Embedded Capacitive Proximity and Touch Sensing Flexible Circuit System for Electronic Textile and Wearable Systems

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Abstract—Electronic textiles (e-textiles) are an emerging technology comprised of electronic circuit systems embedded into the fabric using traditional textile techniques such as knitting and weaving. Such systems can be formed using off-the-shelf passive components and integrated circuits (ICs) available commercially. An e-textile switching mechanism can be provided by proximity and touch sensing input behavior from a human hand to switch circuits, for example, turning on an LED for visual verification of successful switching. Challenges to be overcome to achieve reliable systems include optimised circuit sampling rate, detection sensitivity, and sensing electrode dimensions when operating among textile fibres. This paper presents development of a proximity and touch sensing e-textile flexible circuit system using a commercial capacitive detection chip PCF8883US by NXP Semiconductor. Experiments determine the necessary sensitivity and sampling rate values for this chip to detect through fabric for its optimum capacitance performance value of 20 pF. This paper further details the fabrication of this 150 µm track width, 3.0 mm x 35.0 mm x 0.043 mm dimension flexible, copper-polyimide capacitive sensing circuit and its integration into two e-textile systems—a knitted textile yarn and woven textile fabric. Experiments revealed that when an electrode is strip-shaped for e-textile applications, its width is more influential than electrode length in enabling capacitive dual-functionality proximity and touch sensing. A square-shaped electrode offers a 58.3% increase in nominal proximity detection distance compared to multiple electrodes arranged in the same area.

Index Terms—Electronic Textiles; Circuit Analysis; Digital Integrated Circuits; Switched Capacitor Circuits; Electronic Switching Mechanisms; Wearable Computers; Textile Technology; Wearable Technology; Flexible Electronics.

I. INTRODUCTION

TEXTILES are undergoing a technological revolution and are becoming an emerging technology in the era of ubiquitous systems. Electronic textiles (e-textiles) are defined as those with “seamless integration of textiles with electronics and other high-end materials” [1]. The small size of microelectronics components and microelectromechanical systems (MEMS) sensors enable them to be used routinely in wearable applications [2] and offer the potential for integration in e-textiles. Flexible circuits can be located in the core of a textile yarn [3] or woven into a textile [4]. Touch and proximity sensing human computer interfaces (HCIs) are now ubiquitous in the human interaction with electronic devices (e.g. smartphones, automotive dashboards, and tablets [5]). Such an approach could be an attractive method for interacting with e-textiles and capacitive proximity and touch sensing is fundamentally compatible as the electric field travels through any non-conductive material such as standard fabrics [6]. This approach also offers low-power operation and can be readily adapted for particular applications. For example, the electrodes can be made into a variety of sizes, shapes and have different degrees of flexibility depending on the application [6]. Capacitive sensing can detect and distinguish between different types of interactions, such as touching, movement presence, tapping, and swiping [7] and can operate through surfaces which may be stretched or flexed making it suitable for textile integration [8] providing long-term unobtrusive monitoring of dynamic environment [9].

In order for electronics to be integrated in a non-intrusive and invisible manner within a textile, flexible electronic circuit technology can be used. Realising a flexible capacitive proximity and touch sensing circuit for e-textiles introduces challenges relating to the optimisation of circuit sensitivity due to the electrode geometries that are constrained by the textile-integrating requirements. The idea of using film-based flexible circuit substrates as yarns for electronic textile applications has already been explored in the literature. Previous work used strip-shaped electronic circuits to replace conventional yarns in a woven textile [10], [11], [12]. However, the circuits were exposed and visible, being treated as a standard yarn in the weave, and were not embedded in the textile or protected by the fabric layers. The research presented in this paper has an increased level of electronic integration into textiles by enabling the flexible circuits to be woven inside the fabric or placed within a yarn [13].

This paper presents a comprehensive evaluation of a flexible e-textile proximity and touch detection circuit fabricated on a copper-polyimide substrate using the PCF8883US bare die from NXP Semiconductor. This bare die was chosen specifically for its dual-functionality sensing and it was the smallest commercially-available bare die, a factor that aids the invisible integration of the circuit into a textile via knitting and weaving. The resulting system combines new circuit design methods for e-textiles with current manufacturing methods making the system industrially-scalable and cost-effective.
II. PCF8883US Circuit Design and Fabrication for Flexible Circuits

The motivation for this work was to ensure the electronics were truly integrated and hidden within the textile, would not need to be removed prior to the fabric being laundered and can withstand mechanical deformation without functionality being compromised. The flexible circuit with the PCF8883US has been coupled with capacitive sensing electrodes with a range of dimensions to identify the smallest electrode configuration that achieves the required performance.

A. E-Textile Embedded System Design

Increased integration in the textile has been achieved by embedding the flexible circuit strips within cylindrical textile yarn sleeves or weaving them within the fabric. In both cases an outer textile layer disguises the flexible circuit. In the case of the yarn approach, the circuits are conformably encapsulated with a flexible, thin, hydrophobic layer covering the entire circuit to make the system washable.

The yarn approach surrounds the circuit with inner filler yarns and this is covered by a knitted textile sleeve as shown in figure 1. The weaving approach involves a more planar encapsulation process that enables the circuit to be woven into a channel within the fabric as shown in figure 2.

In this work, the system comprises of the capacitive proximity and touch sensing flexible circuit with a flexible, thin, hydrophobic polydimethylsiloxane (PDMS) layer used to protect the circuit from water, detergent, and fabric conditioner. The PDMS is fabricated with a 20:1 mixing ratio of base to curing agent previously identified as the most suitable blend for this e-textile application [14].

