

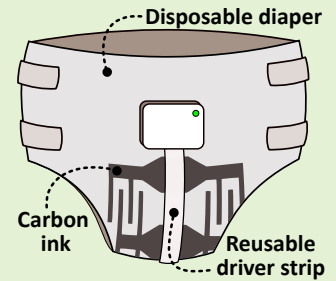
An Environmentally Friendly Carbon-Printed Contactless Smart Diaper

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Abstract— Nowadays, with the aging population, the number of people in homes for the elderly is dramatically rising. Nearly all of them suffer from a degree of incontinence and wear diapers on a daily basis, leading to a lot of super absorbent polymer waste material. Smart diapers increase patient comfort owing to timely diaper changes. At the same time, the absorbent content of smart diapers can be reduced substantially, compared to regular diapers as less margin for late changes is needed. From the medical perspective, smart diapers also reduce painful incontinence-associated dermatitis caused by prolonged exposure to saturated diapers.

This paper proposes a novel contactless smart diaper system that allows caregivers to remotely read out information about diaper contents. The developed system is based on capacitive coupling to a printed structure in the diaper, including multiple detection zones distributed across its length. By printing the sensing pattern into the diaper in carbon ink, a low cost, mass producible and environmentally friendly sensor is obtained. A 4-port differential transmission-measurement technique is employed, resulting in a higher system reliability than many existing smart diaper systems relying on impedance-measurements only. The paper includes both lab- and in-field measurements to demonstrate the successful detection of moisture.

Index Terms— Smart Diapers, Moisture Sensing, Disposable Sensors



I. INTRODUCTION

RECENT studies of the aging population state that the age group of over 65 comprised 27.1% of the European population in 2019, a number which is predicted to increase up to 43.3% by 2070 [1], corresponding to 1.89 billion people worldwide [2]. This population group is well known to increasingly suffer from urinary incontinence [3]. The resulting daily use of standard disposable adult diapers significantly stresses the environment. Efforts are currently being performed to make diapers industrially recyclable by recovering the super-absorbent polymer (SAP) for soil irrigation management in agriculture [4] or, alternatively, investigating bio-degradable SAP materials [5]. The latter alternative unfortunately comes at the cost of a reduced absorbing capacity. In any case, the current use of diapers continues to produce a huge amount of waste material, which, without major changes, will drastically increase in the future due to the continuously rising number of elderly people.

Many smart diaper systems have been described in litera-

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ture or even commercially implemented. Though a range of different sensing techniques have been experimented with, real breakthroughs have been hindered by insufficient reliability, complexity or high cost. An overview of the most relevant existing smart diapers is given in Table I.

The systems described in [6]–[11] employ an antenna or near-field communication (NFC) tag as a means of determining diaper contents based on radio-frequency signals or inductive coupling, respectively. Yet, all these projects are still in a proof-of-concept stage and they suffer from the influence of reflections [11] on the human body. Furthermore, the usage of disposable antennas or tags inside the diaper [6]–[10] is economically and ecologically less attractive. Importantly, the conductivity of carbon ink is insufficient to support the currents needed for inductive coupling or effective antenna radiation. The works in [12]–[15] rely on a disposable strip or patch to be placed inside the diaper to directly sense the moisture. In contrast, the disposable electrodes of [16], [17] are directly printed on the diaper, making them significantly cheaper and more environmentally friendly. Yet, they still rely on galvanic contacts, having hygiene and reliability implications. Recently, electronic skins [18]–[20] have shown a promising integration of sensors and electronics into everyday environments, yet smart disposable incontinence materials need to be even more low-cost and environmentally friendly when disposing.

Other works attempt to make reusable measurement systems, employing some form of contactless interface. Hence, the reusable electronics are never in direct contact with the

soiled diaper, having significant hygiene benefits. Furthermore, a contactless interface can be more reliable for on-body applications as it is less sensitive to movements and dirt-buildup than when relying on galvanic contacts. In [21] a simple temperature measurement indicates when the diaper is soiled in a contactless way such that the electronics are entirely reusable. However, this measurement principle gives no information on the amount of urine in the diaper and only measures in one specific area. The capacitive sensing techniques of [22]–[24] are more promising to determine the amount of moisture in a contactless and reusable way. However, they are all based on a single-ended impedance measurement, leading to reduced reliability compared the novel transmission-based system presented in this manuscript.

In this paper, we describe a system capable of determining diaper conditions by means of a reusable, wearable read-out system, and a sensor printed on the back sheet of the diaper in a low-cost eco-friendly carbon ink [25]. The reusable read-out electronics differentially inject a signal into the measurement structure via a polyimide strip, capacitively coupling the signals without any galvanic contact. This differential signal propagates through the printed pattern and is potentially attenuated by moisture in the diaper. The resulting signal is coupled out in a similar way, resulting in a 4-port transmission measurement. This patented differential transmission measurement technique [26] increases the reliability of moisture sensing. The proposed system is capable of wirelessly issuing an alarm to the caregivers via a Bluetooth-connected smartphone or tablet. The carbon-printed sensing pattern in the diaper is incorporated in the diaper's production process. To the best of the writers' knowledge, this is the first smart diaper that implements this novel patented measurement technique. The main advantage over existing systems is the capacitively coupled differential transmission measurement, which enables highly reliable moisture assessment in the disposable diaper by only adding a carbon-ink sensing pattern to it. The proposed system has been extensively evaluated, not only in lab conditions, but also in a practical setting in a home for the elderly.

