Carbon-Ink Sensing Patterns for a Contactless Smart Diaper System

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***Abstract*—To keep up with the care needs of an increasing population in elderly nursing homes, smart incontinence materials promise to reduce care-taking workload, cut costs and increase user comfort. Therefore, we present two carbon-ink sensors designs that rely on a recently patented differential transmission measurement technique. The proposed sensors are low cost and mass producible, printed directly on the disposable diaper and they interface to the read-out electronics via a reusable flexible strip. In a simulation based on the square resistance of the carbon ink, both designs achieve a similar dynamic range, being most responsive to moisture resistances between $1\,\mathrm{k\Omega}$ and $100\,\mathrm{k\Omega}$. In a practical test on two prototype smart diapers, the designed sensors show promising results by detecting a small volume of only $50\,\mathrm{ml}$, with the two sensors designs being 58% and respectively 55% saturated after adding one litre of moisture.**

***Index Terms*—Smart Diapers, Moisture Sensing, Disposable Sensors, Carbon-printed, Low-cost**

I. INTRODUCTION

With the growing elderly population, the prevalence of urinary incontinence has become a major concern in public health, necessitating innovative solutions for the management of incontinence materials [1]. Conventional adult incontinence products, often incorporating super-absorbent polymers (SAP), have raised economical and environmental apprehensions, which prompted research into sustainable alternatives [2]. Furthermore, a redundant amount of SAP material is often used to avoid diaper leakage, allowing some standard diapers to easily absorb over a litre of moisture. Hence, often, most of the material is needlessly wasted without ever being saturated with moisture. Reducing the amount of absorbent material, however, increases the risk of leakage if no detection system is employed. Furthermore, extended skin contact with excrement is known to result in moisture-associated skin damage (MASD) [3]. Due to the considerable impact of the SAP content on the incontinence material's costs, nursing homes are compelled to select diapers based on a compromise between the amount of SAP used and the frequency of changes. More frequent changes are not only intrusive for the elderly but also further stress the care-giving personnel, which is generally already understaffed [4]. Although the exploration of recyclable alternatives may promise more ecologically durable urinary incontinence management [5], the lion's share of the diaper market remains dominated by SAP-based products because of its dramatically superior absorption characteristics.

To reduce the amount of absorbent material needed without introducing overhead to care-taking personnel, smart incontinence materials or so-called *smart diapers* [6] seek to electronically monitor the diaper, allowing optimal incontinence changes. These systems promise to reduce the economical and environmental impact of the disposables, improving user comfort.

Diapers with a moisture-indicating chemical sensor in the form of a colored line have been around for some time [7], however, their reliability and sensitivity to different amounts of moisture leaves a lot to be desired. Furthermore, these products still must be visually inspected by care-giving personnel, necessitating regular intrusive and labour-intensive checkups, also at night. Several companies and kick-starters have explored the production of smart incontinence materials utilizing electronic sensors to detect the presence of moisture and remotely alarm caregivers [8], [9]. Yet, often these technologies make use of simple impedance measurement methods [10] and lack the capability to reliably estimate diaper saturation. Note that, to achieve the full benefit of a smart diaper system, it is important for care-giving personnel to know how urgent changes are.

The smart diaper in this work, which has been patented recently [11], relies on a reusable flexible strip that capacitively couples with the disposable incontinence material, resulting in a reliable, hygienic and safe alternative to sensors requiring galvanic contact. In this contribution, it is shown how design choices influence the effective dynamic range of the sensor. Two design strategies for the carbon-ink moisture sensors are analysed. Both sensors are compared through measurements of fabricated prototypes. First, section II discusses the smart diaper and the carbon sensor in more detail, which allows to define two different implementation techniques of the sensor. Section III compares both implementations through measurements and finally section IV concludes this work and provides an outlook to future research work.

II. A CARBON-PRINTED DISPOSABLE MOISTURE SENSOR

A simplified overview of the proposed measurement technique is shown in Fig. 1. The disposable incontinence material has a carbon-ink moisture sensor printed on it, allowing for cheap mass production. The diaper has a zone with pre-applied glue on which the reusable sensor strip is pasted just before use. The central carbon-ink pads capacitively couple with copper pads on the interface strip, allowing the sensor to be monitored remotely through Bluetooth low-energy (BLE) connectivity. To optimize user comfort, the flexible strip is

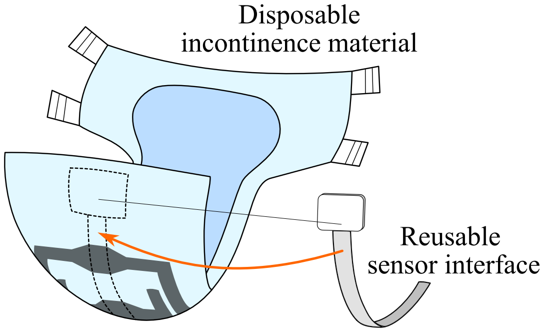


Fig. 1: Overview of the proposed smart incontinence material.

coated in a soft PU material and the thickness of the driver electronics' enclosure is kept to a minimum.

