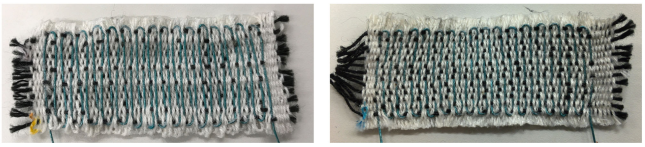
layers, and those between the second and third layers form the capacitor. In the first and third layers, conductive yarns are placed orthogonal to those of the second layer. In the first layer, closer to the right side, fewer conductive yarns appear on the top. Therefore, the capacitance increases toward the left side and decreases toward the right side. The capacitance value varies depending on which part of the fabric is pressed. The second layer in Fig. 10 is designed so that all the intersection points via the third layer consist of F–F type capacitance, as shown in Fig. 4(c); simultaneously, all the intersection points via the first layer consist of N–N, N–F, and F–N type capacitances, as shown in Fig. 4(a) and (b). Fig. 10 illustrates an example of how to weave conductive yarns, in which capacitors with different capacitances are arranged. The proposed fabric has three layers. The role of the second layer of fabric is to input the voltage, whereas the role of the first and third layers is to capture a response depending on the applied force and the location of the applied force.

IV. Prototype of Sensor for Pressure Detection and Localization

We created a prototype fabric with the proposed structure and confirmed that the capacitance differs depending on the applied pressure and where the force is applied.

Fig. 11 depicts the prototyped fabric, which was woven with a tabletop loom. The conductive yarn used in this fabric is the same as the one used in Section III. Fig. 11(a)–(c) correspond to the first, second, and third layers, respectively. The second and third layers have the same number of strands of conductive yarns on the top across all positions; meanwhile, the number of strands of conductive yarns appearing on the top in the first layer, as shown in Fig. 11(a), changes depending on the location. As schematically shown by the pattern in Fig. 12, each warp and each weft intersect more than once in an 8 × 8 square yarn of fabric, keeping form as a fabric. Igarashi *et al.* [18] showed that exposure of weft and warp yarns that are too long results in weakness against external forces such as scratching. Exposure of the yarns can be limited by ensuring that the warp and weft yarns intersect at least once for each row and each column in each $n \times n$ unit region. In the case of the first layer, by setting $n = 8$ for the conductive yarns, the number of continuously exposed intersection points of the weft yarn is suppressed to less than eight. The prototyped fabric contains a pattern of one conductive yarn followed by three nonconductive yarns. Therefore, each fabric contains 29 weft strands with eight strands of conductive yarn and 21 strands of nonconductive yarn. We stacked the three layers in the order of Fig. 11(a), (b), and (c), respectively, from top to bottom, and sewed them together with additional gray nonconductive yarns to align corresponding intersections, as shown in Fig. 11(d).

In order to confirm that the electrostatic capacitance varies according to the number of intersecting points for each weave, we prototyped two additional fabrics for the second layer that differ from that shown in Fig. 11(b). Fig. 13(a) and (b) show the two different weave patterns. Fig. 13(a) shows a fabric in which the intersection points of the conductive yarns are different from those in the fabric shown in Fig. 11(b); however, the



(a) (b)

Fig. 13. Two different fabric patterns for the second layer.

TABLE II
NUMBER OF INTERSECTIONS IN EACH REGION OF FABRICS 1 AND 2

Type of intersection	1st-2nd layer				2nd-3rd layer			
	A	B	C	D	A	B	C	D
N-N	8	24	40	56	0	0	0	0
N-F	0	0	0	0	0	0	0	0
F-N	56	40	24	8	32	32	32	32
F-F	0	0	0	0	32	32	32	32

TABLE III
NUMBER OF INTERSECTIONS IN EACH REGION OF FABRIC 3

Type of intersection	1st-2nd layer				2nd-3rd layer			
	A	B	C	D	A	B	C	D
N-N	4	12	20	28	24	24	24	24
N-F	4	12	20	28	8	8	8	8
F-N	28	20	12	4	8	8	8	8
F-F	28	20	12	4	24	24	24	24

