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DOI:

[10.1109/JERM.2019.2929676](https://doi.org/10.1109/JERM.2019.2929676)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Jiang, Y., Pan, K., Leng, T., & Hu, Z. (2019). Smart Textile Integrated Wireless Powered Near Field Communication (NFC) Body Temperature and Sweat Sensing System. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 1-1. <https://doi.org/10.1109/JERM.2019.2929676>

Published in:

IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology

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Smart Textile Integrated Wireless Powered Near Field Communication (NFC) Body Temperature and Sweat Sensing System

Yutong Jiang, Kewen Pan, Ting Leng and Zhirun Hu, *Member, IEEE*

A battery free wearable sensing device with temperature and sweat sensors embedded into and powered by a smart textile NFC antenna available for both NFC readers and NFC enabled smart phones, which can take part in various medical applications such as daily healthcare, fever detection and wound healing monitoring.

Take-Home Messages

- In this manuscript, body temperature and sweat sensors are integrated with a textile NFC antenna, which eliminates the need for external batteries and realizes real-time wireless monitoring.
- This paper has presented design, fabrication implementation, measurements and real-life applications of smart textile NFC antennas and a battery-free wireless NFC body temperature and sweat sensing device, aiming for truly ubiquitous wireless health and wellbeing monitoring.
- The proposed device targets at body temperature and sweat loss monitoring for daily healthcare, systemic hyperthermia from fever, sweating symptoms caused by various kinds of infection, inflammation and trauma and wound healing monitoring.
- Different from conventional battery enabled and wire connected sensors, the significance of this work is by applying textile NFC as a communication interface as well as a wireless power harvester, battery-free real-time body temperature and sweat monitoring has been realized simultaneously.
- Apart from the device itself, an App has also been developed on Android system for the sensor data to be accessed by smart phones.

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Abstract Near Field Communication (NFC) is a short-range wireless communication technique that has become attractive devices for healthcare and wellbeing monitoring. The work reported here demonstrates the development of a battery free wearable sensing system with temperature and sweat sensors embedded into and powered by a smart textile NFC antenna. The NFC antenna is seamlessly integrated with closed-body garments, and sensor data can be easily acquired by NFC readers and smart phones in order to achieve real time and wireless monitor of health status in a convenient and non-intrusive way. A Dickson charge pump circuit has been designed and implemented in order to pump up the voltage and ensure a steady voltage supply for the sweat sensor. The maximum read range for accessing sensor data is 6 cm. The on-body measurement accuracy of the temperature sensor and sweat sensor are able to achieve $\pm 0.14^{\circ}\text{C}$ and $\pm 0.2\%$, respectively. The presented system can provide wearable battery-free ubiquitous wireless connectivity for point-of-care and any time healthcare and wellbeing monitoring.

Keywords — Near Field Communication (NFC), temperature sensor, sweat sensor, e-textile, integrated sensing systems, low power electronics, IoT.

I. INTRODUCTION¹

IN recent years, great interest has been raised in integrating electronic devices, such as antennas, electrodes and sensors with daily wearables to form e-textiles [1], [2]. Since clothes are the most elemental and necessary wearables in our daily life, e-textile sensing devices for personal health care have taken part in various medical applications and internet of things (IoT) [3], [4]. The significance of close-body sensors is also highlighted in their contribution to preventive healthcare by constantly raising the users' awareness of their health status [5].

The main advantage of e-textile integrated sensors is that they are easy and comfortable to wear while providing a convenient and spontaneous way for real-time monitoring one's health status without affecting one's daily life [6], [7]. Among current researches of textile based sensors for health care, most applications have been limited to textile properties, such as pressure sensors for posture monitoring [8]–[10], stretching sensors for ionic species loss [11], bending sensors for heartbeat and respiration [12], and wetness sensors for salinized liquids [13]. In [14] and [15], body temperature and humidity sensors fabricated with conductive textile have been reported. However, all of these sensors are powered by batteries, and the sensing data are acquired through wires and analyzed with data centers such as PCs. The extra work in sensor charging and data

