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Design and fabrication of touch-sensitive polymeric optical fibre (POF) fabric

Polymeric optical fibres (POFs) can be integrated into a textile structure for illuminative fashion and interior fabric applications, but the usability and functionality of POF textiles still need to be improved. In this study, the development of a touch-sensitive photonic fabric system through the integration of POFs, conductive yarns, and an electronic controlling system was explored. The conductive yarns were woven into the fabric to function as capacitive sensors. Different from conventional capacitive sensor, the capacitive sensor used in this study were embedded into the textile structure using conductive yarns. With the embedded controlling system and RGB light-emitting diodes (LEDs), the POF fabrics were able to transfer sensory signals into illumination. In this project, by combining novel weaving techniques, different materials, and electronic system development, a multi-touch interface based on textile capacitive sensors was developed that can sense both touch contact and noncontact/proximity. The results demonstrated that multiple functionalities can be integrated into the fabric structure to produce an end product with promotes interaction between the user and the textiles, thereby enhancing the functionality and usability of interactive POF textiles as a whole.

Keywords: E-textile; textile touch sensor; POF fabric; weaving

1. Introduction

1.1 Soft touch sensing surface

E-textiles contribute to the development of wearable technology by allowing electronics to be integrated into daily living. The soft touch sensing surface can improve the interaction between textiles and users. For instance, in the Jacquard project by Google (Poupyrev et al., 2016), conductive threads are woven into clothing to take touch inputs from the hand and translate them into input controls for smartphones with the help of a Bluetooth-powered dongle attached in the cuff (Figure 1a).

With embedded sensors, the control panel of e-textile products can be small and lightweight. In terms of different types of sensors, there are resistance sensors, optical sensors, and capacitive sensors (Gonçalves, Ferreira da Silva, Gomes, & Simoes, 2018). Some flexible and sensitive textile-based pressure sensors are made from highly conductive fibres coated with a dielectric rubber material (Jaehong et al., 2015). Embossed controlling switches/buttons are designed to provide visual indication for users to identify the interactive areas. In other cases, printed designs on the control panel indicate the touch-sensitive areas, such as iSkin flexible touch sensors (Figure 1b) (Weigel et al., 2015), which are made of multiple layers of thin, flexible, and stretchable silicone.

Figure 1. a) Google Jacquard; b) iSkin.

Researchers have investigated the capacitive textile sensor method for interior environments. In a research project funded by the Brigstow Institute, Bristol University, a mood cushion was developed (Figure 2). This soft cushion, with an integrated textile interface, enables the user to control light and sound in the home environment (Binary,

2017) . The textile's pressure-sensing component serves as a controller, which is separated from the lighting in this product.

Figure 2. Mood cushion.

1.2 Interactive POF textiles

Polymeric optical fibres (POFs) can be integrated into a textile structure for illuminative fashion and interior fabric applications, but the usability and functionality of POF textiles still need to be improved (Tan, 2015) . To encourage multi-sensing functionality in POF textiles, an interactive photonic cushion called 'Connexion' was developed (Bai, Tan, Johnston, & Tao, 2015). In this study, the authors explored a new method of controlling the lighting of the cushion using capacitive sensors. To enlarge the sizes of the capacitive sensing areas, three pieces of foil were attached to the fabric. However, foil and wires inside the cushion for sensing and connecting affect the appearance and usability of the photonic cushion (Figure 3).

Figure 3. Inside structure of the Connexion cushion.

Another intricate design is the ‘LightCloth’. The cushion consists of embedded optical fibre arrays and sensors. The user utilises an infrared (IR) pen, which is not connected to the cushion, to interact with the system to design the illumination with the desired colour(s) (Hashimoto, Suzuki, Kamiyama, Inami, & Igarashi, 2013) (Figure 4). The drawback of this design is that the interaction between the user and the POF textile can only be realised via the IR pen. In addition, the manufacturing method is complex.