TABLE IV
STACKED FABRICS IN FABRICS 1, 2, AND 3

	First layer	Second layer	Third layer
Fabric 1	Fig. 11(a)	Fig. 11(b)	Fig. 11(c)
Fabric 2	Fig. 11(a)	Fig. 13(a)	Fig. 11(c)
Fabric 3	Fig. 11(a)	Fig. 13(b)	Fig. 11(c)

number of each type of capacitors is the same. The difference in capacitance is dependent on the pattern of capacitors. Fig. 13(b) illustrates a fabric in which the point of intersection is different from the fabrics shown in both Figs. 11(b) and 13(a). This pattern forms N–N capacitors between the second and third layers. Although the weaving pattern has changed, yet the first and second layers have different intersection patterns for each region, while the second and third layers have the same intersection pattern for all regions. Therefore, even if the pattern of capacitors is different from that shown in Fig. 11(d), we expect a different capacitance change to be observed between the first and second layers depending on the position of the applied pressure, while the same capacitance change will be observed between the second and third layers irrespective of the position of the applied pressure. We call the Fabrics 1, 2, and 3 in order of Figs. 11(b), 13(a), and (b), respectively. Combinations of weaving methods for each region of Fabrics 1 and 2 are given in Tables II, and those for weaving methods for each region of Fabric 3 is given in Table III. The compositions of the layers for each prototype fabric are presented in Table IV. In the next section, we show the capacitance of each fabric and the performance as fabric pressure sensor.

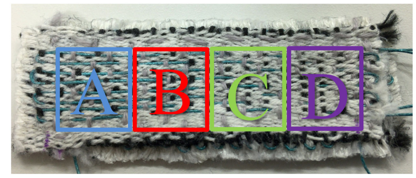


Fig. 14. Four regions to be pressed.

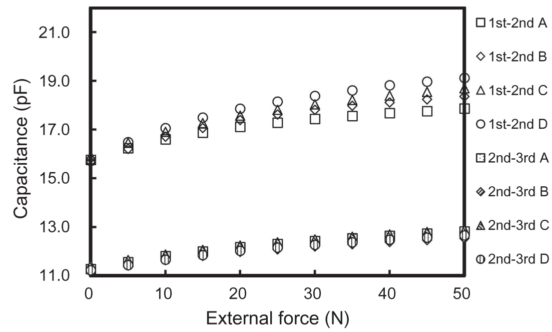


Fig. 15. Capacitance of Fabric 1.

V. EXPERIMENTS

The capacitance was measured separately between the first and second layers and between the second and third layers. When the capacitance between the first and second layers was measured, the third layer was grounded. Similarly, when the capacitance between the second and third layers was measured, the first layer was grounded. In order to confirm that the capacitance changes depending on the location at which the external force is applied as well as the magnitude of the applied pressure, the fabric was divided into four areas to which external force was applied. The four areas, denoted by A, B, C, and D, are illustrated in Fig. 14, and each area corresponds to the same 8×8 grid points depicted in Fig. 12. The width and height of the areas are 1.5 cm each. The head of the digital force gauge, as shown in Fig. 6, was aligned with the position of the corresponding weave in Fabrics 1, 2, and 3, respectively. The conditions for applying external force are the same as those described in Section III. The method of connecting fabrics and the regions where force was applied are common to all the experiments.

In order to evaluate the performance of the fabric sensor, we conducted two experiments on hysteresis and stability. In regard to the hysteresis of the sensor, the capacitance was measured when an external force was applied as well as when the external force was reduced. An external force of up to 50 N was applied and then reduced in 60-s cycles. The conditions for applying external force and reducing it are similar to those given in Table I. In regard to stability, when applying forces for a long time, an external force of 50 N was applied for 30 min; then, the external force was removed for 30 min, and capacitance was measured during every second of this 60-min period.

A. Change of Capacitance

The capacitance of each fabric is illustrated in Figs. 15–18. From Fig. 15, which shows the results from Fabric 1, it is

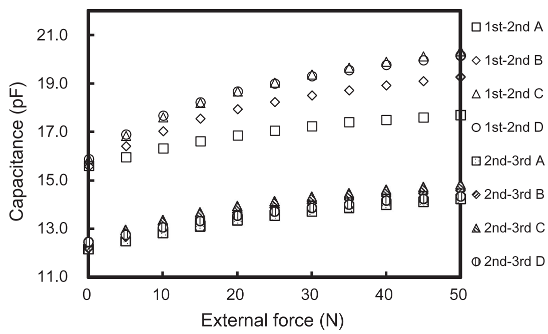


Fig. 16. Capacitance of Fabric 2.