processing makes it less desirable in daily personalized healthcare. In this work, e-textile NFC antennas have been developed to be integrated with external temperature and humidity sensors in order to enable battery-free wireless sensing. NFC antennas can be considered as small energy harvesting devices that contribute to green electronic technology since they only rely on the RF power emissions from the reader [16]. Over the past decade, NFC has become one of the potential solutions in wireless health and wellbeing monitoring applications for its low cost, low power consumption, easy access and ability of integration with multiple types of smart sensors [17], [18]. In [19], interfacing external sensors (temperature, humidity, light, pressure etc.) with smart phones through NFC was proposed. In wearable developments, NFC enabled skin-mounted sensing device for heart rate and blood flow has been presented in [20]. However, the development of integrating body-worn textile NFC embedded with sensors for real-time healthcare and wellbeing monitoring has yet to be reported. Based on the characteristics and performance of e-textile NFC antennas discussed in [21] and [22], the contribution and novelty in this work are by applying textile NFC as a communication interface as well as a wireless power harvester, battery-free real-time body temperature and sweat monitoring has been realized simultaneously.

In this paper, we propose a battery-free smart textile NFC enabled sensing device for body temperature and sweat loss monitoring. The NFC antenna is fabricated with silver coated conductive threads and cotton substrate, which is enabled by an NFC sensor transponder (RF430FRL152H, Texas Instruments) connected to an external humidity sensor. In order to achieve battery-free operation, a voltage-boosting rectifier has been applied to provide the DC power required by the humidity sensor wirelessly. An App has also been developed on Android system for the sensor data

Manuscript received 20th March, 2019. This work is supported in part by UK Engineering and Physical Research Council, EU Graphene Flagship Program under Grant EPN010345. (*Corresponding author: Zhirun Hu*)

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to be accessed by smart phones. This development aims for real-time monitoring personal body temperature and sweat loss associated with systemic hyperthermia from fever and sweating symptoms which are often caused by various kinds of infection, inflammation and trauma [23]. It can also be applied in monitoring wound healing progress, daily healthcare and wellbeing.

The main challenge faced by the proposed design is that the conformal structure of textile can easily affect sensor performance under body movements such as bending and stretching. As a solution, the material influence is reduced by minimizing the circuit size and selecting a relatively less influential body location to place the device.

This paper is structured as follows. Section II will demonstrate the overall structure of the textile sensing circuit as well as the design, fabrication and testing of each constituent part of the system including textile NFC circuits, voltage boosting rectifiers and sensors. In Section III, the experiments and measurement results of temperature and humidity sensors are presented. In Section IV, potential applications of this device both for daily use and medical employment are proposed. Section V summarizes the key results and overall circuit performance.

II. ON BODY CIRCUIT DESIGN

A. Sensing System Architecture

Fig. 1. The sensing system architecture.

The sensing system architecture shown in Fig. 1 presents the overall operation methodology of the proposed textile sensing device. A transponder microchip with a built-in temperature sensor is connected to the textile NFC antenna with conjugate impedance matching for maximum power efficiency. When an NFC reader detects the antenna within a read range, the antenna wirelessly receives power to supply the sensor transponder. The maximum output power of the reader (TRF7970A, Texas Instruments) is 23dBm (200mW), and the operating power of the transponder (RF430FRL152H, Texas Instruments) at 13.56 MHz and the sweat sensor (HIH-5031, Honeywell) are around 2.85mW and 600uW, respectively.

Since almost all commercial humidity sensors operate with external DC voltage source, a Dickson charge pump and a voltage regulator is developed as a voltage boosting rectifier connected between the NFC antenna and the sweat

sensor. Meanwhile, the output voltage of the sweat sensor is connected to an ADC input pin of the NFC transponder so that the reader is able to collect data from both sensors (temperature and sweat) simultaneously.

B. Smart Textile NFC Antennas

Fig. 2. Textile NFC prototypes with inductance of (a) 5.86 μH (Antenna A), (b) 1.84 μH (Antenna B) and (c) 1.42 μH (Antenna C)

Smart textile NFC antennas are NFC antennas fabricated by integrating conductive threads with nonconductive textile substrate, which are enabled by conjugate matching with capacitive microchips.

In [21], we have presented the fabrication process and choices of conductive threads, substrate material and embroidery technique of textile NFC antennas. To further investigate the antenna properties and select the best antenna structure for the sensing device, three textile NFC prototypes of different sizes and inductances presented in Fig. 2 are studied. The prototypes are fabricated with cotton substrate and silver coated nylon threads (Arduino Flux Workshop) with resistance of 17.2 Ω/m .

