ADVANCED MATERIALS TECHNOLOGIES
www.advmattechnol.de

A Full Textile Capacitive Woven Sensor

Marc Martínez-Estrada, Heura Ventura, Ignacio Gil, and Raúl Fernández-García*

In this paper, a full textile capacitive woven sensor integrated over a textile substrate is presented. The sensor consists in an interdigitated capacitance prepared to measure moisture and/or presence detection. In order to evaluate the sensor response to moisture, capacitance has been measured by means of an LCR meter from 20 Hz to 20 kHz in a climatic chamber with a swept of the relative humidity (RH) from 30% to 90% at 20 °C. Subsequently, presence response is evaluated measuring the capacitance of the woven sensor meanwhile a person is sitting down and getting up. The woven sensor results demonstrate its functionality over moisture measurement where sensor capacitance changes from a minimum of 9.74 pF at 30% RH to a maximum of 2.31 uF at 90% RH. The presence detection is also demonstrated, which makes the capacitance variation change from a 10% of capacitance variation when the chair is empty, to a capacitance variation of 170% when a person is sitting on it. The adaptation of the weaving process to accomplish a fully integrated sensor provides a better repeatability than previous embroidered sensors and opens a door to being commercially produced.

1. Introduction

Smart textiles and wearable devices are being developed everyday by researchers with the objective of substitute standard electronic components. People have an increasing interest obtaining information about their health, the world around them and the interactions with others during their daily life. To achieve this, on-body sensors are the most commonly used technology at present, and they can be found in fields as healthcare applications,[1,2] physical training,[3] emergency rescue service, and law-enforcement.[4] Nevertheless, smart textile developments are leading to the appearance of new applications beyond on-body sensors such as gas detection,[5] ballistics,[6] or structural deflection detection.[7] Latest advances are introducing energy harvesting methods on textile sensors to obtain power from other source, which typically are batteries.[8,9]

Although sensors integrated on clothes are the core field nowadays, new ways to use the technology of integrated sensor on textile are taking importance on current research. Fabrics are used in many applications that are not related to personal clothing. Some of these fields are automotive industry, home clothing, agriculture, building materials, maritime industry, and more.[7,10] Applied textile technology to produce smart textiles provides an increase of the product's value used in those fields, which companies could use to launch new products. Smart textiles could provide tools to be used on unexpected applications, such as using the new textile materials and standard electronic devices to add functionalities to the fabrics as humidity or presence detection.[11] Some advantages of integrated textile sensors are the capability to cover longer areas than standard sensors with lower cost, fewer requirements than electronic components, or the ability to monitor physical or chemical stimuli without significantly affecting the structure of the fabric.

Integration methods to produce textile sensor are also a research field over the world, where it can be found a wide variety of methods used. There are chemical oriented methods as the layer by layer self-assembled method,[12] integration by electromagnetic fields (electrospinning)[13] and methods that use the textiles processes to introduce the sensor as embroidery or woven manufacture methods.

Embroidery has been demonstrated over different researches, as the most cost-effective technique for prototyping and low-scale production, due to its fast prototyping and cost of the needed machinery. Previous works[14–16] on capacitive interdigitated sensor were made using embroidery as integration method. However, when the textile sensors are prepared for being used in health care applications, low-scale production could be a drawback. Woven fabrics are known to be produced in large-scale production with lower cost than embroidery. In addition, woven technology could produce textile sensor fully integrated and non-touch-sensitive.[17] Woven electronic textiles are also a growing research field, which have been increasing in the last years.[18,19] Weaving technique provides better results for the integration of the textile sensor, maintaining the textile properties of the substrate.

The humidity has been a crucial factor in hospitals or nursing homes over the years. Injuries related to the long

M. Martínez-Estrada, I. Gil, R. Fernández-García
Department of Electronical Engineering
Universitat Politécnica de Catalunya
Terrassa, Spain
E-mail: marc.martinez.estrada@upc.edu
H. Ventura
Departament de Ciéncia i Enginyeria de Materials – Textile Engineering Section
Universitat Politécnica de Catalunya
Terrassa, Spain

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/admt.202200284.