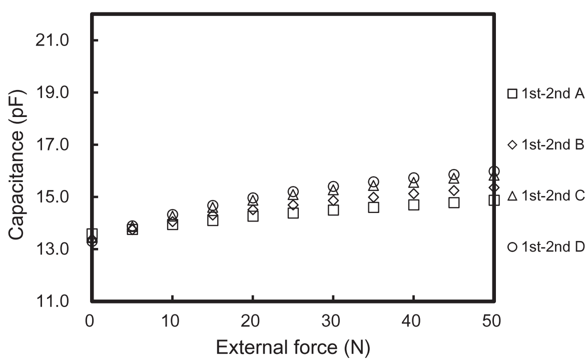


Fig. 17. Capacitance between the first and second layers in Fabric 3.

evident that a larger external force results in a larger difference in capacitance between the first and second layers. However, even when the external force increases, the difference in capacitance between the second and third layers is smaller than that between the second and first layers. When no external force is applied, the capacitance of Fabric 1 was approximately 15.7 pF between the first and second layers, and approximately 11.2 pF between the second and third layers. As the external force is increased, the value of capacitance increases in any region. The capacitance between the first and second layers changed the most in region D. In contrast, the region with the smallest change in capacitance was region A. When an external force of 50 N was applied to region A, the change in capacitance was approximately 1.3 pF less than that in region D.

The relationship between the changes in capacitance showed the same tendencies as the number of intersections presented in Table II. The larger the number of intersections at which the distance between the conductive yarns was smallest, the larger was the change in the capacitance. Because the weave between the second and third layers does not change with location, the same capacitance should be obtained; however, there is a difference in the change in capacitance depending on the location in this experiment. In addition, the capacitance changed even if the number of intersections was the same. The capacitance between the second and third layers is generally smaller than that between the first and second layers. The capacitors between the first and second layers of Fabric 1 are N–N and F–N capacitors, whereas the capacitors between the second and third layers of Fabric 1 are F–N and F–F capacitors. As shown in Fig. 8, because F–F has the smallest capacitance, the second and third

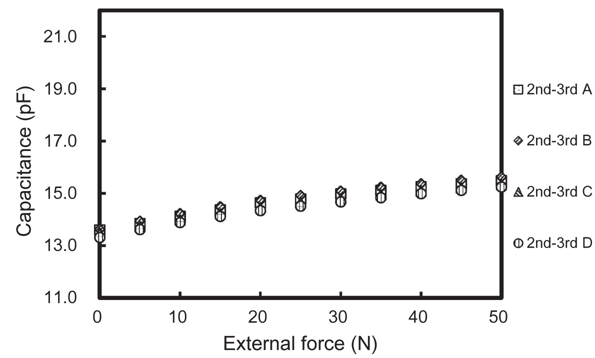


Fig. 18. Capacitance between the second and third layers in Fabric 3.

layers' total capacitance, which includes a larger proportion of F–F capacitors, is smaller than the capacitance of the first and second layers.

Fig. 16 depicts the results for Fabric 2. A similar change in capacitance was seen for each region between the second and third layers of Fabric 2. The change was different for each region between the first and second layers. When applying an external force of 50 N to Fabric 2, the capacitance in region D was about 2.4 pF larger than that in region A. The difference in capacitance was larger than that for Fabric 1. The overall change in capacitance of Fabric 2 was similar to that of Fabric 1 and not Fabric 3. This was caused by the weaving conditions; specifically, the weaves of Fabrics 1 and 2 were similar, while they were not similar to the weave of Fabric 3, as shown in Tables II and III.

Fig. 17 illustrates the measurement results for the first and second layers of Fabric 3. Because the number of intersections with smaller capacitance increases, the capacitance is smaller than that of Fabrics 1 and 2. Although the difference between the capacitances in regions C and D is small, a different change in capacitance is observed for each region. Fig. 18 depicts the results for the second and third layers. While there was a slight difference in capacitance for each region, the change in capacitance when applying external force was almost the same.