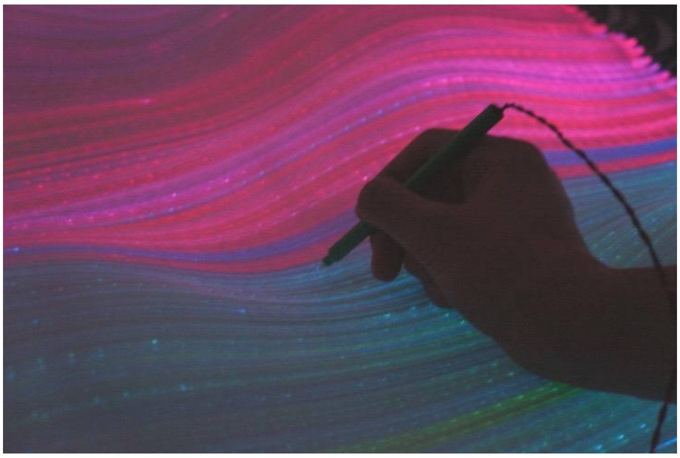


Figure 4. LightCloth.

A comprehensive literature review shows that most of the existing touch sensors in smart textiles are based on plastic, silicon, or rubber materials. Some research on textile touch sensors has been conducted; however, there are very few studies on textile touch sensors in the field of POF fabric. How to seamlessly merge the electronic components into a soft substrate is one of the main challenges. The goal of the current study was to enhance the functionality and usability of POF textiles by developing a novel textile sensing interface. The study makes the following contributions:

- Developing a new integrated textile touch sensor interface for POF fabric;
- Utilising a novel weaving technology to produce a capacitive textile sensor;
- Unobtrusive design to enhance the usability and functionality of POF fabric;
- Realising multi-sensing functions by design of both contact touch-sensing and noncontact-sensing models; and
- Encouraging interaction between the user and the textiles.

2. POF Textile Sensing System

POFs can be woven together with normal yarn to form an illuminative textile surface (Tan, 2015); (Schrank, Beer, Beckers, & Gries, 2017) (Koncar, 2005). With embedded touch-sensitive sensors and LEDs, the POF fabrics can transfer touch signals into corresponding illumination and create an interactive interior environment (Tan, 2015). In this study, a pilot method to bring the end user a new experience of touch sensing by combining POFs, conductive yarn, and a microcontrolling unit (MCU) was explored.

As shown in Figure 5, three parts constituted the POF textile sensing system: a textile sensing array, POFs, and a controlling system. The three parts were seamlessly integrated with advanced weaving and coupling technology.

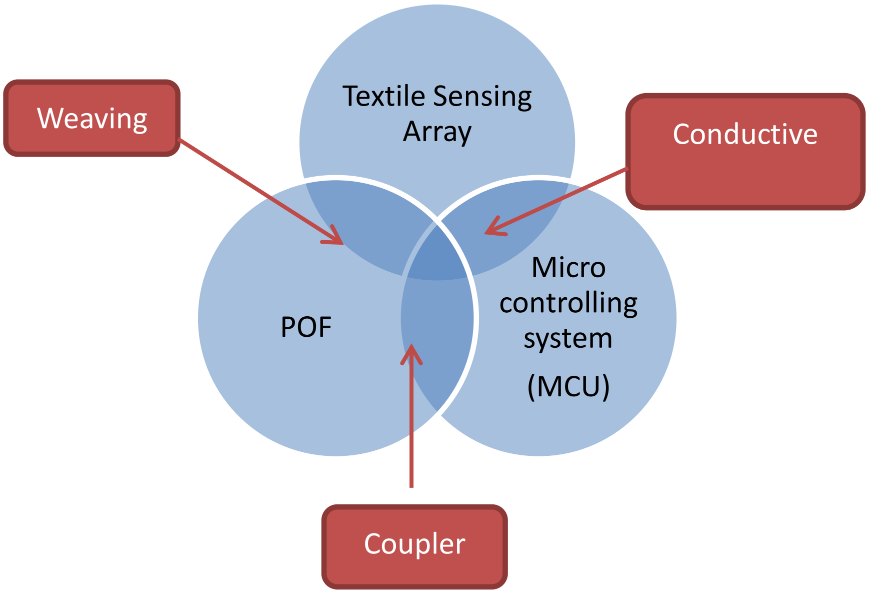


Figure 5. POF textile sensing system.

Because the light source used was a tri-colour RGB LED, three diamond-shaped sensing areas were accordingly designed on the textile surface as the light switches. Each sensing area was connected to the MCU by a group of conductive yarns. The electronic output was generated, and the colour of the light changed only when the diamond shape containing the conductive threads was touched. The colour-mixing effects of the POF fabric were realised when two diamonds were touched at the same time. A schematic diagram of the system is illustrated in Figure 6.

