Multimodal Flexible Sensor for Healthcare Systems

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Abstract— **This paper describes potential applications of our previously developed fabric sensor into wearable healthcare or nursing systems based on its sensing modalities. This sensor is knitted from tension-sensitive electro-conductive yarns; whose structure has an elastic core, wound around by two separated tension-sensitive electro-conductive threads. This makes the sensor *inherently* flexible and stretchable, allowing it to conform to any complicated surface. We have equipped the sensor with three modalities, including *proximity* that allows the sensor to estimate a distance from the sensor to human hand and activates a light touch sensing, which could initiate comfortable and friendly interfaces in order to reduce burden of patients/disable people during interactions with healthcare devices; *tactile perception* that can measures contact force or applied load, especially realize slippage acting on the sensor surface, which is promising to be embedded into wearable devices or smart carpets; and *tensile* that can quantify a volume's contraction/expansion, which can be employed to monitoring muscles activity and so on.**

I. INTRODUCTION

Nowadays, along with the emerging development of the wearable system, developed sensing systems are required to be simple but multimodal and flexible. Simplicity is for ease of using, and cost performance. Multi-modality is for the adaptability to multi-purpose applications of a system. Last but not least, flexibility is for the adaption of the sensing system to any surface that it covers. There are a great deal of research dealing with flexible sensors, including ones that developed technologies to deposit sensing elements onto flexible substrate or embed sensing elements into elastic materials [1]-[3]. Most of these research focuses one sensing function such as force, pH, temperature, fludic flow, etc [5]-[4]. While many novel sensors are for robotic applications, most of flexible sensors developed based on needs in health and medical applications, such as heart rate detection, foot swelling detection, and so on.

In this paper, we attempt to add several modalities for the previously developed fabric sensor by introduce corresponding measurement circuits. As a result, the fabric itself has less variation; instead of that, only external measurement circuits changes depending on specific functions. Our sensor could sense the following modalities:

- Proximity and light touch: the sensor could estimate distance of an conductive object (such as human fingertip) within several centimeters. Also, this sensor can detect a very light touch between the object and the sensor's surface
- Tactile: the sensor can detect a wide range of normal stress. Especially, with design of loops piling up from the sensor's surface, the sensor is sensitive tangential traction, such as slippage.
- Tensile: the sensor can detect relative change of length or contraction and expansion of a volume of object that it wraps around, thanks to elasticity.

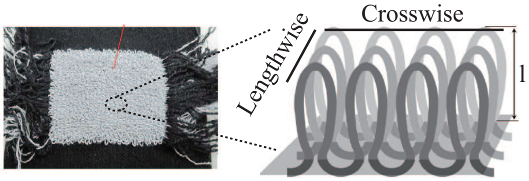

Fig. 1. Slip sensor with piles shaping the surface.

These modalities can be applied in a wide range of health monitoring applications that will be shown hereafter in sections, which are divided as followed: Section II summaries structure, fabrication of the electro-conductive yarns and fabric sensor. Section III-A describes targeted applications regarding to proximity; while Section III-B and III-C suggest applications in term of tactile and tensile. Section IV is a conclusion and future work. While results shown in section III-B can be found in details in [7], results presented in section III-A and III-C are recently developed.

II. SENSOR STRUCTURE AND FABRICATION

We constructed a fabric sensor by knitting double coupling conductive yarns (as *warps*), which are made of a mixture of polyester fibers and stainless steel fibers with high conductivity, onto basal yarns (as *wefts*), which are neither tension-sensitive nor conductive. The yarn's resistance varies when its length changes. Had we employed knitting methods used to fabricate plain woven fabrics or similar products, in which the surface of the fabric is flat and smooth, the tension strain of yarns caused by traction stress on the surface would be small, resulting in an insufficient change in output resistance. Therefore, to enhance the tension strain of the sensor, the yarns were woven to form a *pile cloth*, *i.e.* each yarn had many continuous loops arising on the surface called. Fig. 1 shows a complete fabric sensor 5.0 cm in length and 3.5 cm in width. The length of each pile on the surface was 1.0 mm. These piles are important in detecting traction on the contact surface of the sensor. Each pile that makes contact with the outside world will deform, and the variations in deformity

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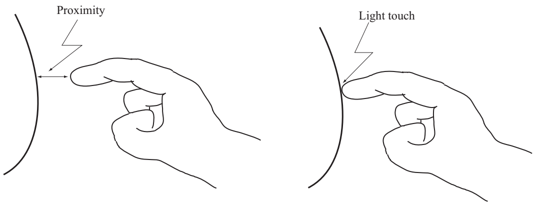

Fig. 2. Proximity

will contribute to the output of the sensor. Moreover, the size of the sensors and the height of the piles can be varied, thanks to the help of the Okamoto Corp. (Japan). Details of fabrication of the fabric sensor can be found in [7].