B. Hysteresis

The results of the hysteresis test are depicted in Fig. 19(a)–(d). The black line in each figure indicates the change in capacitance upon application of the external force. The dotted lines indicate the change in capacitance when the external force was reduced. The results show that the capacitance and changes in capacitance for the first and second layers and the second and third layers did not differ from those shown in Fig. 15. Furthermore, the capacitance between the first and second layers differs from one region to other, whereas the difference of the capacitance between the second and third layers is smaller than that between the first and second layers. In this experiment, the capacitance upon reducing the external force was larger than that upon applying the external force in Fabrics 1–3. This shows that applying pressure to the fabric deformed the yarns, which required time to return to their original positions. Therefore, upon applying an external force of 50 N and then removing the external force, no region

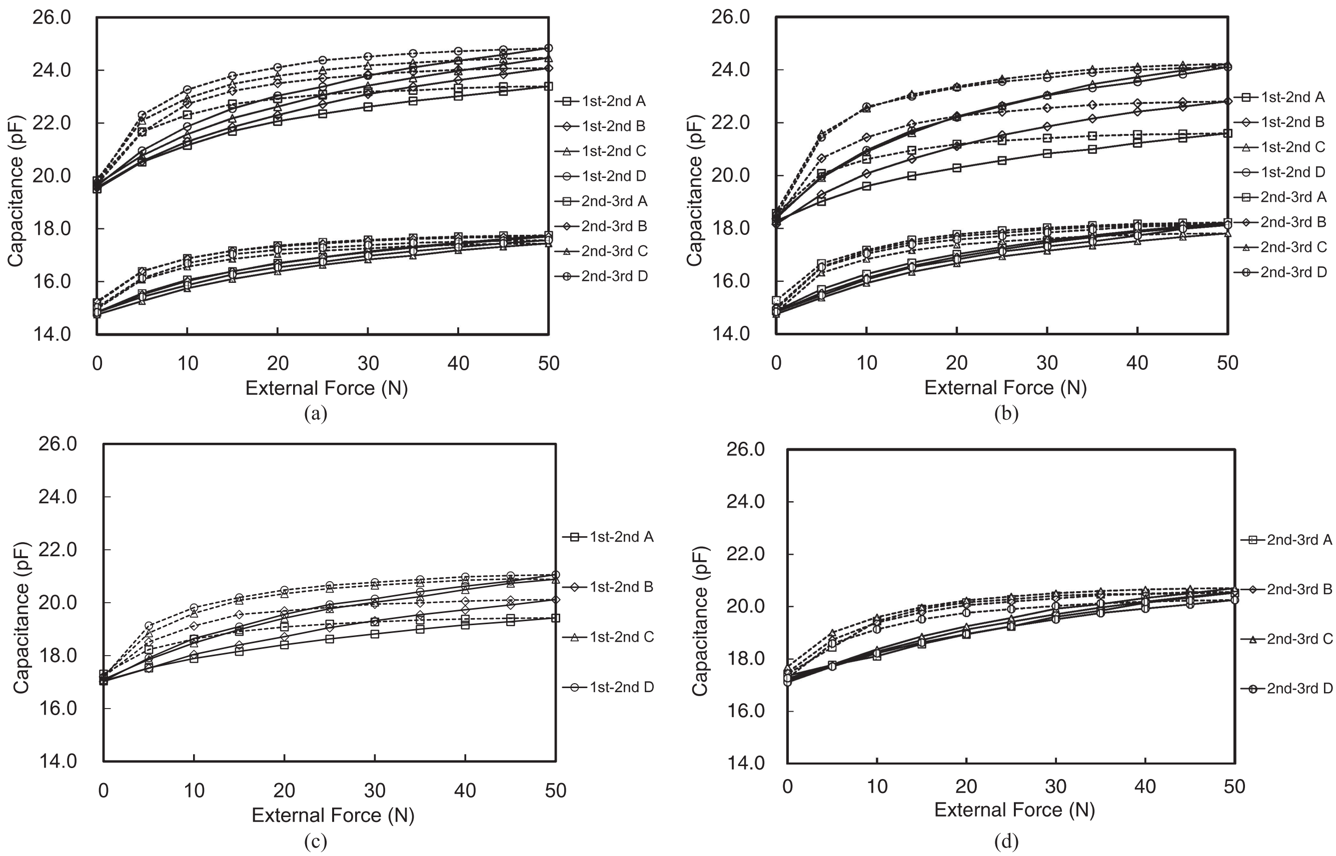


Fig. 19. Hysteresis of the capacitance upon applying and reducing force. Solid line: change while applying force; dotted line: change upon reducing force. (a) Capacitance of Fabric 1. (b) Capacitance of Fabric 2. (c) Capacitance between the first and second layers in Fabric 3. (d) Capacitance between the second and third layers in Fabric 3.

immediately returned to its state prior to the application of the external force. The difference in Fabric 1, shown in Fig. 19(a), ranged from a maximum of 0.40 pF to a minimum of 0.11 pF; the difference in Fabric 2, shown in Fig. 19(b), ranged from 0.39 to 0.06 pF; the difference in Fabric 3, illustrated in Fig. 19(c) and (d), ranged from 0.37 to 0.07 pF.