B. Circuit Design on Flexible Copper-Polyimide Substrate

The PCF8883 is a commercially-available, auto-calibrating, capacitive, proximity and touch switch – in an integrated circuit (IC) form [13]. It requires a conductive sensing electrode to perform capacitive detection of a conductive object such as a human hand. It is available as a SOIC8 or a wafer level chip scale packaging (WL-CSP) – called PCF8883T and PCF8883US respectively. The PCF8883US was used for this research as it was the smallest commercially-available dual-functionality proximity and touch sensing bare die available at the time of this work - with dimensions of 1.16 mm (L) x 0.86 mm (W) x 0.44 mm (H). In addition to its small size, it also enables adjustable sensitivity and sampling frequency, auto-calibrates to accommodate changes in static capacitance, and offers low power consumption (3.0 to 9.0 V and 3.0 µA current).

The sampling frequency, sensitivity, and sensing electrode size influence the time taken and maximum proximity detection distance of a trigger object. The sampling frequency of the PCF8883 to a trigger object, such as a human hand, is controlled by capacitor C_CLIN. Increasing C_CLIN increases the circuit sampling rate and hence is important in reducing the detection response time of the circuit. Circuit sensitivity is defined as its ability to detect a given object. More sensitive circuits detect a given object at a greater distance and circuit sensitivity also affects response time. Sensitivity is governed by capacitor C_CFC. The PCF8883 has two internal RC timing circuits and its charge-discharge cycles are continually compared as part of its sensor logic. The self-capacitive sensing electrode is connected pin 1 (input) of the PCF8883 which connects to one of the internal resistor-capacitor (RC) timing circuits. The other internal RC timing circuit is used as a reference. Both RC timing circuits are originally synchronised, and change when a trigger object is detected. The discharge time of the internal RC timing circuit connected to pin 1 is compared to the reference internal RC timing circuit’s discharge time. Both timing circuits are periodically charged by the internal regulated supply voltage output at pin V_DD(INTREGD) of the PCF8883 and discharged by a resistor going to ground on pin V_SS, where V_SS is the ground supply voltage. Successful trigger object detection causes the capacitance of the sensing electrode to increase at pin 1. This
causes the discharge time of the internal RC timing circuit at pin 1 to also increase. If the voltage at one RC timing circuit falls below the internal reference voltage at the other RC timing circuit there is a logic output LOW, for vice-versa the logic goes HIGH and a pulse signal is sent to pin OUT. Consequently, the chip’s logic output becomes either LOW or HIGH to represent non-detection or detection of a trigger object such as a human hand.

The charge-discharge cycle of this operation controls the time taken for the RC timing circuits’ logic to switch from HIGH to LOW. This is importantly controlled by the sampling rate which is governed by \( C_{\text{CLIN}} \). The auto-calibration feature of the PCF8883 continually functions to equalise the two internal RC timing circuits and compensate for changing static capacitances. The auto-calibration feature of the PCF8883 is controlled by a voltage-controlled current sink at pin 1. This voltage is the same that falls across \( C_{\text{CPC}} \). As a result, an increased \( C_{\text{CPC}} \) value speeds up the comparison of the two internal RC circuits by reducing the voltage needed for the two RC circuits to activate an output response. The compensation needed is lowered and the detection sensitivity is increased.

The value of total capacitance at pin IN for the PCF8883US [16] to operate at optimum functionality is 30 pF, where:

\[
C_{\text{TOTAL}} = C_{\text{SENS}} + C_F
\]  

(1)

- \( C_{\text{TOTAL}} \) is total capacitance at pin IN;
- \( C_{\text{SENS}} \) is the capacitance generated from the sensor (sensing plate, parasitic capacitance, and trigger object);
- \( C_F \) is the capacitance from component \( C_F \) at pin IN which is a smoothing capacitor.

As \( C_F = 10 \text{ pF} \), \( C_{\text{SENS}} \) needs to be approximately 20 pF. Therefore, factors such as electrode dimensions, \( C_{\text{CLIN}} \), \( C_{\text{CPC}} \), and dielectric layers such as the packaging substrate and the textile outer layer would be decided such the resultant \( C_{\text{SENS}} \) value would be approximately 20 pF. The reference circuit design for the PCF8883US chip had to be modified for the flexible strip geometry with components arranged to minimize the width of the circuit. The flexible circuit was designed using Tanner L-Edit IC Layout software (figure 3) with 0402 surface mount components (i.e. 0.4 mm x 0.2 mm) and wired ground and power connections were located at the circuit ends. The circuit was realised with a width of 3.5 mm and a length of 35 mm. A minimum gap of 50 µm was required between tracks. The circuit design is shown in figure 3 and this represents a reduction in the manufacturer’s reference PCB circuit design area of 95.9 %. The circuit is designed to light an LED upon detection of a human hand, by either touch or proximity, and contains an internal sensing electrode of size 1.0 mm (W) x 10 mm (L).

Single-sided copper clad polyimide film was used along with standard fabrication processes such as spin-coating, photolithography and copper-etching. The circuit design was duplicated and printed on a light field acetate mask (figure 4) for use with a positive photoresist [4].

PCF8883US dies were flip chip bonded to the flexible circuits using a FinePlacer lambda a pick and place machine. The passive components and the LED were manually positioned onto the circuit. Lead-free solder paste was put onto the circuit solder pads and then tweezers were used to place the components onto the lead-free solder paste. The lead-free solder paste was cured using a CIF FT05 Batch reflow oven to making the components adhere to the circuit.

Fig. 4. PCF8883US flexible circuit design on acetate mask (left) and on copper-polyimide substrate (right). The copper polyimide is attached to a 150.0 mm silicon wafer for processing.

Copper litz wires encapsulated in silk were soldered to the contact pads providing the power, ground, and sensing electrode connections. The final circuits were conformal-coated in 20:1 PDMS [14] and are shown in figure 5. The 20:1 PDMS conformal encapsulation had an average thickness of 40.3 µm as shown in figure 5.

