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Dispenser printed capacitive proximity sensor on fabric for applications in the creative industries

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ABSTRACT

This paper reports a planar capacitive proximity sensor fully dispenser printed on a standard polyester woven fabric using conductive ink. Dispenser printing is a new digital printing technique offering the advantages of complete geometric design flexibility and the ability to direct write multilayer devices without requiring bespoke tooling. A dispenser printer is also capable of printing a wide range of ink viscosities encompassing those of inkjet and screen printable inks. Previous research has demonstrated the principle of using proximity sensors for human interaction but none of them are fabricated directly on fabric. In this research, the proximity sensor is dispenser printed directly onto the fabric with an optimised loop electrode design which uses 76% less conductive ink while still offering 90% of the detection range when compared with a standard filled electrode design. The loop design also has the highest detection coefficient (maximum detection distance versus the conductive area of the sensor) of 0.23 compared with 0.06 and 0.1 for the investigated filled and spiral designs, respectively. In addition, the ratio of the track width to the width of the entire sensor is investigated showing 1/16 as being the most suitable ratio for the proximity sensor printed on fabric. Proximity sensors with loop widths ranging from 10 mm to 400 mm are evaluated. The maximum detection distance is 400 mm when the largest sensor is used and the linearity of the sensing circuit is 0.79.

1. Introduction

Smart fabrics are fabrics with integrated electronics which are classified into three categories [1]: passive smart fabrics, active smart fabrics and ultra-smart fabrics. Smart fabrics have been widely researched in healthcare, consumer electronics, fashion and the military, and also have many applications within the creative industries. Many creative applications require the smart fabrics, within an artwork or clothing, to be interactive which can be achieved by means of sensors and actuators. Such interaction with the smart fabric results in a more immersive and memorable experience for the user and can be used in fields as diverse as augmented reality and art therapy.

To integrate the sensing element, miniaturised sensors manufactured by silicon microfabrication techniques are often attached to the fabric. However, since these sensors are rigid, they have the potential to cause discomfort if worn. Furthermore, each sensor must be individually mounted on the fabric which is time consuming and costly. Finally, since such a sensor is inherently small, they may not be suitable for large scale creative applications such as in architecture or interior design.

Weaving, knitting and embroidery of electronically functional yarns can also be used to achieve smart fabrics. However, with weaving and knitting, the primary objective is to achieve the desired fabric structure and so the layout of the functional yarn(s) is constrained to coincide with the fabric's structural layout. In addition, since a yarn must follow the entire length of the fabric, difficulties occur with complex designs, in particular where functionalised yarns need to cross since unwanted connections can occur. Furthermore, weaving and knitting methods may not suit the creative industries since yarns must follow orthogonal directions limiting creative design freedom. Embroidery is also used to create conductive tracks on fabric [2] and has no limitation in yarn direction. It can only embroider one type of yarn at a time but achieving multi-layer, multi-material electrically functional devices is difficult because the embroidery process is very abrasive to the yarns and fabric substrate and can therefore damage the previously embroidered layers resulting in short circuits.

Recent dispenser printing research [3–5] offers an alternative digital smart fabric fabrication technique in which the designs are printed, using electronic inks, directly on the fabric in any geometric layout and only where they are needed without the use of

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masks, screens or other tooling, thus allowing rapid prototyping, minimising resource usage and maximising fabric breathability. Unlike weaving, knitting and embroidery, dispenser printing provides almost complete design freedom since the printed layers can have any orientation on the fabric without being restricted to following the yarn directions. Further, multilayer devices are simply achieved by printing the devices in a layer-by-layer planar fashion using different electronic inks, as required. Compared with other printing techniques, dispenser printing allows materials with a wider range of viscosities (0.01–1,000 Pas [6]) to be deposited than screen (3–250 Pa.s [7]), inkjet (0.001–0.02 Pa.s [8]) and aerosol printing (0.001–1 Pa.s [9]). The thickness of each deposited layer can be controlled by means of the dispense parameters allowing selection of a thickness to achieve continuous electronic layers in a single pass.

A proximity sensor detects the presence or absence of a nearby object within a specified distance without requiring any physical contact. This object can be either a conductor or non-conductor depending on the sensing mechanism of the proximity sensor. Such a proximity sensor can be integrated with other printed electronic actuators to form an interactive fabric. It is therefore suitable for integrating interactivity within a smart fabric since the proximity of a person or object may be used to trigger an event. Proximity sensing has been used for applications, such as motion detection/control [10], process control [11] and level control [12]. Sensing the human body such as the arm using proximity sensors has also been reported in the literature [13].

