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Article

Impact of Manufacturing Variability and Washing on Embroidery Textile Sensor

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Abstract: In this work, an embroidered textile moisture sensor is presented. The sensor is based on a capacitive interdigitated structure embroidered on a cotton substrate with an embroidery conductor yarn composed by 99% pure silver plated nylon yarn 140/17 dtex. In order to evaluate the sensor sensitivity, the impedance of the sensor has been measured by means of a LCR meter from 20 Hz to 20 kHz on a climatic chamber with a sweep of the relative humidity from 25% to 65% at 20 ºC. The experimental results show a clear and controllable dependence of the sensor impedance with the relative humidity. Moreover, the reproducibility of the sensor performance subject to the manufacturing process variability and washing process is also evaluated. The results show that the manufacturing variability introduce a moisture measurement error up to 4%. The washing process impact on the sensor behavior after applying the first washing cycle implies a sensitivity reduction higher than 14%. Despite these effect, the textile sensor keeps its functionality and can be reused in standard conditions. Therefore, these properties point out the usefulness of the proposed sensor to develop wearable applications on health and fitness scope including the user needs to have a life cycle longer than one-time use.

Keywords: sensor; e-textile, embroidery, moisture, conductive yarn,

1. Introduction

Textile has been revealed as a natural and convenient substrate choice in the development of wearable electronics applications, due to the fact that humans have been covering our body with fabrics for thousands of years [1]. This fact, together with the rapid miniaturization of electronic components and the development of new materials is allowing the integration of electronic functionalities on fabrics, using well known textile manufacturing techniques, such as, weaving knitting, embroidery, etc. [2]. Between them, embroidery has been revealed as the most effective technique to implement wearable electronics due to the availability of the manufacturing technology and the flexibility of the technologies to make different geometries and layouts over the textile [3]. Among the different embroidery e-textile applications, in the last years, a great effort has been focused in designing new e-textile sensors included in garments. Many of them are focused on fields such as health monitoring [4], physical training [5] and emergency rescue service and law-enforcement [6].

Although previous literature mainly reports single function use sensors. In order to guarantee the long term functionality of these devices, two topics should be addressed; the variability of the electrical behavior with the manufacturing process and the functionality of the involved e-textiles after washing cycles. In this sense, only a few works can be found in the literature focused on the electrical behavior of e-textile after washing cycles [7], these previous publications suggest that the electrical behavior of e-textile is modified after several washing cycles. In order to go in depth in this topic, a capacitive embroidered textile moisture sensor is presented and a full characterization of its response has been carried out taking into account the manufacturing variability and the washing cycles.

The remainder of the paper is organized as follows. Section 2 describes the Material and methods where the textile sensor layout is defined and the measurement set-up as well as the washing cycle's

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procedures are described. In Section 3 the experimental results are shown and discussed. Finally, in Section 4 the conclusions are summarized.

2. Materials and Methods

The proposed moisture sensor is based on a capacitive embroidered interdigitated structure whose dimensions are depicted in Figure 1. A commercial Shieldex 117/17 dtex 2-ply has been chosen as a conductive yarn in order to embroider the interdigitated structures on a high hygroscope substrate. Specifically, a cotton substrate with a thickness (h) of 0.43 mm has been chosen. A Singer Futura XL-550 embroidery machine with a satin fill stitch pattern has been selected in order to achieve a homogeneous yarn distribution over the sensor surface.

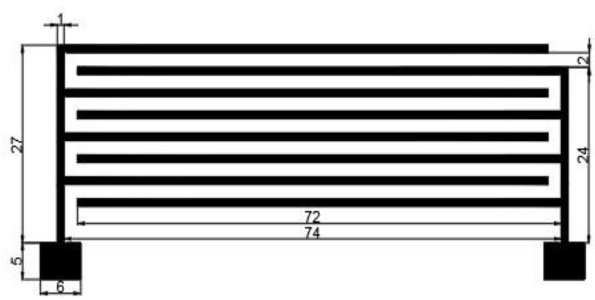

Figure 1. Layout and dimension detail of the proposed moisture sensor (in mm) The bottom squares correspond to the characterization pads.

In order to characterize the sensor behavior, the device has been tested in a *CCK-25/48 Dycometal* climatic chamber and the sensor impedance has been measured by means of an external *Rohde & Schwarz HM8118 LCR* meter. An image of the experimental setup and the embroidered sensor are shown in Figure 2.