Fig. 5. A) Fabricated PCF8883US flexible circuit made from copper-polyimide; B) 20:1 PDMS averaged 40.3 µm conformal packaging with three copper-litz silk wires; C) SEM image capture of averaged 40.3 µm conformal 20:1 PDMS averaged packaging of copper-polyimide flexible circuit substrate.
III. CIRCUIT OPTIMISATION FOR E-TEXTILE APPLICATIONS

The goals of these experiments were to enable proximity and touch sensing functionalities of the PCF8883US flexible circuit using an external copper-polyimide electrode connected to input pin 1. The electrode geometry was restricted to its rectangle/strip-shape, due to constraints introduced by the textile integration approach. Referring to figures 1 and 2, the circuit and sensing electrode would be integrated into a textile using standard automated knitting and weaving machinery. These experiments were based on an earlier circuit prototype of that shown in figure 3. This earlier prototype had an internal sensing electrode size of 2.0 mm x 70.0 mm but could only sense touch and not proximity. In order to obtain operation at proximity, the internal sensing electrode was augmented by an additional external electrode connected in series. The circuit components influencing sensitivity and sampling frequency had to be optimised to achieve the required performance for the electrode geometries being evaluated. To keep the resulting knitted yarn and woven channel as narrow as possible, the electrode had to be a thin as the circuit both of which should be minimised. This would make the circuit as unobtrusive as possible which was a key motivation of this research.

A. Experimental Design

A human hand was used as the trigger object to enable touch and proximity detection of the PCF8883US circuit. The hand was moved to a given position to trigger the operating circuit and was held stationary for each reading and the gap between the hand and the electrode was varied during the measurements. The PCF8883US circuit was positioned on a grounded benchtop to minimise stray capacitances that would otherwise lead to false readings.

The strip-shaped, copper internal sensing electrode of length 7.0 cm on the circuit was extended by attaching an external electrode increasing the effective overall sensing electrode length in 3.5 cm increments with a fixed 2.0 mm width. The external electrode was made from the same material as the internal electrode. The influence of the electrode width was also investigated for a fixed electrode length of 7.0 cm and total widths of 3.0 mm, 6.0 mm, 9.0 mm, 12.0 mm, 15.0 mm, and 18.0 mm. These results are displayed in tables 1 to 4 from sections B to E, where the average detection time in seconds (1.d.p) is given for addition electrode widths and lengths added onto the internal electrode on the circuit. Detection takes 1.0 s or more to occur, whilst 0.0 s denotes a failed reading. A human hand was positioned directly above the internal and external electrode for each reading. Five readings were taken for each measurement and their average was used to create graphs. PCF8883US Circuit component values that would control detection sensitivity and sampling frequency were $C_{\text{CPC}}$ and $C_{\text{CLIN}}$ respectively [15]. Given the electrode constraints, $C_{\text{CPC}}$ and $C_{\text{CLIN}}$ require optimisation for operation within an e-textile and to minimise the electrode size. The default values suggested by the manufacturer are 22 pF for $C_{\text{CLIN}}$ and 680 nF for $C_{\text{CPC}}$. Hence, for the experiments evaluating sampling frequency, $C_{\text{CPC}}$ was fixed at 680 nF whilst $C_{\text{CLIN}}$ was varied using values of 33 pF, 56 pF, and 82 pF. This was within the manufacturer’s recommended range of 22 pF to 100 pF for $C_{\text{CLIN}}$.

Experiments evaluating detection sensitivity used the optimum $C_{\text{CLIN}}$ value as determined experimentally and $C_{\text{CPC}}$ values were varied from 1.0 µF and 2.2 µF. This range was within the 470 nF to 2.5 µF recommended by the manufacturer. The circuits were powered by 4.5 V and 0.003 A.

B. Results: Sampling frequency vs Increasing External Electrode Length

The experimental results are presented in table 1. It shows that for $C_{\text{CLIN}} = 33$ pF, the circuit does not detect proximity for proximity distance in excess of 0.0 cm. For $C_{\text{CLIN}} = 56$ pF, the circuit works as a touch and proximity sensor for electrodes 10.5 cm and longer. For longer electrode lengths, proximity detection occurs for electrode-hand gaps of 0.5 cm and greater. As the sensitivity is kept constant, explanation of this occurrence are higher sampling rates caused by increased $C_{\text{CLIN}}$ values. When $C_{\text{CLIN}}$ is set to 56 pF and 82 pF, the reaction time of the circuit is lowered further due to increased sensor logic speed. Therefore, the PCF8883US is able to overcome the static capacitance at pin 1 more efficiently resulting in successful readings at external electrode lengths greater than 3.5 cm and proximity distances less than 1.0 cm – compared to when $C_{\text{CLIN}} = 33$ pF. Here, the average detection times become faster as the value for $C_{\text{CLIN}}$ increases, with $C_{\text{CLIN}} = 82$ pF showing the fastest averaged proximity detection times.