III. MULTIMODAL SENSING

Human's touch is the most diverse action in the human motory system. It can be represented by numerous linguistic words relating to touch actions: approaching, touch, squeeze, tickle, and so on. A sensing system that can sense and distinguish various action of human's touch is promising to be applied in healthcare or welfare devices. As a result, we attempted to integrate multiple touch-related sensing functions for the fabric sensor by applying various measurement techniques. For the proximity and light touch sensing function, a capacitive sensing measurement was utilized to measure the distance between human hand and the sensor's surface (Fig. 2). For tactile sensing, a Wheatstone bridge for measuring change of sensor's resistance is employed. This would help to detect normal pressure and slippage (Fig. 4). Details will be shown hereafter.

A. Proximity and Light Touch

Sensing the distance from the sensor surface to a conductive object such as human hand can benefit many welfare applications. A patient can just raise the hand near the sensor surface to turn on a light or call doctors without any necessity of force application. Moreover, proximity brings human-oriented sensation, eliminating random approaching of non-conductive objects. In this research, we equipped the sensor with proximity capacitance measurement circuit to not only measure the distance, but also to detect the initial touch between the human hand and the sensor.

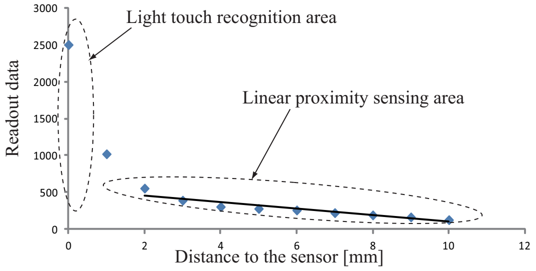

Fig. 3. Response of the sensor when a human fingertip approaching the sensor surface

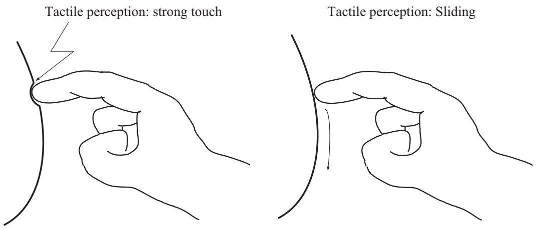

Fig. 4. Pushing

We utilized a common capacitance measurement that have been used widely recently, thanks to Arduino development kit [8]. It only requires one wire connected from the Arduino kit to any position of the fabric sensor. When an object is approaching to the surface of the sensor, a capacitance, inherited between the object and the sensor with an air dieletric, varies accordingly. Fig. 3 shows a response of the sensor when a human fingertip was approaching the sensor surface. The closer the distance to the sensor surface is, the larger the response is obtained. The capacitive reaction of the sensor varies when the conductivity of the object changes. We have employed three typical objects: aluminium, water, paper (carton piece) with different levels of conductivity: high, medium, and low, respectively. Results illustrated in Fig. 5 reveal that highly conducted aluminium resulted in high readout data, while object with lower conductivity produced smaller value. Also, the readout was remarkably high if the object was closed to the sensor surface. The position reference is on top of piles.

Usually, detection of initial touch between human hand and the sensor surface is a rather struggling issue, especially for sensors with simple construction. If we take into account change of resistance of this sensor due to touch, as described in the next section, initial touch would not be able to detected properly due to noise level. One solution is the utilization of proximity to detect the initial touch for this fabric sensor. As aforementioned, when the human hand is approaching to the sensor surface, its measured capacitance increases correspondingly. Especially, when the distance is zero, i.e. an initial touch occurs, obtained signal quickly reaches its peak (see in Fig. 3). As a result, by detection of these peaks

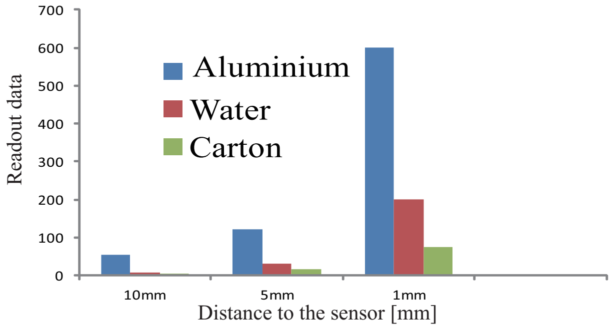

Fig. 5. Comparable results of readout data when the approaching objects vary.

generated during proximity sensing, a light touch can be judged properly.