The inductance, resistance at 13.56 MHz and Q factors for the NFC antennas are listed in Table I, where the quality factors of NFC antennas are calculated using (1). As the relative difference between antenna inductances is much greater than resistances, antenna A possesses the best transmission efficiency due to its large inductance and receiving surface for magnetic flux. In reality, however, the relatively large sized and densely packed conductive threads might make it less practical.

$$Q = \frac{2\pi f_r L_{ant}}{R_{eq}} \quad (1)$$

where L_{ant} represents the antenna inductance, f_r represents the operating frequency (13.56MHz) and R_{eq} represents the antenna resistance at 13.56MHz.

TABLE I: NFC ANTENNA PARAMETERS

NFC antenna	A	B	C
$L_{ant}/\mu\text{H}$	5.86	1.84	1.42
R_{eq}/Ω	24.8	15.9	13.5
Q factor	20.13	9.86	8.96

Since the textile based circuits are so flexible that they can be easily bent from body movements of the user, the bending test demonstrated in [21] has been applied to observe how the electrical properties of the antenna A and C (antennas with highest and lowest Q factors) respond to

bending. The measurements are taken using Keysight Fieldfox VNA N9918A, and the test results are presented in Fig. 3. Fig. 3(a) shows how the inductances of the two antennas vary with increasing bending angles. As each antenna is gradually bent from 0° to 180° with its midcourt line being the axis, the inductance of antenna A and C drops from $5.86 \mu\text{H}$ to $4.73 \mu\text{H}$ and from $1.42 \mu\text{H}$ to $1.04 \mu\text{H}$, respectively. The decrement is particularly rapid at the bend range between 120° and 180° .

$$f_r = \frac{1}{2\pi\sqrt{C_{chip}L_{ant}}} \quad (2)$$

where C_{chip} stands for the transponder capacitance, L_{ant} for the antenna inductance and f_r the resonant frequency.

Fig. 3. (a) Inductance variation of NFC antennas at 13.56MHz with bend angle and (b) Measured magnitudes of S_{11} of Antennas A and C in Fig. 2, where the textile antennas are bent with angles: 90° and 150° .

Fig. 4. (a) NFC tag read range measurement set up (b) NFC tag reading with 150 degree bend angle.

It can be deduced from (2) that decreasing antenna inductance would lead to small increments in the antenna

resonant frequency. In Fig. 3(b), where the S_{11} (magnitude) of antenna A and C are measured with increasing bending angles, the measured operating frequency of the antennas indeed increases with the degree of bending. Corresponding to the trend in Fig. 3(a), the central frequency shift between the bend angles of 90° and 150° appears as the greatest. Since antenna A possesses a much narrower bandwidth, the 10 dB frequency band of antenna A shifts further away from 13.56 MHz than antenna C under bending, which means it would take more influence in wireless reading performance. Therefore, considering a wearable sensing circuit comes under inevitable bending caused by natural body movements, antenna C has been selected as the NFC interface for its stable performance and relatively small size that is more desirable for on-body placement.

As presented in Fig. 4(a), an NFC transponder (RF430FRL152H, Texas Instruments) is connected to antenna C. The read range measured with a TRF7970A (Texas Instruments) reader is 6.09 cm. As it shows in Fig. 4(b), the tag is able to be detected under a maximum bent angle of 150° , where the angle is maintained using scotch tape and plastic tweezers. The read distance under this condition is 1.73 cm.

C. Voltage Boosting Rectifiers

In this work the selected humidity sensor (HIH-5031, Honeywell) (used as sweat sensor) operates at DC voltage of 3V and input current of $200 \mu\text{A}$. The main challenge for an NFC tag to perform as a wireless power supply for external sensors lies in the low AC voltage it provides. To overcome this, a voltage multiplier is developed within the circuit in order to raise the supply voltage level for the sensors as well as smooth up the current [24].

Fig. 5. Dickson charge pump circuit layout.

Fig. 5 presents a modified structure of a Dickson charge pump, which can be regarded as a half-wave N-stage voltage multiplier [25]. The circuit operates by gaining packets of charge from coupling capacitors charged and discharged at two anti-phased clock cycles, and pushing them along the diode chain [26]. Since each coupling capacitor is approximately charged to the input drive voltage, ideally, the charge pump would generate an output voltage at the end of the chain $N+1$ times higher than the supply [27] and the output voltage of such circuits can be calculated as (3) [28],

$$V_{out} = (N + 1) \cdot (V_{cc} - V_T) - \frac{N \cdot I_{out}}{f \cdot C} \quad (3)$$

where V_{cc} represents the input voltage, V_T is the forward voltage of each diode, N is the number of stages, I_{out} is the charge pump output current, f is the signal frequency and C is the capacitance applied at each node.