(**a**) b)

Figure 2. Image of the experimental setup. (a) CCK-25/48 Dycometal (b) Embroidered capacitive sensor.

The sensor impedance has been measured in a frequency range from 20 Hz to 20 kHz in a 25% to 65% of relative humidity environment, meanwhile the temperature has remained constant at 20 ºC. In order to guarantee and analyse the reproducibility, ten different samples have been characterized and analyzed at 200 Hz and the average and standard deviation has been used such as figure of merit.

Finally, in order to evaluate the impact of washing cycles on the electrical behavior, the electrical impedance has been measured before and after to put through the samples to the washing cycles. In

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this process, the selected soap and the washing machine are according to the standard requirements defined on the UNE-EN ISO 6330:2012. A neutral *ECE-Color Detergent ISO 105-C06* soap has been used and 1 kg of support fabric was used in every wash (Figure 3b). The washing machine configuration for cycles was 1000 rpm, temperature of 40ºC and 1% by weight of soap (i.e. 10 g) introduced in the washing machine.

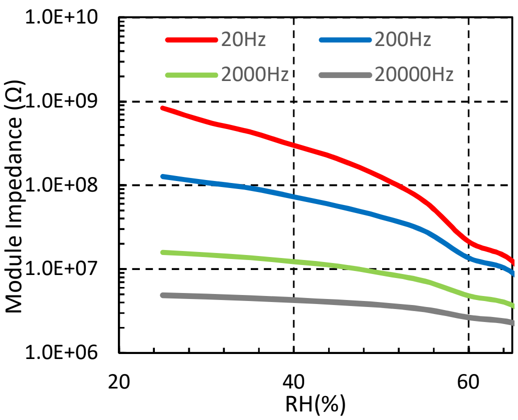
(**a**)

b)

Figure 3. Image of the experimental setup for washing cycles test. (a) Used washing machine (b) Support fabric for washing cycles.

3. Results and discussion

Figure 4 shows the measured sensor impedances when the moisture is swept from 25% to 65% for four different test frequencies. It is observed that the impedance module of the sensor is reduced when the environmental moisture increases. This fact confirms the functionality of the proposed structure as a moisture sensor. The measured phase impedance of the sensor is negative in all the studied frequency range denoting that for low relative humidity the sensor has a capacitive behavior, as expected. However, for higher relative humidity concentration the sensor tends to be resistive. The reason of this behavior is the hydrophilic property of the cotton. Indeed, when the relative humidity increases, the cotton substrate absorbs water and the electrical permittivity of the substrate increases. As a result, the impedance of the sensor is reduced. In particular, for the 200 Hz test signal, the sensor impedance module decreases from 127 MΩ to 9.08 MΩ when the moisture increases from 25% to 65%. For the same moisture range the phase impedance increases from -76.92º to -22.38º.



a) Impendance module

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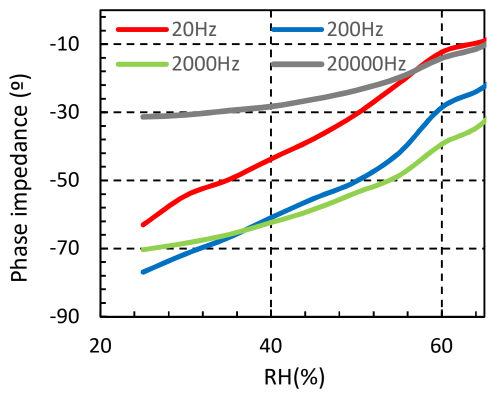


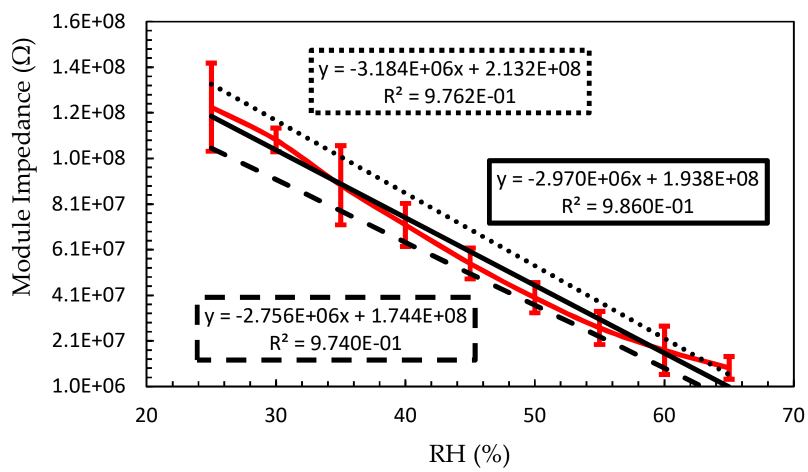
b) Impendance phase

Figure 4. Measured sensor impedance from 25% to 65% RH at different frequencies (T=20ºC).