DOI: 10.1002/admt.202200284

exposures of the patient to the humidity could be minimized having a close control on the humidity state. The staff has many patients to care about, and a system to monitor humidity, providing information in real time could be crucial for improving the attendance. A system to respond that necessity was presented in previous works by the author.[16] To improve the previous system, a textile sensor is produced by weaving process to obtain a better touch feeling, large scale production, and lower production cost.

Furthermore, several applications can be also developed, such as presence detector, using the same sensor. It could be done installing the sensor on the seat textiles. Force Sensitive Resistor(FSR)[20] is the actual technology used on the car seats to detect the presence and send the signal to a microcontroller that activates the seat alarm if the seat belt is not attached and the person is sitting on the seat. Depending on the pressure that actuates on the FSR the resistance variation is higher or lower. Hence, they do not detect the difference between a person or a heavy object. For example, when a bag is disposed on a seat, if the threshold is exceeded the alarm starts ringing. Pressure woven sensors[21] could be the natural textile substitute to FSR sensors in car seats. The woven capacitive sensor presented in this work could avoid the problem presented as example.

In this paper, to demonstrate the viability of the woven technologies to integrate interdigitated sensor on fabrics, a full textile capacitive woven sensor to measure humidity and presence is evaluated. The woven sensor is presented as an improvement of the previous reported embroidered sensors providing a higher degree of integration, more comfort for the user and facilitate large-scale integration of the textile sensor.

2. Experimental Section

The proposed woven sensor is based on an interdigitated structure. **Figure 1** shows the layout and dimensions of the sensor. The sensor was woven on a Dornier LWV8/J weaving machine moved by a Jacquard Stäubli LX1600B, which is shown in **Figure 2**. The woven machine was prepared with a warp beam formed by 100% cotton yarns. Weft yarn was composed by a cotton/polyester yarn (35/65%). These materials formed the substrate where the sensor is integrated. The substrate has a hydrophilic nature, which means that the water particles in the air could be absorbed by the substrate changing its electrical permittivity.

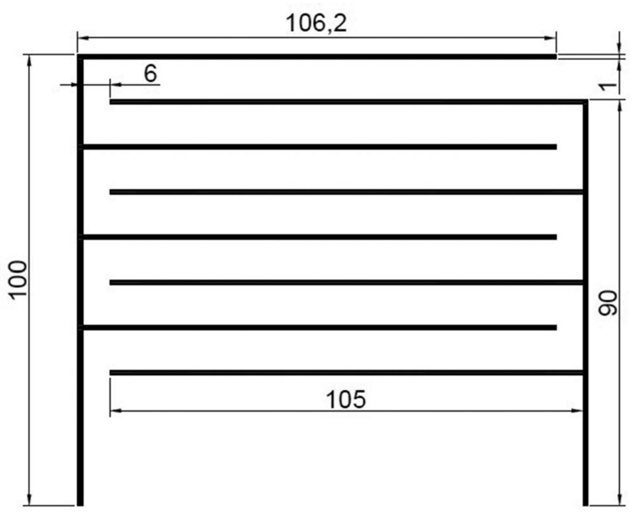

Figure 1. Dimensions of woven sensor in mm.

Figure 2. Dornier LWV8/J weaving machine moved by a Jacquard Stäubli LX1600B.

2.1. Manufacturing Process

The weaving process is the method used to manufacture a fabric through a sequential introduction of a horizontal yarn (weft yarn) between vertical yarns (warp yarns) that come from a beam. To configure the structure of the final fabric, the warp yarns were moved up or down by a Jacquard system corresponding to the position required for the weave. Consecutively for each Jacquard position, a weft yarn was inserted between the warp yarns, causing the link between them and producing the fabric sensor.