C. Stability

The results of the experiments investigating stability are depicted in Fig. 20. We measured the change in capacitance during application of a force of 50 N to region D of Fabric 1 for 30 min as well as during removal of the force. The solid line indicates the change in the capacitance of the first and second layers, whereas the dotted line indicates the change in the capacitance of the second and third layers. In the first and second layers, the capacitance increased to 25.4 pF upon application of the 50 N force. After application of the force, a change in capacitance was observed between − 0.1 and 0.2 pF around the initial value of 25.4 pF. Upon removing the force after 30 min of applying pressure, the capacitance did not return immediately to its original preforce value, which is similar to the result of the experiment on hysteresis. However, the capacitance returned to its original value of 20.1 pF in about 15 min, and it continued to change from approximately − 0.05 to 0.08 pF from the original value of 20.1 pF. The capacitance between the second and third layers also increased from 15.6 to 18.1 pF when force was applied, but an increase of about 0.2 pF was observed during the 30 min for which the force was fixed. After removing the force, the capacitance returned to its original value in about 15 min, but it increased by about 0.2 pF during the remaining 15 min. In summary, the capacitance of each pair changed by about 0.2 pF upon application of continued pressure to the sensor.

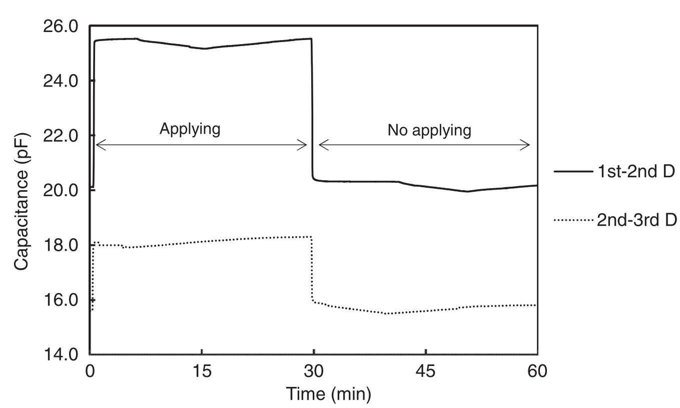


Fig. 20. Change in capacitance in region D of Fabric 1 upon applying force for an extended period (30 min).

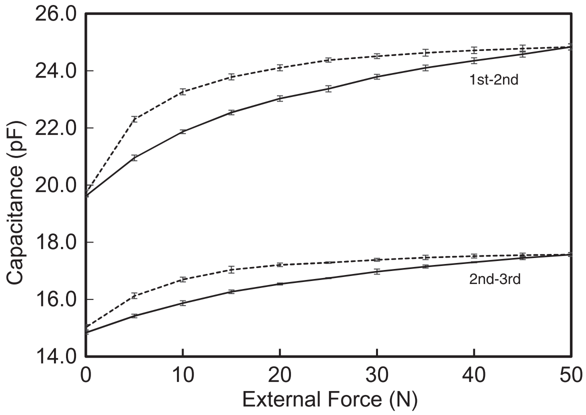


Fig. 21. Change in capacitance in region D of Fabric 1 along with the standard deviation.

In order to confirm the repeatability of these measurements, the capacitance upon application of force to regions A–D of Fabrics 1–3 was measured five times. The change in capacitance and standard deviation in region D of Fabric 1 are depicted in Fig. 21. In region D of Fabric 1, the standard deviation from 0 to 50 N ranged from a minimum of 0.03 pF to a maximum of 0.12 pF. Similarly, in other regions, a maximum standard deviation of about 0.12 pF was obtained, similar to the results shown in Fig. 21. The small standard deviation shows the repeatability of the capacitance upon application of force. For Fabric 2, the deviation ranged from a minimum of 0.01 pF to a maximum of 0.12 pF, whereas for Fabric 3, the minimum value was 0.02 pF, and the maximum value was 0.12 pF. Thus, repeatability was confirmed for Fabrics 2 and 3 as well as for Fabric 1.