A differential measurement method is adopted to reduce external noise and disturbances and to achieve an overall higher accuracy. The measurement relies on a 500 kHz low-power differential input signal to be coupled into carbon traces by the capacitive copper pads on the flexible sensor interface. When the strip is properly connected, the capacitances of these pads have limited influence on the measurement result as their impedance at this frequency is relatively low in comparison to the highly resistive carbon-ink. The signal then travels through carbon-ink traces on the incontinence material and couples with the conductive moisture on the inside of the diaper. Similarly, the output signal is differentially measured through copper pads on the flexible strip that couple with the carbon-ink traces. Relying on this differential transmission measurement technique, two different sensor topologies were designed.

In a first design, the inputs are connected to the corresponding outputs by long carbon traces having a high resistance, as shown in Fig. 2. Hence, when the sensor is dry, most of the input signal will be received at the output. However, as moisture accumulates between the differential traces, as indicated by the blue circle, conductivity in between the differential traces will increase. Hence, the resistance between the traces lowers and a smaller fraction of the input signal will be measured at the output. Note even though the moisture distribution cannot be guaranteed to concentrate around the blue areas, after some time, the SAP inside of the diaper will evenly distribute the moisture to a certain extent, thereby allowing the sensor to detect moisture applied in its wider vicinity.

In the second sensor design, shown in Fig. 3, the corresponding inputs and outputs are connected by a large carbon-ink path, having a comparatively low resistance. The differential signals are coupled to odd and even sets of resistive carbon fingers in an intertwined structure. The number of fingers and their dimensions were determined based on the conductance of the ink and experimental analysis based on early proof of concept tests. Similarly to the first design, the output will receive most of the input voltage when the sensor is dry. When the region between the carbon fingers becomes wet, indicated by the blue circles, the conductance between the positive and negative terminals will increase. As a result, the output voltage again will decrease as moisture accumulates. However, the different layout and resistance values between the inputs and outputs will cause the sensors to respond differently to a realistic moisture distribution and result in a different dynamic range.

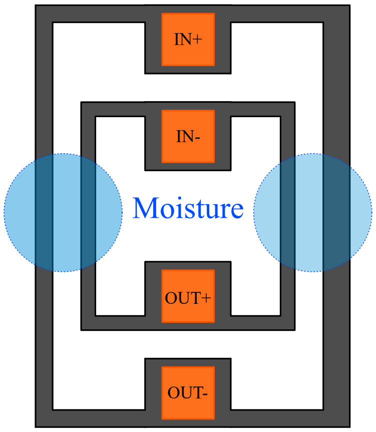


Fig. 2: First carbon-ink differential moisture sensor design.

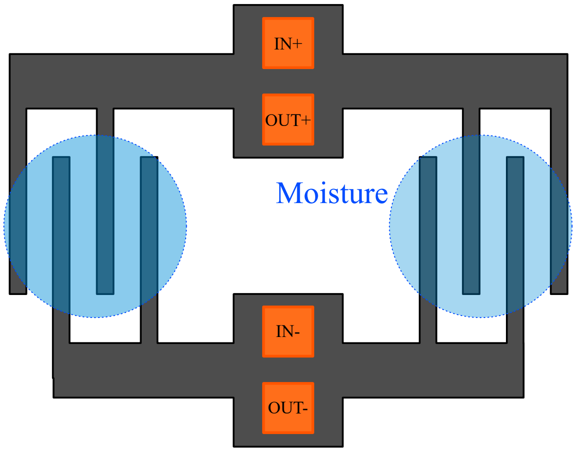


Fig. 3: Second carbon-ink differential moisture sensor design.

When simulating the behavior using a simplified model of these sensors based on the square resistance of the carbon-ink, an estimated relation between the transfer function of the sensor and the resistance of the moisture R_{moisture} can be observed, as illustrated by Fig. 4. Hence, when the sensors operate as intended, the two designs are assumed to offer a similar dynamic range and relationship between the input and output voltages. The majority of the sensor response unfolds within the range of resistances spanning from 1 kΩ to 100 kΩ, which would theoretically allow the sensor to detect both very small and larger volumes of moisture.

III. A PRACTICAL COMPARISON BETWEEN TWO DESIGNS

To practically evaluate the performance of the two proposed carbon-ink moisture sensors, two prototype designs were fabricated on medium-sized adult diapers by Drylock Technologies.