Consequently, by equipping the sensor with a capacitive measurement circuit, the sensor is able to sense the distance between human hand or conductive object to its object, as well as light touch. This perception could bring applications regarding functional manipulations without need of making contact with the sensor, which is suitable for the disable people and patients.

B. Tactile

Tactile perception is the most important role of touch sensors, since it must take into account all basic states of contact and interpret which action is acting on its surface. Thus, the sensor must recognize levels of normal pushing, as well as detect the tangential slippage of objects. For this purpose, we employed a Wheatstone bridge to measure change of the sensor's resistance under deformations caused by normal and tangential stresses [7]. Since this perception had been well investigated in [7], several summaries will be given hereafter.

Fig. 12 in [7] shows a response of the sensor when an indentor applied and released a vertical load in the surface of the sensor. Plots of indentor's load and sensor's response reveal that the sensor counters correspondingly to the slopes of the loading/unloading inputs from the indentor. We also conducted a periodic trapezoidal inputs with frequency of 0.8 Hz in 45 sec, and observed the stability/repeatability of the sensor's output. When the response of the sensor matches the rising/falling of the loaf, the upper bound is variant. It is because of the fact that after each load/unloading trial, sensor's piles takes time to recover to the original state because of the viscosity, and this recovery is slower than the input's frequency.

In term of traction motion, it is well known that relative slide of human hand on the sensor surface can reveal many states of contact. Usually, most of conductive fabric sensors developed beforehand could not detect slippage due to lack of characteristics to enhance absorbtion of tangential traction. Our sensor, with piles coming up from the sensor surface as mentioned in previous Section II, can recognize tangential stress through deformation of piles. Fig. shows response of sensor when an object slides with constant speed on its surface. Fig. 15 in [7] shows the output of the sensor in one slippage trial. We observed a sudden change in output when the soft fingertip (SFT) started the incipient slippage on the contact surface, and a flatten output when the SFT slides overtly. Thus, by monitoring the change in resistance of the sensor, we can determine the sliding states of objects over the surface of the sensor. We also conducted a durable test in which the SFT slides back and forward on the sensor's surface.

Consequently, tactile-related applications are not necessarily limited to human hand. Smart shoes with embedded fabric sensor can monitor walking posture and gait of users by analyzing feet's normal pressure applied to the shoes' base. Also, the fabric sensor can be knitted into normal shocks with the similar purpose as well. The sensing system with the fabric sensor is expected to monitor risk of stroke through gait, foot swelling during long walking or running [6], foot slips [9]. Moreover, possible slippage while walking can be captured and predicted, which is useful for design of sneakers. Smart carpets also can be utilized in welfare house for monitoring walking habit, especially for surveillance of sudden slips or falls on the carpet.

C. Tensile

In this section, we introduce a distinguishing modality of the fabric sensor, which can detect or quantify enlargement/shrinkage of an artificial McKibben muscle. The McKibben muscle could be contracted or extended controlled by a pneumatic bladder, that is vaguely similar to the human muscle. We rolled a conductive yarn, which was used to knit the fabric sensor in Fig. 1, around a McKibben as illustrated in Fig. 6. When an axial length L of the artificial muscle shrank, its cross-sectional diameter D expended, resulting in the change of the yarn's length B correspondingly. We could easily derive the relation between above parameters as followed:

$$L^2 + (N\pi D)^2 = B^2, \tag{1}$$

where N is a number of rounds of the yarn around the McKibben muscle. When the muscle is contracted or extended by a ratio number $c = l/L$, the yarn's new length b is calculated as followed:

$$b = \frac{(Nc)^2 - n^2}{N^2} L^2 + \frac{(nB)^2}{N^2}, \tag{2}$$

where n is the number of current rounds. As a result, change of the yarn's length $\Delta = b - B$ can be reflected into change of its resistance. Consequently, it is possible to detect how the muscle's shape changes during its operation. Fig. 7 performs a linearized relationship between the sensor's output (in voltage) and the muscle's strain up to 60%.