D. Discussion

As shown in Figs. 9 and 10, we proposed a three-layer fabric. When the value of applied force is known, the location can be estimated with just two layers; when the position is known, the force can be estimated with just two layers. However, if both force and location are unknown, then their estimation requires three layers. If we only calculate the location and pressure of the applied force, we can estimate them from a reference table, but we believe that it is important to ensure that the intended change in capacitance is obtained via the weaving structure, as this will contribute to other research. Using our experiments, we confirmed that different changes in capacitance were obtained in each layer.

For Fabrics 1 and 2, the number of each type of intersection is exactly the same, but their arrangement is different. We expected that the change in capacitance shown in Figs. 15 and 16 would be exactly the same, but the results were only similar and not identical. Furthermore, we confirmed that the magnitude of the differences in capacitance is almost preserved between each region. In addition, we confirmed that behaviors that differ from those of Fabric 3, which has different types of intersections, also show different capacitance change depending on its intersections.

In conclusion, these experiments confirm that using different weave structures in a fabric can generate a difference in the capacitance of each region of the fabric. The results show that the combination of different values of capacitance between the first and second layers and between the second and third layers allowed estimation of both the location and magnitude of an applied pressure. By combining two fabrics with different weave structures, two capacitance values can be observed when an external force is applied. Because the capacitance varies depending on the combination of the weave structures, the capacitance can be used to detect the location and magnitude of the applied pressure by recording the change in the weave and thus, in the capacitance in advance. However, in any sample, the capacitance obtained between the second and third layers is not always constant; it includes an error. We suspect that this error is due to the fact that our samples were woven manually, by hand, thereby resulting in variations as shown in Fig. 3. The distance between the conductive yarns was smaller than we intended, as shown in Fig. 3, because the layers of yarns could be sheared in the manually woven samples.

VI. Conclusion

This paper proposed a method for changing the electrical functionality of conductive fabric by using different weave structures in the same materials. The same materials and the same power source could produce different electrical properties depending on the crossing patterns of the warp and the weft. This approach not only made it possible to avoid bringing skin in contact with metal electrodes but also eliminated the need for large numbers of input–output cables.

In this paper, in order to reduce the number of input–output cables connected to the circuit, we introduced a structure in which different weave fabrics were stacked. In the fabric, different changes in capacitance were obtained for each output cable when external force was applied, thereby showing that the location and magnitude of applied pressure could be estimated from the change in the capacitance.

We will explore the applications of these fabrics as input interfaces in the near future. A few promising applications of such fabrics are bedsheets [8, 9, 11], and wearable pressure sensors that sense the status of the human body. However, the fabric currently has limitations that prevent us from using the fabric in such applications. AG-poss T1 consists of silver-plated nylon yarn coated with polyester. It is washable, except for the portion that connects to the control circuit. By replacing this part with washable material, or by coating this part, including the control circuit, the fabric will be completely washable. Such investigation into the practical applications of this fabric is an important future task. We will also improve the weaving method to enable more accurate detection of location and magnitude of the applied pressure. In this paper, we utilized yarns that crossed vertically in order to ensure that the two conductive yarns crossed each other in the same area. To increase the capacitance, the area of intersection should be large; in such a case, a vertical intersection is not the best solution. Furthermore, we also plan to design a power-saving IC that estimates the location and magnitude of applied pressure from the measured capacitance. In this paper, an ac power supply of 100 kHz was used. However, to efficiently detect the capacitance of the proposed fabric and enable actual applications with circuits that are small in size and have low power requirements, further verifications with various power frequencies are required in future work.

In the version of fabric used in this paper, the area to which pressure was applied was constant and must be known. Applying pressure across different pattern areas or multiple positions simultaneously cannot be accurately measured. Reducing these limitations is one of the goals of future work. It may not necessarily be solved by weaving structure alone, but weaving structure could be combined with other suitable sensors. In this paper, we first showed experimental results to demonstrate that different electrical characteristics could be realized using weaving.