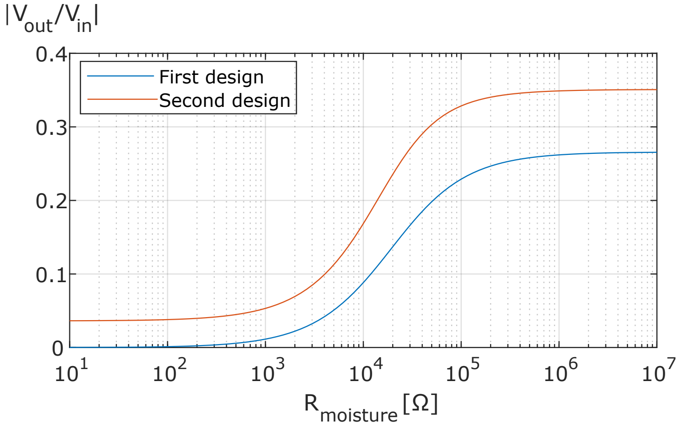
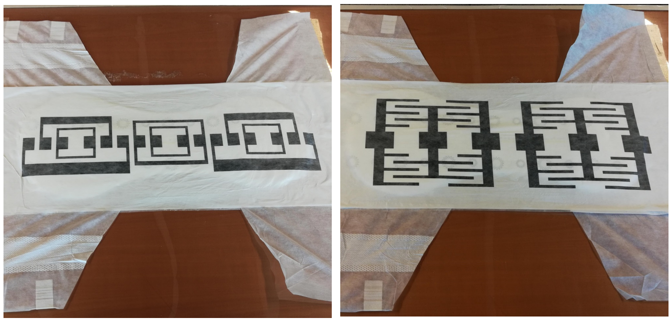


Fig. 4: Simulated sensor response of the two proposed designs in function of moisture resistance.

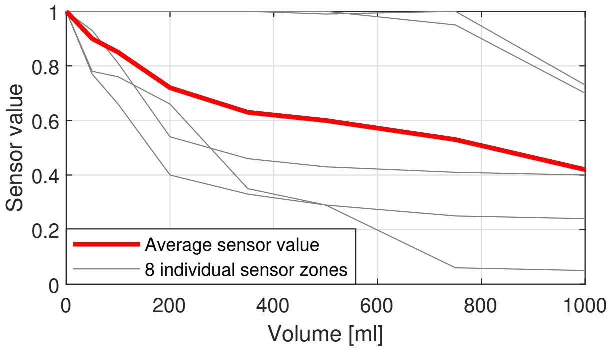


(a) 1^{st} design prototype

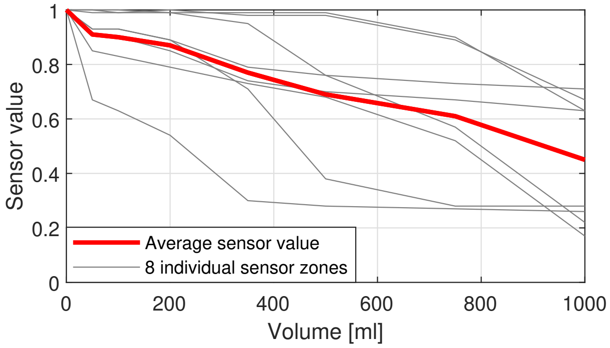
(b) 2^{nd} design prototype

Fig. 5: Fabricated prototype incontinence materials with multiple carbon-ink moisture sensors to cover multiple zones.

The first prototype design, shown in Fig. 5a, implements five sensors of based on the first sensor design. Similarly, a second prototype implements a total of eight sensor zones of the second sensor design, as shown in Fig. 5b. All measurements were performed on these standalone diapers by manually adding measured volumes of a 0.9% saline solution to mimic typical urinary incontinence. The differential transmission measurement is performed by a custom electronic sensing board that capacitively interfaces with the carbon-printed moisture sensor through a custom flexible strip of polyimide PCB material. The responses of the individual sensor zones and the average sensor response of the two fabricated prototypes with respect to the added moisture volume are shown in Fig. 6. The normalized sensor values of the individual sensor zones are plotted in grey, while their average response is shown in red. Both prototypes clearly detect the first volume addition of a mere 50 ml. After adding one litre of the solution, the sensors of the first prototype are on average 58% saturated, whereas those in the second design are 55% saturated. Both prototype sensors clearly demonstrate their ability to respond to moisture inside the diaper and, on average, show a similar dynamic range. However, to provide any statistical data or to be able to estimate the moisture volume using the sensor readouts, more data would be required.



(a) 1^{st} design prototype



(b) 2^{nd} design prototype

Fig. 6: Normalized moisture sensor responses on two smart diaper prototypes.

While both designs show promising results, in practice the first sensor design encounters an inherent issue due to its strong dependency on the moisture distribution inside of the diaper. When moisture accumulates in the region between the positive and negative input ports (see IN+ and IN- in Fig. 2), the differential input signal is effectively shorted and the input voltage is no longer transmitted to the output, thereby preemptively saturating the sensor. Therefore, the second carbon-ink sensor design was selected for further development, as it proves less susceptible to this problem, owing to the significantly increased spacing between the differential inputs. In future work, with larger data sets, the combined sensor signals will evaluate the sensor reliability.

IV. CONCLUSION

In this work, two carbon-ink moisture sensors were designed and evaluated. The sensors were printed on a mass-producible, disposable diaper and capacitively interface with a differential measurement system through a custom flexible polyimide strip. During a practical test, the two sensor designs demonstrate their ability to measure the detect moisture additions from 50 ml up to 1 l. While both prototypes demonstrate a similar dynamic range, the first design could potentially saturate prematurely due to the input signals being electrically shorted as a result of an unfavorable moisture distribution. In the future, the second design will be further evaluated over a large number of samples to statistically predict the volume inside the incontinence material based on the measured sensor responses.

V. Acknowledgment

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