Warp beam was prepared with high-cost process and only a few companies of the zone have the machinery need. The weft yarns were prepared in a yarn rack and connected to one of the six introduction yarn systems that our weaving machine had. As it can be observed, **Figure 3** shows the weaving process scheme. The method of the introduction of the weft yarn varied depending on the specific technology. In Figure 3, it can be observed as a flying shuttle, which is the hand-made system. In the case of the Dornier LWV8/J weaving machine, an insertion by air pressure was used.

In order to weave the sensor two different conductive yarns were used. One of them was a commercial Shieldex 117/17 2-ply(S), which was a silver 99% coating covering a polyamide filament. The second yarn used was a Bekaert 20/2 Tex (B) polyester mixed with stainless steel fibers with a proportion of 60/40%, respectively, which was produced by ring yarn procedure. The yarns had different properties; on one hand, Shieldex yarn had more tensile resistance and lower electrical resistance. On the other hand, Bekaert yarn was more comfortable and lighter. Properties of conductive and non-conductive yarns used are presented on **Table 1**.

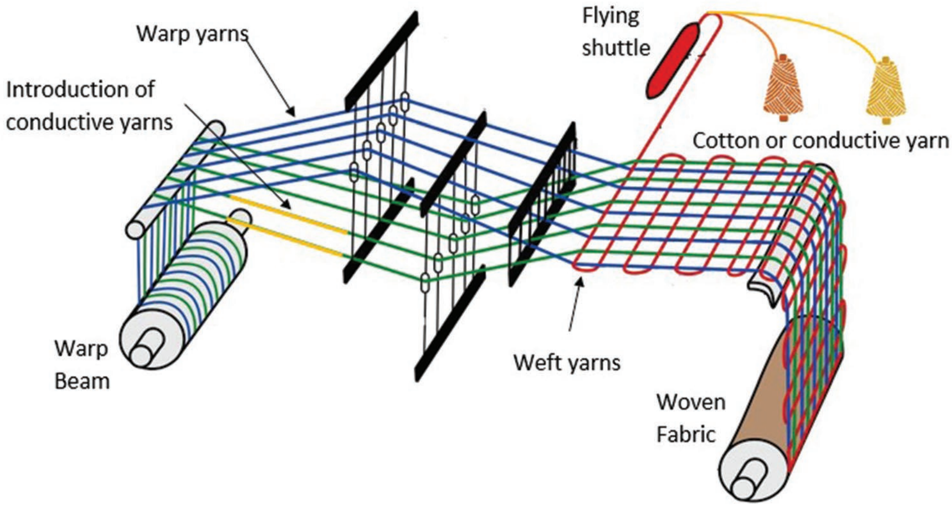

Figure 3. Weave process scheme.

To weave the sensor, the conductive yarns should be introduced on the warp and weft. Preparing a new warp beam is unfeasible due to the cost and the machinery need. Instead of it, warp single yarns are being partial substituted by hand. In Figure 3, it is shown where the yarns are substituted. The process followed was to cut the initial cotton warp yarn on the beam and knot a portion of conductive yarn to both ends of the initial warp yarn, which is represented as yellow yarns in the figure. This process is repeated for each substitution.

Regarding the manufacture process of the sensors with Shieldex yarn, 12 individual yarns of the warp were substituted by Shieldex conductive yarns. These yarns formed two vertical lines along the woven fabric, which were the lines that connected the different horizontal lines. Afterward, Shieldex conductive yarn was introduced on the weft system to proceed with the weave process of the fabric. The same methodology was performed with the Bekaert yarn. As a result, two types of sensors were obtained. Sensors produced with warp and weft yarn from Shieldex were defined as USTS, and sensors made with warp and weft yarn from Bekaert were defined as UBTB. The resulting fabric from the process counts with 40 yarns cm^{-1} in warp direction, 26 yarns cm^{-1} in weft direction and a mass per surface of 292 \texg m^{-2}.

2.2. Sensor Characterization

The proposed woven textile sensor was characterized with relative humidity and evaluated as a presence sensor. **Figure 4** shows the two woven sensors.