References

[1] J. Lee *et al.*, "Conductive fiber-based ultrasensitive textile pressure sensor for wearable electronics," *Adv. Mater.*, vol. 27, no. 15, pp. 2433–2439, 2015.

[2] J. J. Liu *et al.*, "A dense pressure sensitive bedsheet design for unobtrusive sleep posture monitoring," in *Proc. Int. Conf. Pervasive Comput. Commun.*, 2013, pp. 207–215.

[3] I. Baldoli *et al.*, "Pressure mapping with textile sensors for compression therapy monitoring," *J. Eng. Med.*, vol. 230, no. 8, pp. 795–808, 2016.

[4] W. Xu, M.-C. Huang, N. Amini, L. He, and M. Sarrafzadeh, "Ecushion: A textile pressure sensor array design and calibration for sitting posture analysis," *IEEE Sensors J.*, vol. 13, no. 10, pp. 3926–3934, 2013.

[5] I. Wicaksono and J. A. Paradiso, "Fabrickeyboard: Multimodal textile sensate media as an expressive and deformable musical interface." in *Proc. Int. Conf. New Interface Musical Expression*, 2017.

[6] A. Peshock, J. Duvall, and L. E. Dunne, "Argot: A wearable one-handed keyboard glove," in *Proc. Int. Symp. Wearable Comput., Adjunct Program*, 2014, pp. 87–92.

[7] M. T. I. Molla *et al.*, "Surface-mount manufacturing for e-textile circuits," in *Proc. Int. Symp. Wearable Comput.*, 2017, pp. 18–25.

[8] S. Takamatsu, T. Kobayashi, N. Shibayama, K. Miyake, and T. Itoh, "Fabric pressure sensor array fabricated with die-coating and weaving techniques," *Sens. Actuators A, Phys.*, vol. 184, pp. 57–63, 2012.

[9] T. Yamashita, S. Takamatsu, K. Miyake, and T. Itoh, "Fabrication and evaluation of a conductive polymer coated elastomer contact structure for woven electronic textile," *Sens. Actuators A, Phys.*, vol. 195, pp. 213–218, 2013.

[10] S. Takamatsu, T. Yamashita, T. Imai, and T. Itoh, "Lightweight flexible keyboard with a conductive polymer-based touch sensor fabric," *Sens. Actuators A, Phys.*, vol. 220, pp. 153–158, 2014.

[11] Y. Enokibori, A. Suzuki, H. Mizuno, Y. Shimakami, and K. Mase, "E-textile pressure sensor based on conductive fiber and its structure," in *Proc. Conf. Pervasive Ubiquitous Comput. Adjunct Publication*, 2013, pp. 207–210.

[12] J. S. Heo, J. Eom, Y.-H. Kim, and S. K. Park, "Recent progress of textile-based wearable electronics: A comprehensive review of materials, devices, and applications," *Small*, vol. 14, no. 3, 2018, Art. no. 1703034.

[13] J. Anjae *et al.*, "Textile resistance switching memory for fabric electronics," *Adv. Functional Mater.*, vol. 27, no. 15, 2017, Art. no. 1605593.

[14] I. Poupyrev, N.-W. Gong, S. Fukuhara, M. E. Karagozler, C. Schwesig, and K. E. Robinson, "Project Jacquard: Interactive digital textiles at scale," in *Proc. Conf. Human Factors Comput. Syst.*, 2016, pp. 4216–4227.

[15] Y. A. Samad *et al.*, "From sewing thread to sensor: Nylon fiber strain and pressure sensors," *Sens. Actuators B, Chem.*, vol. 240, pp. 1083–1090, 2017.

[16] S. Takamatsu, T. Lonjaret, D. Crisp, J.-M. Badier, G. G. Malliaras, and E. Ismailova, "Direct patterning of organic conductors on knitted textiles for long-term electrocardiography," *Sci. Rep.*, vol. 5, 2015, Art. no. 15003.

[17] B. Huang *et al.*, "Wearable stretch sensors for motion measurement of the wrist joint based on dielectric elastomers," *Sensors*, vol. 17, no. 12, 2017, Art. no. 2708.

[18] T. Igarashi, M. Toyoura, and X. Mao, "Dithering method for reproducing smoothly changing tones and fine details of natural images on woven fabric," *Textile Res. J.*, vol. 88, no. 24, pp. 2782–2799, 2017.

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