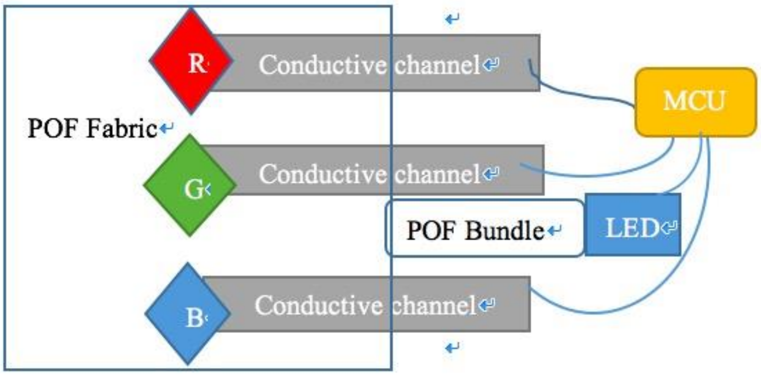


Figure 6. Schematic diagram of touch-sensing POF fabric: POF fabric (1st layer), conductive yarn (2nd layer), POF bundle.

3. Design of Textile Structure

To fulfil the functions illustrated in Figure 6, the conductive area and nonconductive area need to be separated from the textile surface. Usually, for a flexible touch-sensing interface, an embossed 'button' is designed to guide the user to touch a certain area (Takada, Shizuki, & Tanaka, 2016). In the current study, an embossed 'button' was created by using a novel weaving technique. The structural contrast between the inside of the diamond area and the outline of the diamond area highlighted the diamonds as 'button' switch/controls and provided visual indication enabling users to identify the interactive areas. The textile structure design is illustrated in Figure 7.

3.1 Weave design

At the front layer of the POF fabric, the conductive yarns were woven into the areas inside the diamonds to enable capacitive sensing. At the back layer of the POF fabric, conductive yarns were woven in long floats. One side of the conductive yarn floats were bundled together for electronic connection, whereas the other side of the conductive floats were cut off. As a result, on the front layer of the POF fabric, only the areas inside the diamonds contained conductive yarns, enabling these areas to have capacitive sensing ability.

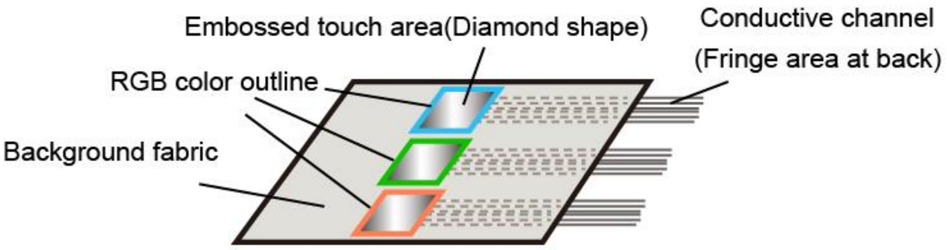


Figure 7. Textile structure design.

(1) Weave design for embossed texture

The embossed surface inside the diamond area was used to improve visual communication for user interactivity. The contrast in texture between the diamond and the background (nondiamond area) was formed by using different weave structures and different placement of elastic spandex yarns (detailed weave design is illustrated in Section 3.2). The diamond areas were woven with an unstitched double-layer structure, whereas the diamond outlines and background were woven with a stitched double-layer structure.

(2) Weave design for electronic connection

The conductive channel(fringe area in figure 7) was woven with a three-layer compound weave. Floats of POFs and conductive yarns were designed at the front and back of the fringe area, respectively, whereas spandex was woven with a plain weave structure between the POFs and the conductive yarns. Plain weave was chosen as the weave pattern under long floats to balance the interlacement with the double-layer structure. The separation of POF floats and conductive yarn floats was directly achieved via weaving to ease the subsequent bundling process for electronic connections.

3.2 Experimental work

The POF fabric was woven on a Jacquard loom (Dornier Weaving Loom PTV 8/J with the STAUBLI Jacquard Head JC6) with four filling materials: POF (MITSUBISHI® optical fibres 0.25 mm in diameter), spandex, commercialised silver conductive yarn, and light-grey polyester. The proportion of the four filling materials was 1:1:1:1. The warp was polyester yarn. The warp density was set as 47 ends/cm and the filling density was set as 18 picks/cm (Table 1). The weave construction was designed with textile design software ArahWeave®. The pattern was designed to combine a stitched double-layer structure and an unstitched double-layer structure. Five-harness satin weave was used for both layers in all double-layer structures.