3.1 Manufacturing variability

Once the functionality of the proposed sensor to measure the moisture ambient has been demonstrated, the reproducibility of this sensor has been evaluated in order to know the impact of manufacturing variability on its performance. In this analysis, the previous sensor capacitor structure has been used and the electrical impedance of ten samples have been measured from 25% to 65% RH at 200 Hz with a 95% of confidence interval.

Figure 5 shows the measured module and phase impedance at 200 Hz, where the red line represents the average measured impedance with 95% of confidence interval error, continuous black line depicts the linear regression for the average value and the dot line and dash line represent the linear regression for +9% confidence interval and -95% of confidence interval, respectively. The linear regression equations are also shown in the graph. From this data, it is observed a linear dependence behavior with the moisture. However, due to the manufacturing variability the static sensor characteristic shows a clear variability. Table 1 summarizes the dispersion measured on the sensitivity and zero shift parameter of the sensor impedance. In particular, the sensitivity of the sensor impedance module has a value of 2.97 MΩ/%RH ± 7%, meanwhile the average zero shift is 193.8 MΩ ± 10%. Meanwhile, the value of the sensor impedance phase achieves a sensitivity value of 1.272º/%HR ± 7.3% and the zero shift a value of -111º ± 0.9%.



a) Module

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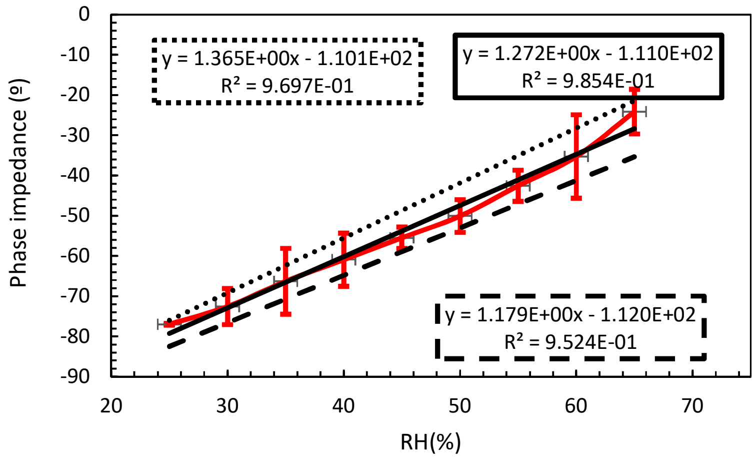

b) phase

Figure 5. Sensor impedance at 200 Hz with a 95% of confidence interval. Red line represents the average measured impedance with 95% of confidence interval error, continuous black line represents the linear regression for the average value and dot line and dash line represent the linear regression for +9% confidence interval and -95% of confidence interval, respectively. The linear regression equations are also shown in the graph.

Table 1. Sensor impedance properties with process variability for 95% of interval of confidence.

	Impedance Module				**Impedance Phase**		
	min	typ	max		min	typ	max
Sensitivity$\left(\frac{M\Omega}{\%RH}\right)$	-31.84	-29.7	-27.56	**Sensitivity**$\left(\frac{º}{\%RH}\right)$	1.179	1.272	1.365
Zero shift($M\Omega$)	174.4	193.8	213.2	**Zero shift** (º)	-112	-111	-110

From the previous dispersion values, it is possible to determine the expected error on module and phase impedance, due to manufacturing variability. The results are depicted in Figure 6. A maximum error lower than 6% on the moisture measurement is obtained. It should be noted that the error decreases with the moisture when the impedance module is measured. Meanwhile the phase error increases with the moisture. According with this behavior and in order to reduce the error up 4% on the moisture measurement, for moisture values lower than 40%RH, the impedance phase should be used. However, for higher moisture values, the moisture value should be obtained from the impedance module measurement.