The diodes in this circuit are selected as Schottky diodes (SMS7630, Skyworks), and each coupling capacitor is 15 nF. The minimum voltage to operate the transponder (i.e. charge pump input voltage) is 1.5 V, the maximum diode forward bias current (i.e. charge pump output current) is 50 mA and the maximum forward voltage of each diode is 0.24 V. At 13.56 MHz, the minimum output voltage of the 4-stage charge pump is calculated at 5.32 V.

D. Sweat Sensor Implementation and Testing

Fig. 6(a) illustrates the charging circuit for the humidity sensor (HIH-5031, Honeywell), where V1, V2 and V3 represent the input voltage obtained from the NFC antenna, the voltage output of the Dickson charge pump which goes into a voltage regulator (LP2985-N, Texas Instruments) and the regulator output that supplies the sensor, respectively. As the NFC tag is activated by a reader, V2 and V3 are measured with an oscilloscope (Agilent DSO1014A). Fig. 6(b) presents how V2 and V3 vary with increasing tag read distance. V2 decreases in direct proportion with the read distance. As the read distance is raised from 1 cm to 6 cm, V2 is reduced from 14.5 V to 5V which corresponds to the calculated minimum output voltage (5.32 V). Meanwhile, the regulator output voltage (V3) only fluctuates slightly between 3.35 V and 3.38 V, implying that as long as the reader stays within the NFC read range (6cm in our case), the sweat sensor will operate properly.

Fig. 6. (a) Sweat Sensor circuit layout and (b) V2 and V3 vs NFC read distance.

The complete smart textile NFC enabled temperature and sweat sensing device is presented in Fig. 7. The sensing circuit is fabricated on Rogers RO3006 high frequency substrate with thickness of 0.25 mm. The ground plane of the sensing circuit is covered by a thin layer of insulating adhesive to prevent short circuits due to contact between the circuit board and the NFC antenna.

Fig. 7. Top view of the complete smart textile NFC enabled sensing system.

III. WIRELESS SMART TEXTILE NFC ENABLED TEMPERATURE AND SWEAT SENSING SYSTEM

A. Temperature Sensor

The transponder (RF430FRL152H, Texas Instruments) has a built-in temperature sensor, and the operating range of which is 0°C -70°C. In this work, the sensor is calibrated with two point calibration method. After calibration, the internal sensor accuracy is able to achieve $\pm 0.14^\circ\text{C}$, which is better than most medical body thermometers on the market ($\pm 0.3^\circ\text{C}$) [29]. During measurements, the sensor data is collected with a TRF7970A reader and displayed on a PC.

Fig. 8. (a) Overview of the smart textile NFC sensing system integrated with a shirt, and NFC sensing system read with (b) 15°, (c) 60° and (d) 90° angle between arm and body

The effect of human body towards read range has been investigated in [21], revealing that the influence of skin contact is slight enough to be neglected. As shown in Fig. 8(a), the proposed sensing system is placed slightly below the arm pit since not only axillary temperature is one of the most accurate measurements for body temperature, but the arm pit also generates great percentage of body sweat [30]. Other than general health conditions, the proposed system is also applicable during exercise to monitor body temperature rise and increment of sweat as the oxygen intake (exercise intensity) increases [31]. The sensing

device is positioned to make the sensors face towards human body. In this case, the sensors are protected by the cotton substrate and ensured for more accurate measurements.

Fig. 9. Body temperature measured with three arm positions in Fig. 8 (b), (c) and (d)

In order to investigate how the temperature measurements are affected by body movements, Fig. 8(b), (c) and (d) demonstrate three different arm positions for the temperature sensor to be read (labelled as 1, 2 and 3), where the arm is lifted from the body by 15° , 60° and 90° . The read temperature results are presented in Fig. 9, and the average measured temperature is 36.8°C , 34.4°C and 33.4°C , respectively. Naturally, the closer the textile NFC sensing system stays to the body, the higher and more accurate the measured temperature is. Since the sensor is placed most closely to the body for position 1, it tends to introduce small fluctuation to the results due to inevitable breathing action. On the other hand, the measurements from position 2 and 3 have fluctuation since there is less and less direct contact between the sensor and skin surface. However, these results are much less reliable and tend to vary with small changes of body position. In comparison, position 1 is considered the most suitable way for measurements since all the ripples shown in the test are less than $\pm 0.5^\circ\text{C}$.