Table 1. Properties for the yarns used on the research.

Properties	Shieldex(S)	Bekaert(B)	Warp (CO)	Warp (CO/PES)
Density (tex)	11.7/2	20/2	19/2	24/2
Linear R(Ω cm^{-1})	30	50	–	–
Thread type	Twisted multifil.	Ring yarn	Ring yarn	Ring yarn

With regard to the humidity characterization, the sensor was introduced into a CCK-25/48 Dycometal climatic chamber to observe the behavior facing a swept from 30% to 90% of relative humidity and temperature has remained constant at 20 °C. To obtain the optimal behavior of the sensor, it is maintained 5 min at the initial relative humidity. This time was used to balance the relative humidity with the humidity that remained into the substrate, avoiding hysteresis during the measurements. The temperature was fixed due to at hospitals and nursing homes, the temperature is controlled. During this test, the capacitance was measured all over the swept by means of an external Rohde & Schwarz HM8118 LCR meter. The test was performed three times for each sensor. At the end, 9 groups of values were obtained for each type.

To check the sensor behavior as presence sensor, it was placed over a chair. A person, whose weight was 70 kg, sat down on the chair while the capacitance values were recapped, the actions duration was 10 s and it was repeated four times. Additionally, 3 cycles of the presence test were repeated for a 4,6,10, and 15 kg bag, covering the sensor to demonstrate that the sensor is able to distinguish between a person and an object. The sensor capacitance had been measured from 20 Hz to 2 kHz.

The sensor operation principle is based on the permittivity (ε_{RH}) change, which can be produced by a change in the humidity (humidity sensor) or a change on the contact material (presence sensor). The equation that describes the total series capacitance of an interdigital capacitor can be written as follows:[22]

$$C_{RH} = \frac{\varepsilon_{RH} \cdot 10^{-3}}{18\pi} \frac{K(k)}{K'(k)} \cdot l \cdot (N-1)\ (pF) \tag{1}$$

$$\frac{K(k)}{K'(k)} = \frac{\pi}{ln \times 2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}} \tag{2}$$

$$k = \tan^2\left(\frac{a\pi}{4b}\right) \tag{3}$$

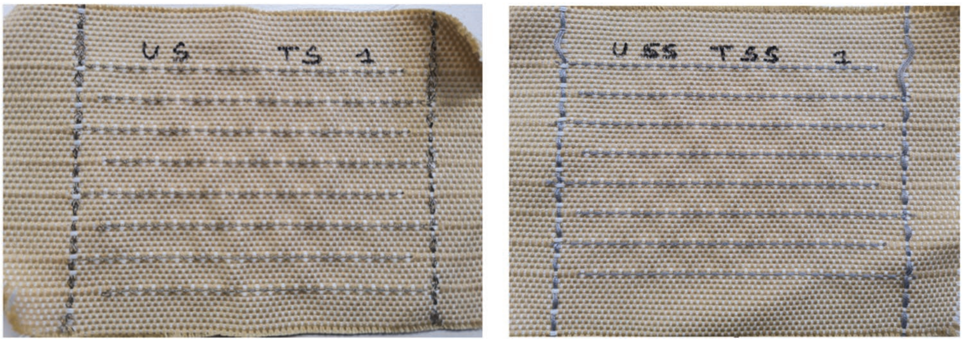

Figure 4. Textile woven sensor.

$$a = \frac{W}{2} \quad (4)$$

$$k' = \sqrt{1 - k^2} \quad (5)$$

$$b = \frac{W + S}{2} \quad (6)$$

where l is the length of the fingers in microns, N is the number of fingers, (ε_{RH}) is the parameter that suffers changes with moisture level or when a person is touching the textile sensor.