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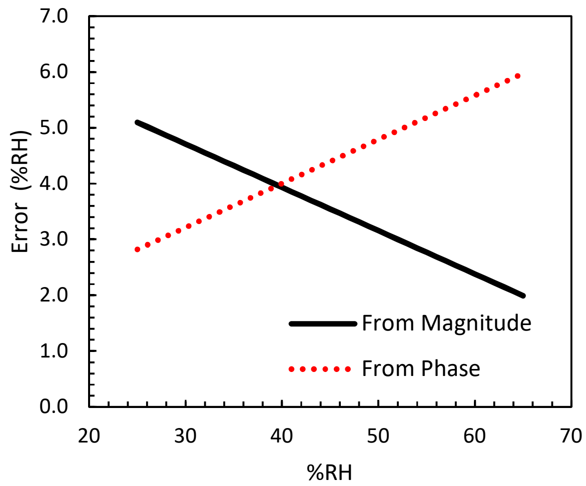

Figure 6. Error of relative humidity at 200 Hz due to the manufacturing variability. The errors are obtained from the magnitude and phase impedance measurement of the sensor.

3.2 Washing cycles

In order to assure the success of e-textiles in real applications, these products should guarantee their functionality after washing process. At this point, the electrical behavior of the proposed interdigitated textile sensor has been evaluated after applying a washing process. Figure 7 shows the sensor impedance module and impedance phase without washing (continuous line), after applying one conventional washing cycles (dash-dot line) and after applying two washing cycles (dash-line). The linear regression for each case and the corresponding equation are also shown.

It is observed that after applying the washing cycles, the impedance module increases for all moisture values whereas the impedance phase is reduced. This behavior points out that after washing cycles the capacitance behavior of the proposed sensor decreases, meanwhile the resistance increases. Small significant difference has been observed between one and two washing cycles. This fact is explained due to the commercial fabrics manufacturing process. In order to guarantee the distributions, the textiles are subjected to a specific antibacterial treatment. After washing, this treatment disappears and this fact can explain the reason of the similar electrical impedance after one and two washing cycles.

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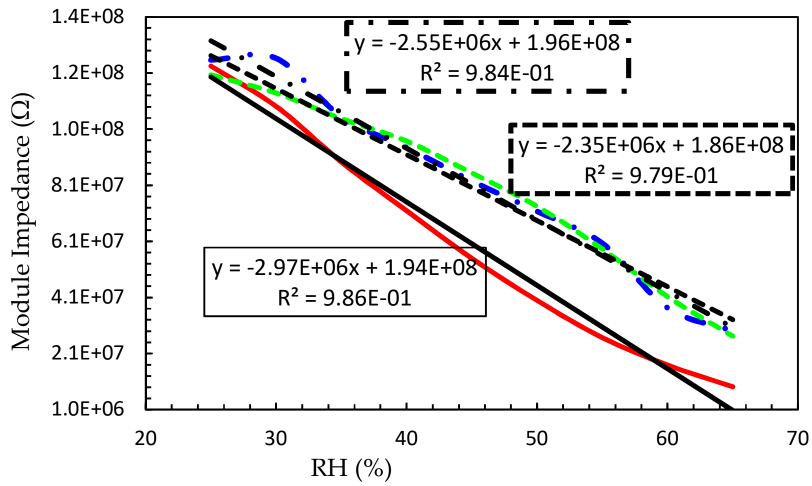
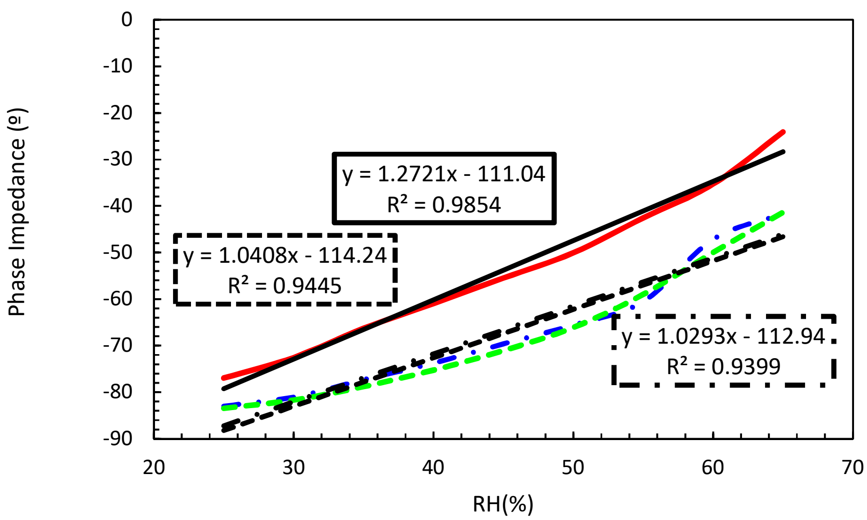


a) Module impedance.



b) Phase impedance.