<table>
<thead>
<tr>
<th>$C_{\text{CLIN}}$ (pF)</th>
<th>Average detection time (s)</th>
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<tbody>
<tr>
<td>33 pF</td>
<td></td>
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<tr>
<td>External electrode length (cm)</td>
<td>Averaged detection time (s)</td>
</tr>
<tr>
<td>17.5</td>
<td>1.0 0.0 0.0 0.0 0.0</td>
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<tr>
<td>14.0</td>
<td>3.0 0.0 0.0 0.0 0.0</td>
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<tr>
<td>10.5</td>
<td>9.7 0.0 0.0 0.0 0.0</td>
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<tr>
<td>7.0</td>
<td>12.0 0.0 0.0 0.0 0.0</td>
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<tr>
<td>3.5</td>
<td>19.0 0.0 0.0 0.0 0.0</td>
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<tr>
<td>Proximity distance (cm)</td>
<td>0.0 0.5 1.0 1.5 2.0</td>
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<tr>
<th>$C_{\text{CLIN}}$ (pF)</th>
<th>Average detection time (s)</th>
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<tbody>
<tr>
<td>56 pF</td>
<td></td>
</tr>
<tr>
<td>External electrode length (cm)</td>
<td>Averaged detection time (s)</td>
</tr>
<tr>
<td>17.5</td>
<td>1.0 30.0 11.3 11.0 6.0</td>
</tr>
<tr>
<td>14.0</td>
<td>5.3 36.0 66.7 37.7 0.0</td>
</tr>
<tr>
<td>10.5</td>
<td>15.0 6.3 19.0 42.7 1.0</td>
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<tr>
<td>7.0</td>
<td>14.3 0.0 0.0 0.0 0.0</td>
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<tr>
<td>3.5</td>
<td>13.3 0.0 0.0 0.0 0.0</td>
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<tr>
<td>Proximity distance (cm)</td>
<td>0.0 0.5 1.0 1.5 2.0</td>
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<tr>
<th>$C_{\text{CLIN}}$ (pF)</th>
<th>Average detection time (s)</th>
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<tbody>
<tr>
<td>82 pF</td>
<td></td>
</tr>
<tr>
<td>External electrode length (cm)</td>
<td>Averaged detection time (s)</td>
</tr>
<tr>
<td>17.5</td>
<td>1.0 1.0 2.3 2.0 2.0</td>
</tr>
<tr>
<td>14.0</td>
<td>4.7 34.7 36.0 24.0 2.0</td>
</tr>
<tr>
<td>10.5</td>
<td>16.7 15.0 1.0 17.7 11.7</td>
</tr>
<tr>
<td>7.0</td>
<td>8.0 0.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td>3.5</td>
<td>9.7 0.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td>Proximity distance (cm)</td>
<td>0.0 0.5 1.0 1.5 2.0</td>
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</table>

Table 1. Average detection time for sampling frequency vs increased electrode length for fixed $C_{\text{CPC}} = 680$ nF and 2.0 mm electrode width

As the $C_{\text{CLIN}} = 82$ pF offered the fastest sampling frequency and more successful proximity detection readings. Therefore $C_{\text{CLIN}} = 82$ pF was used for the fixed, default value for the next
experiment that evaluated detection sensitivity and varied \( C_{\text{CPC}} \).

C. Results: Detection Sensitivity vs Increasing External Electrode Length

According to the PCF8883US datasheet [15], capacitor component \( C_{\text{CPC}} \) is the most important variable in enabling proximity detection. Results showed that with a fixed \( C_{\text{CLIN}} = 82 \text{pF} \); a \( C_{\text{CPC}} = 1.0 \mu\text{F} \) gave 51 % detection readings across 0.0 cm to 2.0 cm range whereas 2.2 µF gave 15 %. From a 0.5 cm to 2.0 cm proximity detection range, \( C_{\text{CPC}} = 1.0 \mu\text{F} \) provided 36 % readings and \( C_{\text{CPC}} = 2.2 \mu\text{F} \) gave 20 %. Hence, a \( C_{\text{CPC}} = 1.0 \mu\text{F} \), the second highest value, gives a more reliable circuit to detect proximity when the electrode width is fixed at 2.0 mm.

If electrode length was a primary influencer to proximity detection performance, when proximity was detected subsequent lengths would also enable proximity detection and the average time elapsed would be smaller. This is not the case when \( C_{\text{CPC}} = 2.2 \mu\text{F} \). In table 2, \( C_{\text{CPC}} = 1.0 \mu\text{F} \) shows minimal time taken to detect touch and proximity across all added electrode lengths. Proximity detection from 0.5 cm is not attained above 3.5 cm and 7.0 cm additional electrode length but when increased to 10.5 cm. Yet, for \( C_{\text{CPC}} = 2.2 \mu\text{F} \) proximity detection is attained by adding 10.5 cm to existing copper electrode length but limited to 0.5 cm detection distance.

If \( C_{\text{CLIN}} \) is the most important variable in enabling proximity detection of the circuit more efficient compared to when \( C_{\text{CPC}} = 1.0 \mu\text{F} \). This can be logically explained by the circuit’s increases sensitivity to interference which is a risk when increasing the \( C_{\text{CPC}} \) to its maximum setting. Experiments show that increasing sensing electrode length does not allow the circuit to operate at its highest sensitivity setting, however, the subsequent experiments investigated if increasing the sensing electrode width could enable an improved \( C_{\text{CPC}} \) value of 2.2 µF.

D. Results: Sampling Frequency vs Increasing External Electrode Width

As mentioned previously, the fixed electrode length for this experiment was 7.0 cm and the original 0.2 cm width was increased by 0.1 cm, 0.4 cm, 0.7 cm, 1.0 cm, 1.3 cm and 1.6 cm.

<table>
<thead>
<tr>
<th>External electrode width (cm)</th>
<th>Averaged detection time (s)</th>
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<tbody>
<tr>
<td>1.5</td>
<td>10.4</td>
</tr>
<tr>
<td>2.0</td>
<td>10.5</td>
</tr>
<tr>
<td>2.3</td>
<td>10.7</td>
</tr>
<tr>
<td>2.7</td>
<td>10.9</td>
</tr>
<tr>
<td>3.0</td>
<td>11.0</td>
</tr>
<tr>
<td>3.5</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Table 3. Average detection time for sampling frequency vs increased electrode width for fixed \( C_{\text{CPC}} = 680 \text{nF} \) and 7.0 cm electrode length

It is clear in table 2, that \( C_{\text{CPC}} = 1.0 \mu\text{F} \) is the best option out of the two values to achieve proximity detection when the electrode width is fixed at 2.0 mm, with a varied electrode length. In this case, the circuit was triggered by proximity approximately 33 % of the time in less than 3 s when a trigger object was 0.5 cm to 2.0 cm away from the sensing electrode. This compared to 0 % triggering for 2.2 µF. Comparing this to the 16 % when \( C_{\text{CLIN}} = 82 \text{pF} \) when \( C_{\text{CPC}} = 680 \text{nF} \) in the previous set of tables, it suggests that increasing sensitivity can make the proximity detection of the circuit more efficient than varying \( C_{\text{CLIN}} \) alone.