3. Results and Discussion

3.1. Humidity Sensor

In order to validate the sensor behavior, the capacitance of the sensor at 20 Hz was evaluated. **Figure 5** shows the sensor capacitance against humidity response for the USTS and UBTB sensors. It is shown how the logarithm of the capacitance (Y = log_{10}(C)), where C is the capacitance in Farads, increases as the relative humidity increases for both sensors. The measurement range presented for USTS sensorson Figure 5a starts at –11.01 (9.74 pF) at 30% of relative humidity and develop till –5.79 (2.31 µ F) at 90% of relative humidity.

On Figure 5b can be observed the behavior of the UBTB sensors. The Bekaert yarns show good stability around the swept in relative humidity. The measured capacity range goes from –10.97 (11.9 pF) at 30% of relative humidity and grows till –6.42 (0.3 µ F) at 90% of relative humidity.

Linear regression is evaluated for each sensor logarithmic capacitive values. Linear regression follows the equation:

$$log_{10}(C) = a \cdot \mathrm{HR} + b \quad (7)$$

where HR refers to the relative humidity value on percentage. On **Table 2**, values from linear regression are displayed.

Linear regression evaluation provides the sensitivity of each sensor, which is the slope of the line. Linear regression shows that UBTB has a lower slope and its $62 \times 10^6 \mathrm{Sm}^{-1}$ is higher, being more linear than USTS sensor and matching better with its equation.

USTS has the highest dispersion between 75% to 85%, the standard deviation values go from 4.3% to 5.5% regarding the average value. Being the highest standard deviation point on 75% of relative humidity with a value of 5.5%. Instead, UBTB standard deviation values are more stable. There are not as big differences as for USTS values. The highest standard deviation values are on 80% and 85% of relative humidity with a value of 2.5% and 2.9%, respectively, regarding the average value.

The differences between these materials could be explained by their electrical properties. On one hand, the range of values is wider on the USTS due to the silver conductivity. Silver is more conductive ($[1.28 - 1.32] \times 10^6 \mathrm{Sm}^{-1}$) and it has lower resistivity than stainless steel ($log(C)(\mathrm{RH})^{-1}$). On the other hand, UBTB has a lower standard deviation than USTS. The fact that stainless steel yarns are made by

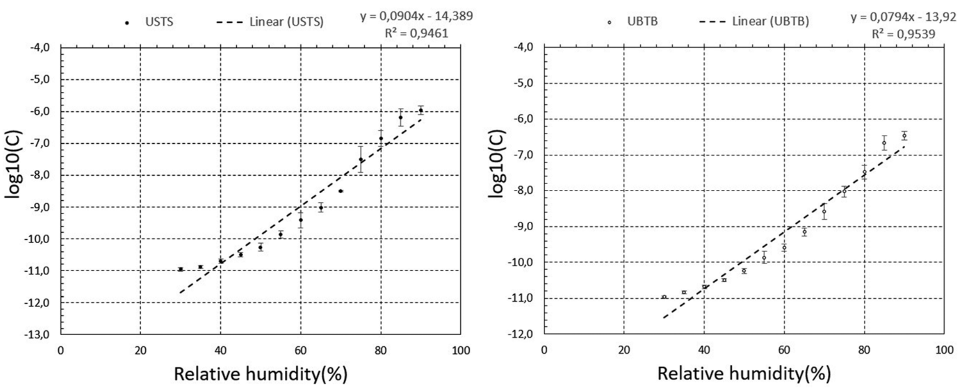

Figure 5. Relative humidity response for woven sensors.

Table 2. Properties for the yarns tested.

Sensor	Linear Regression	R^2
USTS	0,0904· HR-14,389	0,9461
UBTB	0,0794· HR-13,92	0,9539

ring yarn process, which is the same method as the common yarns used on the substrate, could have better behavior when the yarn is woven.

Data presented can be compared to previous works to confirm the expectations about the weaving sensor. In **Table 3** embroidery data acquired in previous works[14,15] are compared with the data obtained. It is observed how the weaving process decreases the standard deviation in comparison with the sensors. Embroidery presents, on average, a 2.1% on standard deviation, considering three different sensors and repetitive test. Meanwhile, woven sensor has a 1.34% of standard deviation on average. As a result, this process produces sensors with higher repeatability and with less dispersion. Sensitivity is also modified from embroidery to weaving. The sensitivity has an increase of 0.0168 $log(C)(RH)^{-1}$ for woven sensor.