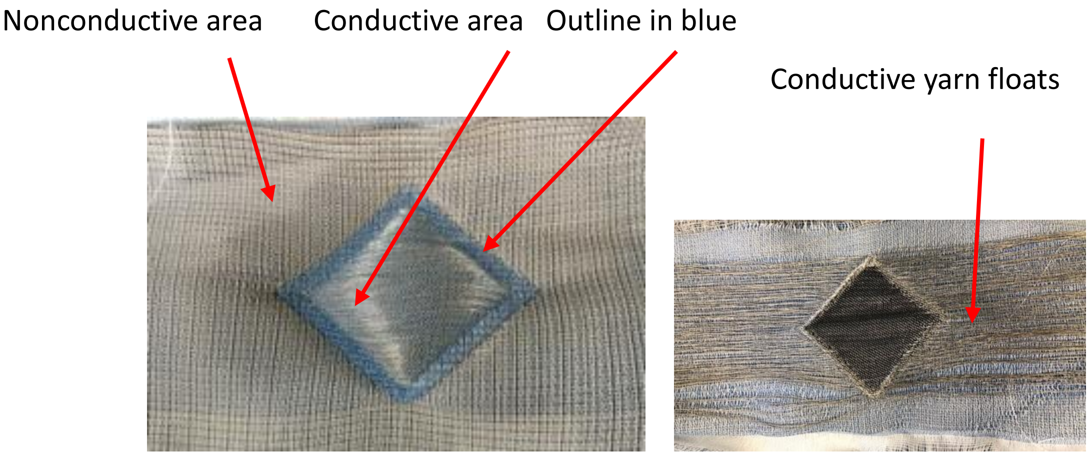
Table 1. Essential specifications of the POF jacquard fabric

FABRIC DENSITY	warp: 47 ends/cm; filling: 18 picks/cm
MATERIAL	warp: 100D white polyester; filling: 0.25 mm POF, 32 blue spandex, 210D silver-coated conductive yarn (18% silver and 82% nylon), 150D grey polyester
WEAVE	<u>Dark-grey background:</u>

	Stitched double cloth with long floats of conductive yarns on top (POF and grey polyester at front, blue spandex at back in 5h satin) Diamonds: Unstitched double cloth (POF, spandex, and conductive yarn at front, black polyester at back in 5h satin) Diamond outlines: Stitched double cloth (spandex at front, others at back in 5h satin)

The dimensions of the textile sensing areas (the diamond shapes) were 6 cm × 6 cm, to provide a large contact region. The bundle of conductive yarns for electronic connection was designed at the back layer of the POF fabric so the appearance of the POF fabric would not be affected.

By adjusting the structure and tension, a diamond-shaped embossed textile switch was developed (Figure 8). The conductive yarn connected the sensing part and the controlling system.



Front view

Back view

Figure 8. Front and back structures of the textile capacitive sensors.

This diamond-shaped embossed touch sensor with woven-in POFs and conductive threads enable the user to interact with the POF fabric. When the diamond area is touched, the whole piece of POF fabric is illuminated in the colour indicated by the outline of the diamond. The debossed layout of diamond shape was designed in RGB colours as indicators for multiple touch activities, such as colour changing and colour mixing of the POF fabric by touch.

4. Design of Electronic System

Capacitive sensing was adopted for the interactive function of the POF textile. Capacitive sensors can be designed for both contact touch and noncontact/proximity sensing by changing the value of the charging resistance (Amjadi, Pichitpajongkit, Lee, Ryu, & Park, 2014); (Kim & Kim, 2016). When the charging resistance is decreased, the sensor can sense the contact touch. When the charging resistance is increased over a threshold, the sensor can sense the noncontact touch. Therefore, multiple functions can be realised.