For increasing external electrode length, when \( C_{\text{CPC}} = 2.2 \mu\text{F} \), this graph shows a limited ability to achieve proximity detection compared to when \( C_{\text{CPC}} = 1.0 \mu\text{F} \). This can be logically explained by the circuit’s increases sensitivity to interference which is a risk when increasing the \( C_{\text{CPC}} \) to its maximum setting. Experiments show that increasing sensing electrode length does not allow the circuit to operate at its highest sensitivity setting, however, the subsequent experiments investigated if increasing the sensing electrode width could enable an improved \( C_{\text{CPC}} \) value of 2.2 µF.

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1 In the frequency response vs electrode length experiment, \( C_{\text{CLIN}} = 82 \text{pF} \) was discovered to give the most efficient proximity sensing circuit. Therefore, it became the \( C_{\text{CLIN}} \) value for future experiments.
circuit operates as a fast operating touch and proximity sensor as the electrode width increases. Compared to table 1, when electrode length is 7.0 cm and electrode width is 2.0 mm, there were no readings for proximity detection when \( C_{CLIN} = 33 \text{ pF} \). In contrast, in table 3 for a fixed electrode length of 7.0 cm proximity detection is enabled up to 2.0 cm when \( C_{CLIN} = 33 \text{ pF} \) when the electrode width is increased by 1.0 mm. For \( C_{CLIN} = 56 \text{ pF} \), increased external electrode widths for a fixed 7.0 cm electrode length failed to function. This differs from results in table 1 which showed the thinner width of 2.0 mm operating as a proximity sensor for the same \( C_{CLIN} \) value. As this result occurred repeatedly, an explanation could be the PCF8883US unable to adapt to changes in static capacitance at pin 1 with a wider sensing electrode. This suggests the geometry for the strip-shaped sensing electrode is more influential than \( C_{CLIN} \) and \( C_{ CPC} \) to enable full functionality of the PCF8883US.

Previous work has explored the different geometries of capacitive sensing regions and how reliable the touch and proximity detection becomes as a result. Round-shaped capacitive electrode sensing pads are favoured for touch detection as the geometry mimics the rounded fingertip [17]. Whilst the sharp-edged shapes such as squares and rectangles feature can cause localised electric field strength increase at the corners [18] which introduce electromagnetic interference (EMI) compliance issues due to field distortion [19]. Although literature favours round-shaped sensing electrodes, the experimental result gives some indication that there is optimisable strip-shaped sensing electrode geometry for the PCF8883US. The experiments suggest that this strip-shaped geometry is more influenced by having a greater width rather than a greater length in producing more reliable and quick-detection of short-range proximity and touch sensing.

Literature states that with proximity sensing the electric field is projected much further from the sensor into the air compared to with touch sensing [21]. In an ideal case, the sensing area for proximity sensing would need to increase. However, the constraints on this e-textile circuit as to be a small and thin as possible. Therefore, in order to overcome the increased parasitic capacitance experienced during proximity detection \( C_{CLIN} \) can be increased to 82 pF. This is because \( C_{CLIN} = 82 \text{ pF} \) appears to give more successful proximity detections compared to \( C_{CLIN} = 33 \text{ pF} \) over a wide range of electrode widths. Only when the circuit has \( C_{CLIN} = 82 \text{ pF} \) shows sufficient activity to argue that strip-shaped electrode width influences proximity detection.

E. Results: Detection Sensitivity vs Increasing External Electrode Width

Section C indicated that if \( C_{CLIN} = 82 \text{ pF} \), the electrode width was fixed at 2.0 mm and the electrode length was varied that \( C_{ CPC} = 1.0 \mu\text{F} \) gives the best proximity and touch sensing response. However, by increasing the electrode width beyond 2.0 mm, increasing \( C_{ CPC} \), and keeping the internal electrode length as 7.0 cm the PCF8883US’ performance is improved. Comparing \( C_{ CPC} = 2.2 \mu\text{F} \) in table 2 and table 4, table 4 shows that the circuit can have its detection sensitivity increased beyond \( C_{ CPC} = 1.0 \mu\text{F} \) if its electrode width is increased. When \( C_{ CPC} = 2.2 \mu\text{F} \) and \( C_{CLIN} = 82 \text{ pF} \) the circuit could accurately detect a trigger object in less than 10 s at a proximity range of 0.0 cm to 1.0 cm when the total external electrode width is no greater than 0.7 cm. However, greater proximity detection distances of 1.0 cm to 2.0 cm were achievable with external electrode widths of 1.0 cm to 1.3 cm. Table 4, \( C_{ CPC} = 1.0 \mu\text{F} \) shows fast reaction time to touch and proximity detection as proximity distance increases and electrode width increases. Performance is further improved for \( C_{ CPC} = 2.2 \mu\text{F} \) which provides the shortest elapsed time to detect touch and proximity. Comparing these graphs to the Electrode Length vs Sensitivity Settings, specifically, there are fewer appearances of failed readings meaning these circuit parameters make performance more reliable and usable. Switch sensitivity \( C_{ CPC} \) has the highest influence compared to \( C_{CLIN} \) and total input capacitance of the PCF8883US [16]. A higher \( C_{ CPC} \) value allows the sensing electrode area to be reduced. This enables proximity sensing and to sense more reliably at a greater distance [15, 16].