A comparison with other sensors on the literature is done in **Table 4**. As it can be seen, woven technology performed as well as the other interdigital sensors. These results demonstrate its functionality as humidity sensor and the possibility to provide the value of relative humidity measured. The woven sensor provides better capacitance values with less dispersion compared with the embroidered integration method. Humidity applications that need large-scale production could be satisfied with the woven sensor presented.

3.2. Presence Sensor

The second part of the Experimental Section presents the characteristics of the woven sensor as a presence detector. As explained in section 2, a presence test is performed to evaluate the sensor feasibility to be used as presence detector. A person sat down over the woven sensor (occupied state) and stand up (void state) 4 consecutive times. It was done in periods of 10 seconds. **Figure 6** shows the capacity shifts results of the test for USTS and UBTB. USTS is represented as a continuous line, meanwhile, UBTB is represented as a dashed line.

As it can be observed, the response of USTS after a person is sitting on the sensor is a significant increase on the capacitance, which is maintained at a high state till the person got up. After a person occupied the place and got up, the sensor presents a slight increase in its void state. Sensor void state

Table 3. Comparison between technologies.

Technology	Sensitivity $log(C)(RH)^{-1}$	Standard deviation (average(%))	Improvement %
Embroidery	0.0736	2.1	–
Weaving	0.0904	1.34	36.2%

Table 4. Comparison with other interdigital humidity sensor. In this case, the impedance sensitivity is used to be able to compare with other sensors.

Reference	Sensitivity $log(Z)(RH)^{-1}$	Working Range %RH	Size H × W(mm)	Integration Technology
This work	0.0673	30-90	100 × 106.2	woven
[23]	0.0559	20-90	4.25 × 4.25	drop-coated
[15]	0.0535	25-80	27 × 74	embroidered
[24]	0.0804	40-90	150 × 220	embroidered

values are between 0% and 15% of capacity variation, meanwhile sensor occupied values are between 100% and 170% of their initial capacitance value.

The UBTB sensor presents a good response when presence is detected. The void values are similar to USTS, being around 0% to 15% of capacity variation. In this case, the sensor increases its values to 120–170% of capacity variation.

The behavior of the sensor has been evaluated when a heavy object is placed on it, such as a shopping bag. Specifically, a bag with 4,6,10, and 15 kg was tested, as shown in **Figure 7**. The capacitance values showed an increase to a maximum of 20% of capacitance, similar capacitance values than previous void states. The capacitance remains constant between 15% and 20% values in all the different load cases, when the bag is placed over the sensor. Different loads do not present significant capacitance values, which means that the sensor variation is due to the textile of the bag, which has a different permittivity. It is demonstrated that the sensor is capable to differentiate between a bag and a person.

Both sensors present and increase of their capacitance when the place is occupied. Void state and object occupation are clearly differentiated from a person occupied state. As a result, the woven sensor demonstrates its functionality on presence detection, and it opens a door to continue this research line. The adaptability of the woven capacitive sensor is demonstrated along the paper, showing that it can be used as a humidity detection sensor and also as a presence sensor with good performance.

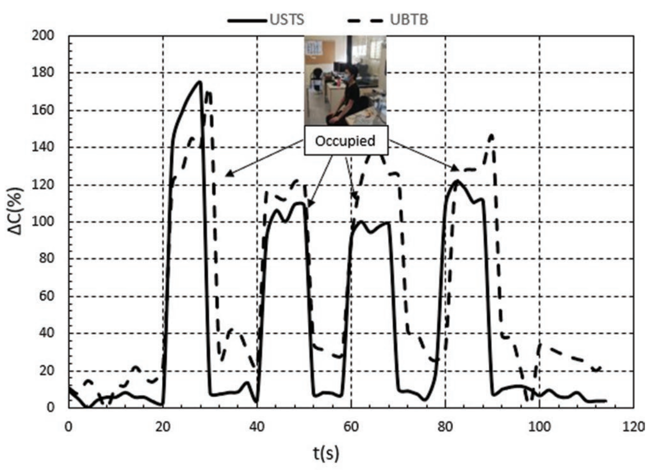

Figure 6. Capacity shift, in percentage, during presence detector test.