4.1 Principle of Textile Capacitive Sensors

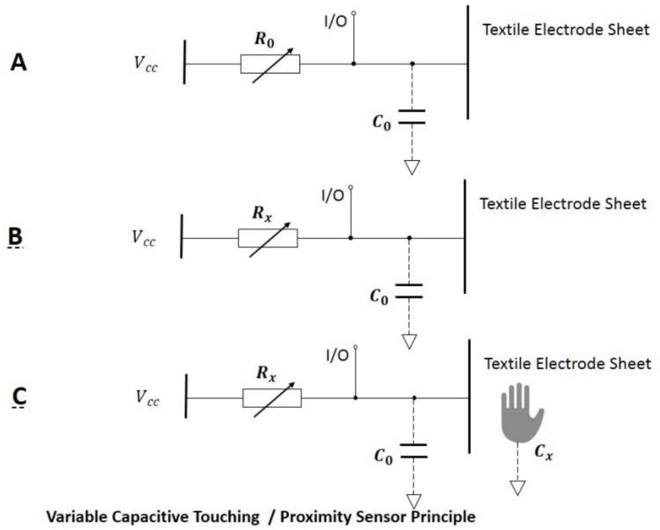
Capacitive textile sensors can be used to obtain bio-signals without contact touch (Babusiak, Borik, & Balogova, 2018). They have been applied in biological signal detection, such as medical EEG and ECG measurements (Lim, Kim, & Park, 2006) (Singh, Sarkar, & Anoop, 2016); (Fuhrhop, Lamparth, & Heuer, 2009). Capacitive sensors could be further classified into double-electrode sensors and single-electrode sensors. Double-electrode sensors are widely applied to textile pressure sensors. Single-electrode sensors are used to measure how long it takes to charge the capacitance between a textile electrode and a human hand (Karvinen, Karvinen, & Valtokari, 2014). In this study, a single-electrode sensor was adopted. Figure 9A and Figure 9B show the process of circuit initialisation after adjusting the variable resistance from R_0 to R_x. There is an initial charging time caused by parasitic capacitance C_0 in the circuit. The circuit is restarted to get an accurate initial charging time t_0' under R_x charging resistance.

$$t_0 = R_0 C_0 \cdot \ln(\frac{V_{cc}}{V_{cc}-V_t}) \tag{1}$$

$$t_0' = R_x C_0 \cdot \ln(\frac{V_{cc}}{V_{cc}-V_t}) \tag{2}$$

$$C = \frac{\varepsilon \cdot S}{4\pi k \cdot d} \tag{3}$$

In the Eq. 3, ε is the dielectric constant value in the air which is 1.00053, and K=$9.0 \times 10^9 N \cdot m^2/C^2$ is electrostatic force constant. t_x represents the charging time when touching. V_{cc}=3.3V is charging voltage in all formula. V_t is specific voltage value, taken as 0.9V_{CC}. S means effective area size of capacitive electrode sheet. d is the distance between two capacitive electrode sheets.



Variable Capacitive Touching / Proximity Sensor Principle

Figure 9. Principle of textile variable capacitive sensor.

In Figure 9B and Figure 9C, when a person’s hand is close to or touching the textile electrode, there would be a capacitance C_x, which is under a charging process. The charging time is

$$t_x = R_x(C_0 + C_x) \cdot \ln(\frac{V_{cc}}{V_{cc} - V_t})$$

$$t_x = t_0' + R_x \cdot \frac{\varepsilon \cdot S}{4\pi k \cdot d} \cdot \ln(\frac{V_{cc}}{V_{cc} - V_t}) \tag{4}$$

Therefore, when time meets the condition in Eq. 5, the sensor receives body touching input or body proximity input.

$$t_x \geq t_0' + \Delta t \tag{5}$$

$$t_0' + R_x \cdot C_x \cdot \ln\left(\frac{V_{cc}}{V_{cc} - V_t}\right) \geq t_0' + \Delta t$$

$$R_x C_x \cdot \ln(\frac{V_t}{V_{cc} - V_t}) \geq \Delta t$$

$$C_x \geq \frac{\Delta t}{R_x \cdot \ln(\frac{V_{cc}}{V_{cc} - V_t})}$$

$$\frac{\varepsilon \cdot S}{4\pi k \cdot d} \geq \frac{\Delta t}{R_x \cdot \ln(\frac{V_{cc}}{V_{cc} - V_t})}$$

$$4\pi \mathrm{k} \cdot \mathrm{d} \leq \frac{\varepsilon \cdot S R_x \cdot \ln(\frac{V_{cc}}{V_{cc} - V_t})}{\Delta t}$$

$$\mathrm{d} \leq \frac{\varepsilon \cdot S R_x \cdot \ln(\frac{V_{cc}}{V_{cc} - V_t})}{4\pi k \cdot \Delta t} \tag{6}$$

In the coding process, Δt is designed as 546 ms. The sensing distance is shown by Eq. 6.