<table>
<thead>
<tr>
<th>Proximity distance (cm)</th>
<th>1.0 µF</th>
<th>2.2 µF</th>
</tr>
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<tbody>
<tr>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
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<tr>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
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</table>

Table 4. Average detection time for detection sensitivity vs increased electrode length for fixed \( C_{CLIN} = 82 \text{ pF} \) and 7.0 cm electrode length

In summary, the results show optimum circuit performance can be achieved by increasing the external electrode width to 3.0 mm from the original 2.0 mm, and selecting capacitor values of \( C_{CLIN} = 82 \text{ pF} \) and \( C_{ CPC} = 2.2 \mu\text{F} \). Experimental results showed that increasing electrode length was less influential than increasing width to produce a reliable and greatest nominal proximity distance. However, as the value of \( C_{ SENS} \) for the PCF8883 had to be approximately 20 pF, further investigations were made. This was to determine the smallest electrode dimensions that would match the desired \( C_{ SENS} \) for optimised PCF8883 circuit operation and be the least detectable within a textile.
IV. EXPERIMENT DETERMINING THE SMALLEST EXTERNAL ELECTRODE SIZE FOR IMPROVED PCF8883US CIRCUIT
SAMPLING FREQUENCY AND DETECTION SENSITIVITY

Once the need for an external electrode was established further work was carried out to determine the influence of the layout of multiple electrodes on performance. Three factors were investigated in this section: number of electrodes for improved touch and proximity detections, nominal proximity detection distance, and the capacitance value generated by the sensing plate and the human hand. This created two experiments, the first evaluated the layout of multiple electrodes to increase the proximity detection distance using the optimised $C_{\text{CLIN}}$ and $C_{\text{CPC}}$ values. The second experiment determined shortest electrode length to produce the desired $C_{\text{SENS}} = 20 \text{ pF}$, to make the embedded hardware most unobtrusive within the textile.

A. Experimental Design

Although the width of the sensing electrode was previously found to be more influential than electrode length, increasing width is contrary to the objective of minimising the circuit width to aid seamless integration into a textile. The 3.0 mm electrode width was previously identified as the least acceptable size to achieve improved touch and proximity sensing. To increase the maximum proximity detection distance further, the surface area of the external sensing electrode could be increased by connecting multiple individual electrodes together. The woven textile structure enables electrodes to be located within woven channels. To connect the electrodes together with wires increases the surface area of the electrode which could increase the proximity detection distance of the PCF8883US circuit. In theory, the electrodes could be placed in parallel or series and located adjacent to the sensor circuit (figure 6) which is also embedded into the textile. In the yarn form, this concept could be executed by having one electrode per yarn and individual yarns placed in parallel in the weft direction. The result would be the multiple electrodes in the system designs for within the core of a yarn (figure 1) or in a woven channel (figure 2).

To connect the electrodes together, wires can extend through the yarns if in parallel and within the yarn if in series. In practice, the parallel electrode configuration for yarns was not feasible as it would require soldering wires during the automatic knitting process to create a seamless and robust yarn structure. Similarly, for the woven fabric channels created during the weaving process, the circuit and external electrodes can be placed in individual channels in a parallel arrangement and connected via wires. In practice, it was feasible to create a single large channel/pocket that could contain a large electrode. However, having multiple electrodes pre-wired together would get caught inside the roving machine used.

Or, without the electrodes being permanently fixed in place, they would likely move inside the channel and would affect the PCF8883US sensing performance.

As shown in Figure 6, the left-hand side shows the parallel (top) and series (bottom) internal electrode configuration when knitted into the core of a yarn. The right-hand side shows the parallel (top) and series (bottom) when woven as part of a channel opening to become fabric.

The values for $C_{\text{CLIN}}$ and $C_{\text{CPC}}$ were 82 pF and 2.2 µF respectively. In the first experiment, square surface area electrodes were evaluated for their nominal proximity detection distance. Their lengths 4.0 cm to 16.0 cm with 1.0 cm increments produced areas of 16.0 cm$^2$ to 256.0 cm$^2$. These electrode square-regions were connected to the internal electrode on the circuit using copper wires. This was compared to evenly-spaced multiple electrode strips. Each electrode was connected to each other with copper wires. They were arranged to fit into surface area that gave the greatest nominal proximity detection distance for the single electrode. The purpose of this was to determine the electrode surface area needed to produce a particular proximity detection distances for the PCF8883US circuit – if electrode size was not restricted. It would be helpful to compare if thin, multiple electrodes arranged in the same area could offer the same nominal proximity detection distance – ideal in making the conductive elements within the textile minimised.

The circuit was connected to a DSO3062A digital storage oscilloscope to check the functionality of the circuit and supplied 4.5V voltage and 3.0 mA current. A ruler was clamped to a stand perpendicular to the working desk as a reference to position a human hand at specified proximity distances. A stopwatch was used to measure the time taken for the pulse signal to be sent to pin OUT and turn the LED at pin OUT to illuminate due to proximity and touch detection. For each surface area, the proximity distance reading was collected five times and then averaged.

For the second experiment verifying $C_{\text{SENS}}$, the lengths of the electrode were 3.5 cm, 7.0 cm, 10.5 cm, 15.0 cm, and 17.5 cm. The electrode width was fixed at 3.0 mm. Compared to the last experiments, this experiment was to determine which electrode length produced the desired $C_{\text{SENS}} = 20 \text{ pF}$ necessary for optimised PCF8883 operation. The shortest length would make the final PCF8883US capacitive proximity and touch sensing circuit the most undetectable when embedded into the textile. The capacitance of the sensing electrodes, $C_{\text{SENS}}$...
measured at 100 Hz as this closely matches the sampling frequency when $C_{\text{CLIN}}$ equals 82 pF [15]. Five measurements were performed for no trigger object, proximity detection at 2.0 cm distance, and touch detection with the tip of a human index finger. The graphs present the average result from those five data readings per electrode arrangements, per detection type.

B. Results: Nominal Proximity Detection Distance with Tailored Electrode Surface Area and Strip-layout

As expected, increasing the surface area of the electrode increases the maximum proximity detection distance. The optimised PCF8883US circuit with improved detection sensitivity and sampling frequency was able to detect a human hand with multiple electrodes connected together with equivalent surface areas of 16 cm$^2$ to 256 cm$^2$. The proximity distance peaked at a 196 cm$^2$ electrode surface area, with an average proximity distance of 15.0 cm. The proximity distance then decreased back to 3.5 cm to 6.0 cm. This, and the anomaly at 196 cm$^2$, was due to larger electrodes being affected by interference, stray electric fields, and parasitic capacitance.