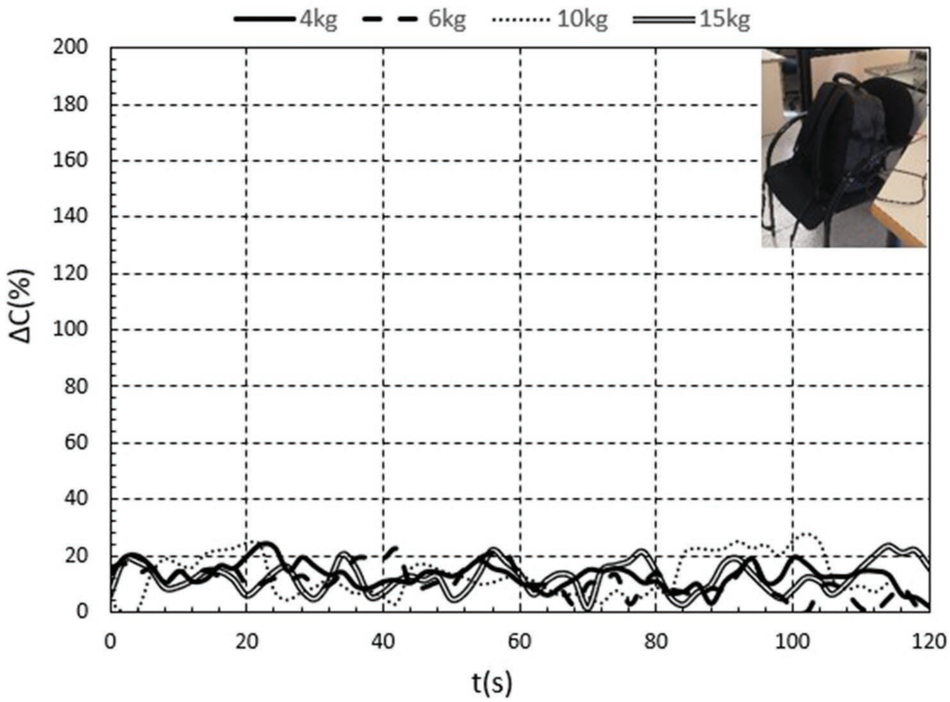

Figure 7. Capacity shift, in percentage, during load test.

4. Conclusions

A woven sensor was presented and its work-ability on the relative humidity measurement and the presence detection was demonstrated. Sensor behavior to measure humidity demonstrates the functionality of the sensor application with a high repeatability and large-scale production option, due to the weaving process. Capacitive values increase directly with humidity and a linear dependence with lower standard deviation comparing with embroidery technique is achieved. Presence detection test results demonstrate its usability, providing clear values for occupied and void situations, which should make ease to apply to new applications. Results encourage researchers to continue with the presence detection sensor for future works. The adaptation of the previous works to a new manufacturing procedure has provided a new way to produce the sensor with lower standard deviation and better textile properties. The woven technology expands the applications where the textile capacitive sensor can be applied where previously properties, as the touch feel, were a drawback. The most important objective achieved along this work is the complete integration of the sensor into the fabric, encouraging to use them without bothering the user.