4.2 Design Diagram of the Hardware Electronic Circuit

The textile capacitive sensor receives a signal from a touch input, which is transferred to the microcontroller unit. According to the coding order, the MCU controls the driver to switch on the battery and turn on the RGB LED (Figure 10).

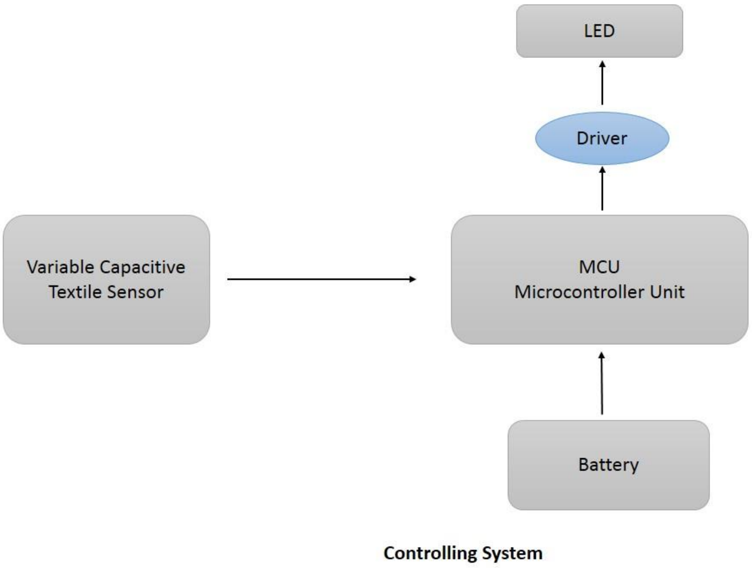


Figure 10. Diagram of hardware electronic circuit design.

The hardware electronic circuit consists of a system power supply, voltage stabiliser, resetting circuit, USB port circuit, serial wire debug (SWD), download circuit, sensor system circuit, MCU circuit, and LED drive circuit (Figure 11).

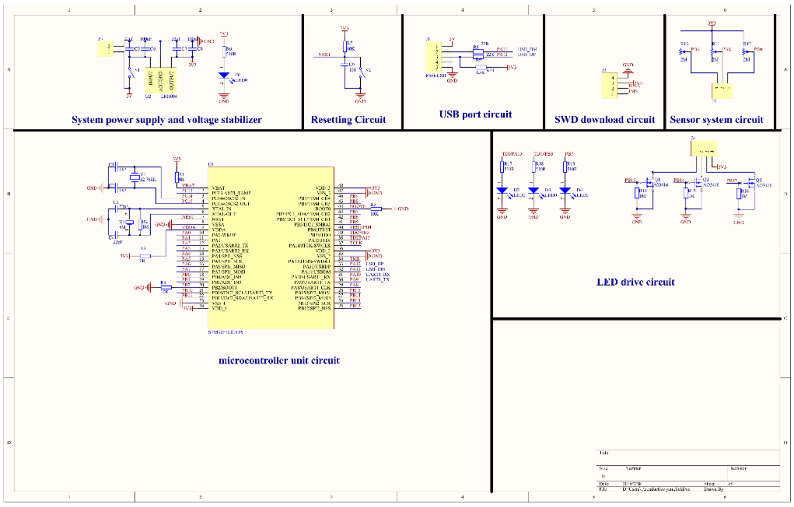


Figure 11. circuit principle of the hardware electronic part.

4.3 Printed Circuit Board Design and Process

According to circuit principles, the printed circuit board (PCB) was designed with the MCU STM32[6], which is small and capable of controlling the whole circuit board, with a size of 3.7 cm × 5.5 cm. The PCB, pictured in Figure 12, is more suitable than traditional module circuits for wearable technology applications.

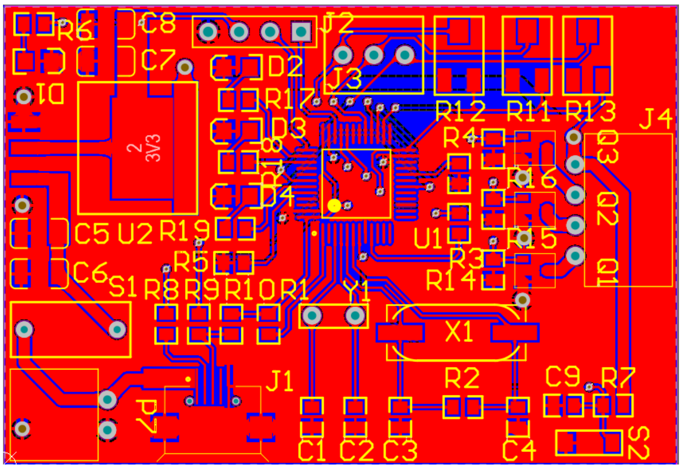


Figure 12. printed circuit board of the textile variable capacitive sensor.