The capacitive mechanism, which changes the measured capacitance of an electrode due to proximity of a grounded object, can be used to sense the proximity of humans and has been achieved on both rigid and flexible substrates [14–17]. Togura et al. used a commercial sensing module to interact with a person in a car [14]. Two sensing electrodes of 50 mm × 50 mm and 100 mm × 100 mm are installed in the instrument panel and the ceiling, respectively, achieving a maximum detection distance of 300 mm. Lee et al. reported a capacitive proximity sensor made of PDMS and copper for robotic applications [15]. Electrode layers were formed by electroplating copper onto a PDMS layer. Five separate layers, including a bump layer, upper and lower electrode layers, an insulation layer and a spacer layer are bonded to form a sensing unit. An array of 256 sensing units on the same substrates results in a total sensor area of 22 mm × 22 mm. To sense the proximity event, two neighbouring electrodes form a capacitance based on the fringe effect of which the capacitance reduces when the object approaches; a maximum detection distance of 170 mm is achieved. Although the above research illustrates the principle of capacitive detection of human proximity, none of them have been realised on fabric with which their fabrication techniques are not compatible.

To enable a fabric-based proximity sensor, Wijesiriwardana et al. reported a proximity sensor array made by knitting conductive polymer yarns into polyester fabric to form the electrodes [16]. An array (3 × 3) of nine electrodes with a rectangular pattern of 15 mm × 18 mm was knitted. The electrode in the middle acts as the sensing electrode and the other eight surrounding electrodes are grounded. Due to the limitations of knitting, a dielectric fabric has to be attached separately on top of the knitted electrodes to avoid any unexpected electrical connection. Norgia et al. reported a capacitive proximity sensor as a safety switch for cutting off the power from a chainsaw when it is too close to the operator [18]. The conductive wire cloth embedded within the whole garment acts as one electrode and the chainsaw is the other one. When the chainsaw is close to the conductive wire cloth, the safety switch is triggered and the power of the chainsaw is cut off. As a result, 100 mm was achieved as a safety distance for the power being cut off. No detailed results on the distance detected are given and the authors describe this approach as a near field proximity sensor. None of these reported proximity sensors are fabricated by printing directly on the fabric. They all require a complex fabrication process (e.g. MEMS microfabrication processes, knitting) with the limitations described earlier.

This paper reports dispenser printing of a proximity sensor on a 100% polyester woven fabric. The capacitive proximity sensor consists of a one-layer structure to detect proximity capacitively. This layer is a conductor layer which is the sensing electrode forming one electrode of the capacitor; the object to be detected forms the other electrode. Three electrode designs: filled, spiral and loop, are evaluated in this paper and compared to obtain a trade-off between the amount of ink used and the maximum detection distance. A simple detection circuit based on a proximity sensor chip is presented to allow ease of operation.

2. Proximity sensing mechanisms

Potential mechanisms that can be used to detect the presence of an object are: inductive [21], optical [19], ultrasonic [20] and capacitive [15]. The inductive mechanism generates an electromagnetic field and detects the eddy current losses when ferrous and nonferrous target objects enter the field [21]. Inductive proximity sensors normally consist of a metal coil, an oscillator, signal detector and an output circuit. The optical mechanism uses light reflection to determine the distance. Different light emitting sources can be used depending on the application, such as lasers with different wavelengths. The ultrasonic mechanism uses a similar principle to optical but based on an ultrasonic wave so colour and transparency of the object do not affect the results. The sensor radiates a series of short ultrasonic pulses and listens for their return from the reflecting object. Once the echo is detected, the distance is then acquired. The ultrasonic mechanism strongly depends on the transmission of air and the sonic reflectivity of the object. The capacitive sensing mechanism changes the capacitance due to the presence of an object. As the approaching object affects the electric field, the capacitance is changed.

Table 1 summarises the key parameters of each proximity sensing mechanism. Inductive sensing can only detect conductive objects and the maximum detection range is about the same as the diameter of the sensing coil [22]. Even though both optical and ultrasonic mechanisms are able to detect conductive and non-conductive objects, the complex light source or sound generator respectively are difficult to achieve on fabric. In addition, the detection distance is dependent on the surface finish and material properties of the object being detected. The capacitive mechanism is able to detect both conductive and non-conductive objects so is suitable for detecting people and passive objects. The capacitive mechanism is also simple to set up and needs fewer components compared with other sensing mechanisms. It is the most suitable mechanism for a printed realisation since a simple conductive electrode of any shape can be used as the sensing element. A simple sensing element of any shape is advantageous for creative applications as the sensor can be designed to any artistic shape to meet the designer‘s requirements.

3. Design and fabrication

3.1. Proximity sensor design

There are two potential sensor configurations [23], shown in Fig. 1, of the capacitive proximity sensor.

Configuration (a) is based on the principle of a parallel plate capacitor and only requires a single conductive plate to form one electrode of the capacitor. The object acts as a virtual earth. When an object, such as a human hand, approaches, the capacitance between