Acknowledgements

This work was supported by Spanish Government-MINECO under Project TEC2016-79465-R and AGAUR-UPC(2020 FI-B 00028). Agencia de Gestión de Ayudas Universitarias y de Investigación, Generalitat de Catalunya.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

humidity, presence, sensor, smart-textile, textile, woven

Received: February 22, 2022
Revised: July 10, 2022
Published online:

[1] R. R. Rajanna, N. Sriraam, P. R. Vittal, U. Arun, *IEEE Sens. J.* **2020**, *20*, 1573.
[2] J. Cai, M. Du, Z. Li, *Adv. Mater. Technol.* **2022**, *5*, 2101182.
[3] M. Lou, I. Abdalla, M. Zhu, X. Wei, J. Yu, Z. Li, B. Ding, *ACS Appl. Mater. Interfaces* **2020**, *12*, 19965.
[4] G. Tartare, X. Zeng, L. Koehl, in *Proceedings - 2018 IEEE Industrial Cyber-Physical Systems, ICPS 2018*, IEEE, ISBN 9781538665312 **2018**, pp. 561–566.
[5] S. H. Lee, W. Eom, H. Shin, R. B. Ambade, J. H. Bang, H. W. Kim, T. H. Han, *ACS Appl. Mater. Interfaces* **2020**, *12*, 10434.
[6] F. Seng, D. Hackney, T. Goode, A. Noevere, A. Hammond, I. Velasco, K. Peters, M. Pankow, S. Schultz, *International Journal of Impact Engineering* **2021**, *150*, 103800.
[7] P. Hofmann, A. Walch, S. Arnold-Keifer, S. K. Selvarayan, G. T. Gresser, *Composites, Part A* **2019**, *126*, 105603.

[8] D. Zhang, Z. Xu, Z. Yang, X. Song, *Nano Energy* **2020**, *67*.
[9] D. Zhang, L. Yu, D. Wang, Y. Yang, Q. Mi, J. Zhang, *ACS Nano* **2021**, *15*, 2911.
[10] A. Kefal, I. E. Tabrizi, M. Yildiz, A. Tessler, *Mechanical Systems and Signal Processing* **2021**, *152*, 107486.
[11] T. Agcayazi, J. Tabor, M. McKnight, I. Martin, T. K. Ghosh, A. Bozkurt, *Adv. Mater. Technol.* **2020**, *5*.
[12] D. Zhang, D. Wang, P. Li, X. Zhou, X. Zong, G. Dong, *Sens. Actuators, B* **2018**, *255*, 1869.
[13] D. Wang, D. Zhang, P. Li, Z. Yang, Q. Mi, L. Yu, *Nano-Micro Lett.* **2021**, *13*.
[14] M. Martinez, B. Moradi, R. Fernandez-Garcia, I. Gil, *Sensors* **2018**, *18*, 3824.
[15] M. Martínez-Estrada, B. Moradi, R. Fernández-Garcia, I. Gil, *Sensors (Switzerland)* **2019**, *19*, 1.
[16] M. Martínez-Estrada, R. Fernández-García, I. Gil, *J. Text. Inst.* **2021**, *112*, 881.
[17] Z. Zhao, Q. Huang, C. Yan, Y. Liu, X. Zeng, X. Wei, Y. Hu, Z. Zheng, *Nano Energy* **2020**, *70*, 104528.
[18] H. Y. Song, J. H. Lee, D. Kang, H. Cho, H. S. Cho, J. W. Lee, Y. J. Lee, *J. Text. Inst.* **2010**, *101*, 758.
[19] T. Kuroda, H. Takahashi, A. Masuda, *Wearable Sensors* **2021**, 249.
[20] Interlink Technologies, FSR 402 Data Sheet, Technical report **2013**, http://www.interlinkelectronics.com/FSR402short.php.
[21] G. Kim, C. C. Vu, J. Kim, *Appl. Sci. (Switzerland)* **2020**, *10*.
[22] A. M. Khan, H. V. Manjunath Reddy, R. S. Beeresha, *International Journal of Research in Engineering and Technology* **1994**, *05*, 273.
[23] P. G. Su, X. H. Lee, *Sens. Actuators, B* **2018**, *269*, 110.
[24] M. E. Marc, G. Ignacio, F. G. Raul, *IEEE Sens. J.* **2021**, *21*, 26234.