4.4 Software Design and Coding Control

The software control logic diagram is shown in Figure 13. STM32 is controlled by coding in the C programming language. After the normal initialization step, the initial data of parasitic capacitance is collected by the MCU, and then the parasitic capacitor is discharged. The MCU continuously measures and compares the capacitive charging time with the initial parasitic capacitive data. The next step is the judgement step. If the charging time difference is greater than 546 ms, the LED is turned on. Otherwise, the MCU continuously detects capacitive charging time until touch contact or proximity is detected.

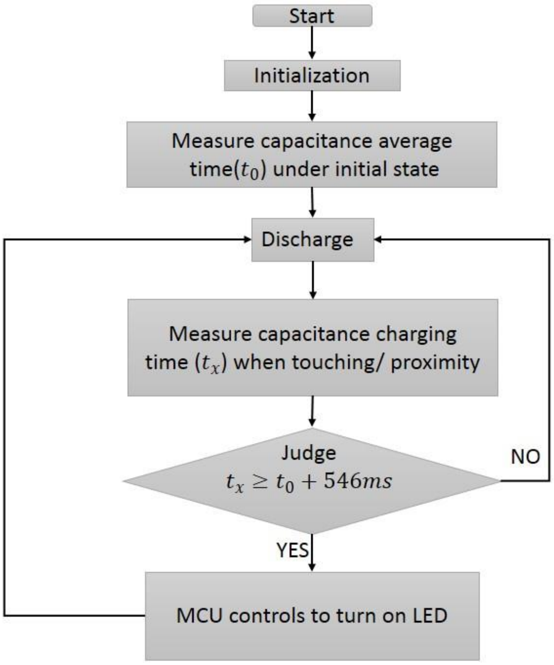


Figure 13. Software control logic diagram.

5. Results

The final POF fabric with touch-sensitive function is shown in Figure 14 (back view). Compared with Connexion (Figure 4), the overall design of this product is unobtrusive and lightweight. A benefit of the integral textile sensing array is that the number of connecting points and hard wires have been reduced.

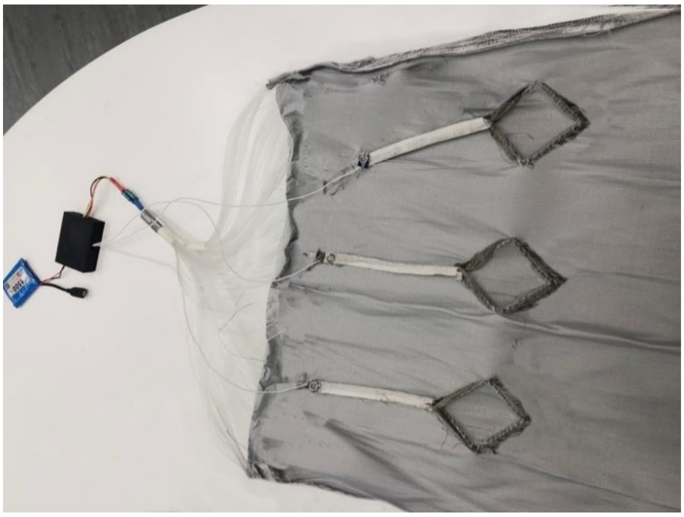


Figure 14. Structure of the touch-sensitive POF fabric (back view).

In Figure 14, to the left of the diamonds, the three groups of long float conductive yarns acting as electrical wires are each bundled and then connected to the MCU. The conductive yarn bundles are insulated to prevent activation of the touch sensors when the hand is above the conductive yarn floats and to prevent the conductive yarns from unintentionally touching, preventing the sensors from behaving as planned. To the right of the diamonds, all conductive yarns are trimmed off. All POFs are bundled together and coupled with an RGB LED (15 W, diameter 8.4 mm) that is also controlled by the MCU. The three embossed diamonds at the face side containing the conductive yarns can sense the touch (both contact touch and noncontact/proximity) and the MCU controls the LED to illuminate the POF fabric in different colours.