B. Sweat Sensor

The NFC transponder (RF430FRL152H, Texas Instruments) has two ADC ports, including ADC1 (reference resistor) and ADC2 (thermistor), mainly for determining an external thermistor value. In the resistive bias mode, a current source is sent to both reference pin and thermistor pin in order to obtain their resistance. Since the humidity sensor (HIH-5031, Honeywell) (used as sweat sensor) now connected to ADC2 operates on voltage bias, the current source is terminated for the data obtained from the transponder to completely depend on the voltage variation.

Fig. 10 shows the results of how the sweat sensor voltage output varies with detected moisture level. The change rate of humidity factor calculated from this trend is $91.3\%/V$, which is applied into the coding of the ADC input data of the NFC transponder. The real time humidity was measured wirelessly by a reader for three different conditions: room environment, normal body humidity and body after workout humidity (under the armpit area) as presented in Fig. 11.

Different from body temperature results, the humidity measurements are hardly affected by slight variation of arm positions since the humidity level around the armpit area is much more stable than temperature. The measured data indicates that for measuring environments where the humidity level is relatively steady, the sensor works smoothly in a ten-minute period with ripples less than $\pm 0.2\%$. In the cool down process of a body workout, although the basic trend gradually drops from 77.9% to 38.1% as expected, some fluctuations still occur during this time period possibly due to slight body movements.

Fig. 10. Sweat sensor test results

Fig. 11. Wireless measured humidity at room environment (32.1% moisture level), normal body (36.9% moisture level) and body after work out (77.9% moisture level)

IV. APPLICATIONS

A. Mobile Handset Reading

For the sensor data to be accessed by smart phones, we have developed an Android program that reads and displays body temperature and sweat continuously from RF430FRL152H, enabling the data to be transferred into cloud storage in order to keep a record of the user's health status. As it presents in Fig. 12(a), the App uses "start" and "stop" buttons that launch and terminate the reading progress, respectively. The software interface displays four types of messages showing the tag connection status, including "Place phone on tag", "Tag connected", "Reintroducing the phone" and "Tag disconnected". It is also able to save readings by time and date.

Fig. 12(b) presents our App works on an NFC enabled Huawei Mate 7 mobile phone. The measured room temperature (24.44°C) shown on screen agrees with the one measured with a Fisher Scientific thermometer (24°C).

Fig. 12. NFC reader software on Android (a) Basic functions (b) Verification of the accuracy of the mobile temperature reading.

B. Wound Healing Monitoring

Fig. 13. Comparison between wrist ('wound') temperatures by wireless NFC sensor and Testo surface thermometer.

It has been stated in [32] and [33] that once wound tissue temperature falls below 33°C , the activity of fibroblast and epithelial cells decreases, which might lead to a delay in the healing progress. Research about how dressing methods can affect wound healing rate has been reported [32]. However, monitoring the healing always requires multiple measurements taken before and after the clothing is changed. On the other hand, if the wound temperature goes higher than normal body temperature for certain duration, it might indicate an infection has occurred [34]. Furthermore, a high moisture environment also prevents wounds from healing [35]. For all these conditions, the proposed smart textile NFC sensing system can be a suitable tool to wirelessly detect the temperature and humidity of trauma such as wounds caused by surgical debridement and accidental injury, in order to maintain normothermia as well as prevent and detect infections.

In Fig. 13, the temperature of a 'wound' on a wrist is measured with the NFC sensing system. The proposed smart textile NFC enabled sensing device is embedded between layers of gauze that are tightly wrapped around a wrist. The measured wrist ('wound') temperature (25.96°C) is compared with the temperature measured by Testo surface thermometer for validation. As a result, the accuracy of the wrist temperature measurements is $\pm 0.14^{\circ}\text{C}$.

V. CONCLUSION

This paper has presented design, fabrication implementation and measurements of smart textile NFC antennas and a battery-free wireless NFC body temperature and sweat sensing device. The textile antenna is integrated with daily garments and the sensing system is wirelessly powered, aiming for truly ubiquitous wireless health and wellbeing monitoring. The measurement results have shown that the textile NFC antennas can still perform properly under bending up to 150° . Both temperature and sweat sensors powered wirelessly by the reader are able to provide accurate and reliable results. Potential real-life applications relating to this smart textile sensing device, including mobile application and wound healing monitoring, have also been proposed. It is believed that the wireless powered smart textile sensing system reported here possesses potential to be widely applied into daily health care system and wellbeing monitoring.

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