Fig. 8 illustrates the response of the sensor when the McKibben muscle'length, *i.e.* muscle's cross-sectional diameter, varies frequently. These contraction/expansion cycles of the McKibben muscle are similar to that of human muscles motion during training or working out. Based on the relation

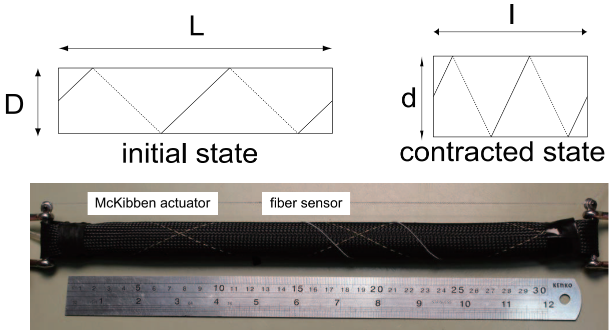

Fig. 6. Fiber sensor rotates around a McKibben muscle.

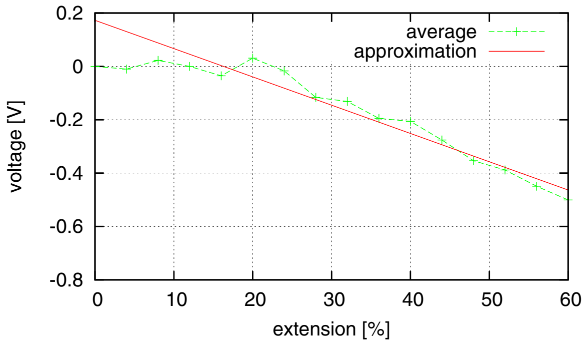

Fig. 7. Linearized relationship between the sensor output and the artificial muscle's strain.

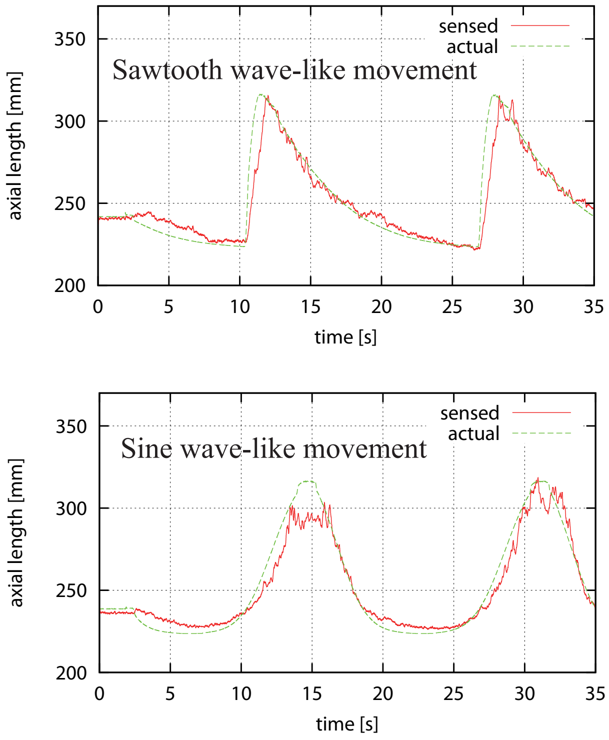

Fig. 8. Approximated strain based on the sensor output and the actual one.

derived in Fig. 7, it can be assessed that the output of the sensor is appropriate to cycle change of the artificial muscle's shape.

Consequently, the ability of the sensor in detection of the artificial muscle's contraction/expansion can be utilized in monitoring human muscles motion during training, estimation of burnt calories and so on, by embedding it into training suits or wearable devices.

IV. CONCLUSIONS

We have described our attempts to develop a simple sensing system for potential usages in wearable devices or health-monitoring system. This sensor is cheap in fabrication, flexible to be adaptive to any curved surfaces, and able to sense three different modalities such as proximity and light touch, tactile, and tensile. In the future, we have planned to develop each of these modalities into real applications that have been mentioned in this paper, and investigate the possibilities of the sensor in term of safety to be embedded in human-related systems.

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