When a specific textile area (diamond) is activated, the change in parasitic capacitance and resistance can be detected by the electronics, and then the MCU controls the LED to illuminate a specific colour (red, green, or blue according to the touched area), resulting in the whole piece of POF fabric illuminating with the corresponding colour (Figure 15). By touching different sensing areas, different colours (red, green, or blue) can be activated. Because noncontact/proximity can also cause a change in capacitance, the POF fabric illuminates when a hand is close to the sensing area (Figure 16).

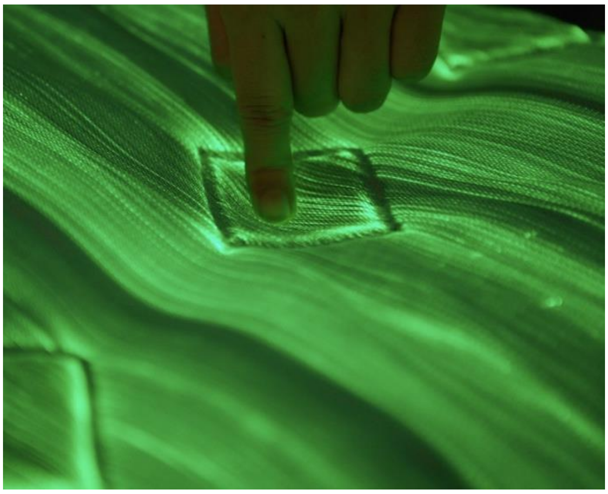


Figure 15. POF fabric in monocolour when only one sensing area is touched.

Figure 16. Noncontact sensing.

When two textile switches are touched simultaneously, colour mixing can be realised. The woven-in touch sensor enables the user to interact with the POF fabric by allowing them to change the colour of the POF fabric (Figure 17).

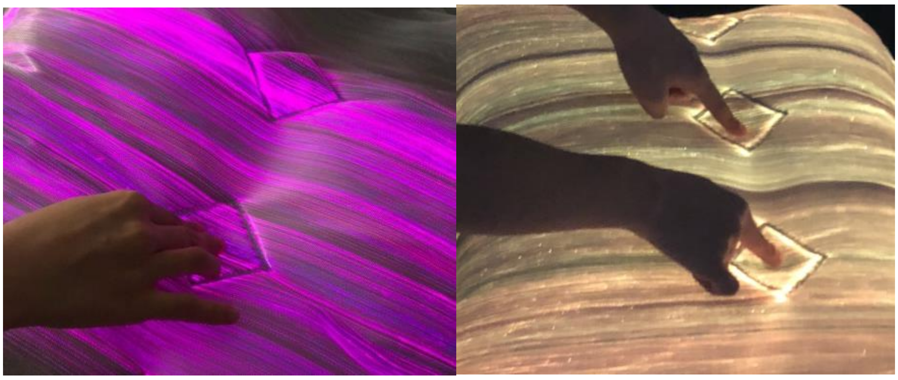


Figure 17 Colour mixing by multi-touch

A textile sensing system that combines POF, textile capacitive sensors, and a microcontrolling system was developed. Three embossed shapes of textile capacitive sensors were produced to act as switches for RGB colour changes in the POF fabric. The conductive threads with long floats on the back side of the POF fabric function as the connectors between the touch-sensing areas and the MCU. When someone touches the textile switches, the change in parasitic capacitance and resistance can be compensated for by the electronics. Therefore, the conductive threads have a marginal influence on the sensed signal.

The RGB LED is coupled with POF bundles. When someone touches the three diamond switches with one hand, the red, green, and blue lights show accordingly (Figure 17). When someone touches two switches at the same time, the colour-mixing effect can be realised. A new interactive experience is produced for the end user, allowing them to manipulate the colour and light of the cushion through a tactile textile interface.

6. Conclusion

In this study, the development of a touch-sensitive POF fabric was explored, which seamlessly integrated POFs, conductive yarn and electronics together. The POFs and conductive arrays were successfully produced by novel weaving techniques to create a soft sensing surface. The electronic system which is based on the capacitive sensor enables multi touch sensing function. By touching different sensing areas, the photonic fabric can illuminate different colours, and colour-mixing effects can also be realized. The unobtrusive design enhances the usability and functionality of the POF fabric and encourages interactive activity between the user and textile. This textile sensing interface has potential applications in smart clothing and fashion items, as well as in interior textiles, to create personalised and customised products.

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