![Fig. 7. Graph of increasing surface area of external electrode (cm$^2$) and resulting average proximity detection distance (cm)](image)

Consequently, for the hand surface area (HAS) in this experiment, an electrode surface area of 121.0 cm$^2$ offered the greatest proximity detection distance of 12.0 cm. The overall trend of the collected data (shown in figure 7) shows a positive correlation between electrode surface area and the proximity detection distance. The nominal proximity detection distance initially peaks at 12.0 cm before declining for subsequent electrode areas at 144.0 cm$^2$ and 169.0 cm$^2$. The maximum electrode area of up to 121.0 cm$^2$ produces a proximity detection distance of 12.0 cm which is adequate for applications and increasing the surface area beyond this is not necessary.

However, when placing multiple electrode strips within this 121.0 cm$^2$ area as the number of electrode strips forming the sensing electrode area increases, the nominal proximity detection distance increases. This is shown in figure 8, whereby adding two 7.0 cm x 3.0 mm electrodes to the PCF8883US does not change the previously achieved 2.0 cm nominal proximity detection distance achieved in previous experiments. However, increasing the number of electrodes to 3 increases the nominal proximity detection distance to 4.0 cm with a 4.8 cm nominal proximity detection distance achieved for 7, 8, and 9 electrodes. The nominal proximity detection distance plateaus at these electrode numbers, and going beyond 9 electrodes would exceed the surface area limit of 121.0 cm$^2$. Nonetheless, using electrode strips compared to square-shaped electrodes decreased the average nominal proximity detection distance by 58.3%. This is due to the sensitivity of the circuit decreasing. With multiple electrodes, the electric field strength between the electrodes is relatively less than the field strength above the electrodes. This could be resolved by having wider electrodes or having smaller gaps between the electrodes. Widening the electrode is undesirable as the maximum was 3.0 mm. The gaps between the electrodes decreased as the number of electrodes added increases, and the proximity distance was maintained at 4.8 cm.

![Fig. 8. Graph of increasing number of strip-shaped external electrodes (cm$^2$) with a fixed 121 cm area and resulting average proximity detection distance (cm)](image)

Changing the sensing plate to one electrode to multiple electrodes changes the capacitance sensing from self-capacitance to mutual capacitance [21]. Unlike self-capacitance, mutual capacitance is influenced by the gap between the electrodes. Electrodes with a greater distance between them project the electric field upwards. However, the overall generated signal becomes significantly weaker in this circumstance. When a finger is in proximity of the electrodes, part of the electric field moves towards the finger instead of the neighbouring electrodes - causing the overall electric field to weaken [21]. As a result, the circuit requires more energy consumption to sense as efficiently. For this reason, proximity detection with mutual capacitance is not advised in literature [21] despite it being more noise-resistant. However, as the configuration in this paper does not have the typical external
electrode and internal electrode arrangement, the effect is similar to increasing the area of a single electrode. This is would explain the linear trend between figure 7 and figure 8.

Overall, experiments show that a square-shaped electrode - rather than multiple electrode strips arranged to give the same surface area - would offer the greater nominal proximity detection distance for e-textile applications. Based on this, an equivalent conductive textile demonstrator with multiple strip-shaped electrodes was created (figure 9) with an electrode surface area equivalent to 121.0 cm$^2$. This was formed by arranging seven identical copper-polyimide strips using the woven channel approach - of size 11.0 cm (L) x 3.0 mm (W) separated 1.5 cm apart. This gives a total surface area of 11.0 cm x 11.1 cm = 122.1 cm$^2$. The arrangement was one electrode per channel, and copper wire was made into a textile form using the woven technique. The electrodes were located into channels but the wires had to be soldered onto the electrodes after weaving. Integrating the electrodes into fabric reduced the proximity detection distance to approximately 5.0 cm on average (figure 9). It seemed that, by separating the electrodes into channels, the resultant surface area of the electrode reduced. This can be explained by the analysis given for figure 8. Therefore, a single electrode to enable proximity and touch sensing was pursued to be compatible with the knitting and weaving machinery used. The experimentally-verified electrode length to provide the 20 pF $C_{SENS}$ value was investigated to determine the final sensing electrode dimensions.

![Image of textile electrode made from multiple electrodes woven into fabric](image.png)

**Fig. 9.** Textile electrode made from multiple electrodes woven into fabric and connected with copper wires to achieve approximately 5.0 cm nominal proximity detection distance (left) and successful touch detection (right).

**C. Results: Smallest single electrode dimension to enable proximity and touch sensing for optimum circuit performance, $C_{SENS}$ value**

When no human hand is interacting with the external sensing electrode the capacitance value increases as the surface area (ultimately the length) of the sensing electrode increases. However, when sensing proximity and touch the capacitance value increases as the surface area decreases. The first result is expected, as more charge is present on larger capacitive plate and therefore the measured capacitance would increase. However, the presence of a human hand seems influential and therefore hints the relative sizes of the plates of a capacitor influence the generated capacitance. Ideally, the capacitor plates should be the same size to generate and even/uniform electric field between them [20].

Comparing the $C_{SENS}$ values between no trigger object, proximity, and touch detection the values are increasing and this is consistent with all electrode lengths under test. This is expected from self-capacitance as when supplied a charge the electrostatic capacitance of the electrode increases. When there is a greater sensing plate area, more charge can be collected and hence the electrostatic capacitance increases.