Figure 7. Effect of washing cycles in the impedance in 200Hz. Before washing (continues line), after one washing cycle (dot-dash line) and after two washing cycle (dash line). The linear regression for each case and the equation are also show.

Table 2 summarizes the impact of washing cycles on sensor behavior. A clear difference before and after washing is observed. After the first washing impedance module sensitivity is reduced a 14.14% meanwhile the zero drift is shifted just a 1%. However, after the second washing cycle only an additional 7.8% of reduction is observed which represents a reduction of 20,88% with regard to unwashed samples. With respect to the impedance phase, almost any differences are observed between one or two washings. After washing the sensitivity is reduced between 18-19% and the offset about 2% in both cases. As previously aforementioned, the used fabric has an antibacterial treatment that modifies its dielectric properties. In fact, this antibacterial treatment consists of increase the electrical conductivity of the fabric. Therefore, before washing, the treatment makes the sensor more conductive but, when the sensor was washed this treatment was deleted, decreasing the conductivity of the fabric and therefore increasing the sensor impedance.

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Table 2. Relation between the parameters measured and the relative humidity.

	Module				Phase			
Impedance	**Sensitivity** $\left(\frac{M\Omega}{\%RH}\right)$	**ΔS%**	**Zero Shift** $M\Omega$	**ΔZs %**	**Sensitivity** $\left(\frac{º}{\%RH}\right)$	**ΔS %**	**Zero Shift º**	**ΔZs %**
No-wash	-2,97		194		1.272		-111.04	
1 wash	-2,55	-14.14	196	1.03%	1.029	-19.1	-112.94	1.71
2 washes	-2,35	-20.88	186	4.12%	1.041	-18.16	-114.24	2.88

4. Conclusions

In this work an interdigitated embroidered textile sensor has been proposed and the manufacturing variability and washing impact have been characterized. The sensors have been embroidered over a cotton substrate with a commercial Shieldex 117/17 dtex 2 yarn. The measured results demonstrate experimentally the usefulness of the proposed sensors at the kHz range to develop wearable application over textiles materials for health and fitness applications, such as the sweating measurement. Due to the manufacturing variability process, an error lower that 6% on the RH measurement are obtained. However, this error can be reduced up to 4% when both, the module and phase impedance of the sensor is measured. The washing process of the textile sensor also has impact on the electrical behavior, mainly after the first washing cycle, when the treatment of the fabrics disappears, this effect is mainly observed as a reduction on the sensor sensitivity. In any case, the devices lose his functionality.

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References

[1] E. J. W. Barber, Prehistoric textiles : the development of cloth in the Neolithic and Bronze Ages with special reference to the Aegean. Princeton University Press, 1991.

[2] L. M. Castano and A. B. Flatau, “Smart fabric sensors and e-textile technologies: a review,” Smart Mater. Struct., vol. 23, no. 5, p. 053001, 2014.

[3] A. Tsolis, W. G. Whittow, A. A. Alexandridis, and J. Y. C. Vardaxoglou, “Embroidery and Related Manufacturing Techniques for Wearable Antennas: Challenges and Opportunities,” pp. 314–338, 2014.

[4] J. Saenz-Cogollo, M. Pau, B. Fraboni, and A. Bonfiglio, “Pressure Mapping Mat for Tele-Home Care Applications,” Sensors, vol. 16, no. 3, p. 365, 2016.

[5] J. Wu, C. Qiu, Y. Wang, R. Zhao, Z. Cai, and X. Zhao, “Human Limb Motion Detection with Novel Flexible Capacitive Angle Sensor Based on Conductive Textile,” 2018.

[6] G. Tartare, X. Zeng, and L. Koehl, “Development of a wearable system for monitoring the firefighter’s physiological state,” in 2018 IEEE Industrial Cyber-Physical Systems (ICPS), 2018, pp. 561–566.

[7] Y. Y. Fu et al., “Experimental Study on the Washing Durability of Electro-Textile UHF RFID Tags,” IEEE Antennas Wirel. Propag. Lett., vol. 14, pp. 466–469, 2015.