![Graph of self-capacitance of external electrode with increasing length](graph.png)

**Fig. 10.** Graph of self-capacitance of external electrode with increasing length with no trigger object, proximity, and touch detection

Figure 10 also shows that when proximity and touch sensing detection occurs, the capacitance overall decreases when the external electrode length increases. When a detection event occurs, the human hand capacitively-couples with the sensing electrode. This produces an additional electrostatic capacitance. The human hand has a dielectric constant is similar to water – 80 [22] - which is greater than air - 1.00059 [23], and this causes an increased electric field strength and hence greater capacitance. Additionally, the human skin has conductive properties and acts as the second capacitive plate – which has been explained previously. This explains why the capacitive value has increased for proximity and touch detection for all electrode lengths under test.

A factor which could have caused this is the relative sizes of the capacitive plates – the human hand and the electrode plate. The distance from top of the middle finger to the bottom palm of the human hand used in these experiments was 17.0 cm and width was 10.0 cm. A larger plate area produces more charge collected on the plates (flux) for a given electric field force. However, when one capacitive plate is larger than the other, the electric field flux is more concentrated closest to the smaller electrode plate, which results with a larger overall capacitance. It appears that when the electrode plate connected to the circuit is smaller this generates a larger capacitance compared to when such electrode plate is relatively smaller to the human hand. Nonetheless, the $C_{SENS}$ values when proximity and touch sensing occurs is approximately 20 pF. Values are above 20 pF for 3.5 cm when detecting touch.

**V. RESULTING PROXIMITY AND TOUCH SENSING E-TEXTILE DEMONSTRATORS**

As a result of research detailed in subchapters II, III, and IV, two types of state-of-the-art e-textile demonstrators were created. These were capacitive, dual-functionality proximity and touch sensing e-textiles featuring a flexible PCF8883US copper-polyimide circuit with conformal, flexible, 40.3 μm-
thick PDMS hydrophobic layer. The system designs in figures 1 and 2 were implemented and as the PCF8883US circuit was optimised to textile environments, it could sense through fabric once embedded. These demonstrators were a knitted sensing yarn (figure 11) and a woven fabric swatch (figure 12).

VI. CONCLUSIONS

In conclusion, the goal to develop a completely unobtrusive, invisible, and embedded flexible sensing circuit to create a state-of-the-art e-textile using industrially-available processes was successfully achieved.

System design requirements were focused on developing a functional sensing circuit that can respond to a human hand when it is embedded into a textile. For this, the circuit had to be designed such that was thin (3.0 mm width or less) to fit inside the core of the yarn using the automated knitting machine and also to be handled by the manual looming weaving machine – the two e-textile demonstrator formats that would be made by this research. The PCF8883 IC chip by NXP Semiconductor was chosen and used its bare die/WLCSP form – the PCF8883US. This was because it had the smallest dimensions at time of research, its customisable sensing ability, and dual functionality operation.

Results from this paper have shown that the optimum geometry of the sensing electrode is influenced by the $C_{CLIN}$ and $C_{CPC}$ values. For a strip-shaped sensing electrode to detect a human hand, electrode width is more influential than electrode length to enable proximity and touch detection using the PCF8883US. However, the electrode width needs to be as thin as possible to make the electrode as unobtrusive when woven or knitted into a textile swatch or yarn. Experiments showed that the minimum electrode width achievable for the PCF8883US for a strip-shaped geometry is 3.0 mm. The sampling response value for the PCF8883US will influence the electrode length needed to enable proximity detection for a desired distance range. Together with purposefully selecting an electrode length, the proximity detection distance of a flexible PCF8883US capacitive proximity and touch sensing circuit can be controlled for many applications and usages.

Moreover, when $C_{CPC}$ is above 1.0 $\mu$F for a fixed 2.0 mm electrode width the circuit becomes too susceptible to static noise [16] making the circuit unable to detect proximity. On the basis of usability, the most reliable circuit when embedded into a textile either at the core of the yarn or in a woven textile channel is $C_{CLIN} = 82$ pF and $C_{CPC} = 2.2$ $\mu$F for an electrode width is 3.0 mm allowing for shorter electrode lengths, such as 3.5 cm (35.0 mm), to allow the circuit to perform suitably.

Multiple electrode configurations arranged in parallel and series is a potential way to increase the surface area of the sensing electrode. A square-shaped single electrode of 121.0 cm$^2$ area gave a 12.0 cm nominal proximity detection distance whilst multiple electrodes arranged in the same area gave 4.8 cm - a 58.3% difference. The desired 20 pF $C_{SENS}$ capacitance value, formed by the sensing electrode and the human hand, was achieved with electrode dimensions – 35.0 mm x 3.0 mm and 105.0 mm x 3.0 mm. For the PCF8883US, both electrode sizes can be used within textiles to ensure the bare die performs at its optimum. Furthermore, two types of textile demonstrators were fabricated, a woven textile and a knitted yarn. The resulting circuit was fully integrated into the textile as 35.0 mm x 3.0 mm would offer the smallest strip-shaped electrode dimension, then a smallest, single external electrode dimension of 35.0 mm x 3.0 mm would be needed to enable proximity and touch sensing for the PCF8883US for $C_{CLIN} = 82$ pF and $C_{CPC} = 2.2$ $\mu$F. The e-textile demonstrators could perform touch and proximity for short-range capacitive sensing.

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VIII. REFERENCES


IX. BIOGRAPHIES

Olivia O. Ojuroye received a B.Eng. (Hons.) Electronic Engineering degree from the University of Southampton in July 2015. Her electronic engineering PhD research is on Washable and Flexible Sensor Electronic Circuits for E-Textiles and Wearable Technology. She is part of the Smart Electronic Materials Systems Research Group (SEMS) at the University of Southampton and supervised by Professor Steve Beeby and Dr. Russel Torah. Her publications cover experiments on overcoming the challenges integrating electronics into textiles and increasing electronics’ mechanical and aqueous survival in textiles. Furthermore, she has published theories on wearable technology and e-textile applications in artificial intelligence, education, connected vehicles, smart homes, and wireless sensor networks. Her research interests include electronic textiles, wireless networks, artificial intelligence, user experience, internet of things, wearable technology, and ubiquitous computational systems.

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