Our proposed solution offers advantages for the elderly as well as for the caregivers. For the elderly, their privacy and life comfort is enhanced, as less frequent physical diaper checks are necessary while still avoiding leakages. A diaper only needs to be checked when an alarm is triggered by the system, indicating a change is likely necessary. Thereby, in homes for the elderly, where the staff is typically very occupied, personnel can spend their time on more targeted diaper changes than on frequent intrusive diaper checks. This reduces the amount of necessary staff, the patient discomfort and possible skin irritation. Additionally, the diapers will no longer have to accumulate huge amounts of urine. Therefore manufacturers will be able to produce diapers with less SAP, reducing the environmental impact. Currently, adult diapers contain enough SAP to hold up to a liter of urine, resulting in the disposal of many only partially saturated diapers, and in a lot of waste material.

The amount of SAP is a major factor in the maximum volume of liquids the diaper can hold. Hence increasing the SAP content reduces the likelihood of leakages and generally

improves user comfort. However, in case there is little or no discharge from the patient, the abundant amount of SAP poses an unnecessary economical and environmental challenge. Because the SAP content has a significant effect on the cost of the diaper, nursing homes are forced to find compromise solutions between diaper quality and changing frequency, thereby negatively affecting the user comfort. Furthermore, large-scale recycling of SAP has proven to be one of the many difficulties in the waste industry, with an estimated 6.3 billion metric tons produced, the majority of it finally ending up in landfills or the environment [27]. Hence, ecological stress caused by SAP is clearly a well-known issue, but the material remains crucial in the diaper industry. Although the research into environmentally friendly alternatives to SAP shows promising results, these bio-based solutions have not matured enough for large-scale industrial adoption [28].

A good compromise to reduce the enormous amount of waste product resulting from diapers could be to reduce their (bio-based) SAP content and changing them shortly after being soiled. Yet, performing the necessary checks manually would be too time-consuming for caregivers and is also too intrusive and disturbing for the elderly. Hence, the need for a smart diaper, alerting caregivers when and to which degree a diaper has been saturated, becomes apparent. Additionally, a smart diaper system also offers improved life quality to the elderly in a different way. The daily use of diapers causes a risk of skin diseases to the senior population and prolonged contact of the skin with urine or faeces is well-known to cause painful incontinence-associated dermatitis (IAD), with potential skin infections as an additional problem [29]. IAD prevalence is likely to be significantly reduced by employing smart diaper technology, forming an extra benefit, apart from the waste reduction. Smart diapers have the ability to prevent leakages and to avoid extended urine-to-skin contact. Additionally, when a good assessment of the diaper content can be made electronically, health care personnel is able to follow up the moisture balance of patients. Patient-specific diapers can be used to further decrease the amount of diaper waste material whereas at the same time patient comfort is enhanced. Summarized, smart diapers will help reaching a number of sustainable development goals, such as sustainable communities, responsible consumption and production as well as improved health and well-being.

This paper is further organized as follows. Section II focuses on the total system and the basics of the capacitive measurement principle, of which further details are described in Section III. The system performance, as measured in the lab, is described in Section IV, whereas the results from the field tests follow in Section V. Further, in Section VI, a procedure is proposed to generate reliable and timely alerts. Finally, the conclusions follow in Section VII.

II. MATERIALS AND METHODS

To enable a large-scale adoption of smart diapers, the production and maintenance costs must be small enough such that elderly homes are willing to invest in their usage. Furthermore, the impact of mass manufactured disposable diapers on the

Ref.	Sensor implementation	Contactless measurement method	No added disposables*	Technology stage
[7]	Metal-hydrogel antenna	Radio-frequency	✗	Proof-of-concept
[8]	LC resonator tag	Inductive coupling	✗	Proof-of-concept
[9]	LC resonator tag	Inductive coupling	✗	Proof-of-concept
[10]	Antenna link	Radio-frequency	✗	Proof-of-concept
[11]	Antenna impedance	Radio-frequency	✓	Proof-of-concept
[12]	Disposable electrode patch	✗	✗	Proof-of-concept
[13]	Disposable electrode patch	✗	✗	Proof-of-concept
[14]	Disposable electrode strip	✗	✗	Commercially available
[15]	Electrode-strip battery	✗	✗	Proof-of-concept
[16]	Imprinted disposable electrodes	✗	✓	Proof-of-concept
[17]	Imprinted disposable electrodes	✗	✓	Commercially available
[21]	Temperature sensor	External temperature	✓	Proof-of-concept
[22]	Textile electrodes	Capacitive coupling	✓	Proof-of-concept
[23]	Reusable electrode strip	Capacitive coupling	✓	Proof-of-concept
[24]	Reusable electrode strip	Capacitive coupling	✓	Commercially available
This work	Differentially coupled carbon-ink sensor	Capacitive coupling	✓	Proven in field tests

TABLE I: Comparison to state-of-the-art smart diapers. *With the exception of conductive ink structures or pre-applied glue strips directly on the diaper.

environment must be minimized. Therefore, the electronic circuitry should be entirely reusable and only ecological materials can be applied to the disposable diapers themselves. Recent works have demonstrated how bio-degradable moisture sensors can be conceived on cellulose and wax substrates [30]–[32] or even leaf skeletons [33]. Furthermore, the trend towards printed moisture and humidity sensors [34]–[36] has promising applications to directly implement the sensor on the diaper.

In this work, the cost-increase of the manufacturing process was limited to € 0.005 per diaper. Hence, the sensor had to be implemented as a carbon-ink structure printed directly on the diaper, with the all the active electronics being external and reusable. Furthermore, the interfacing between the reusable electronics and printed structure should be contactless to improve hygiene and reliability. Figure 1 provides an overview of the proposed solution to this problem. The complete smart-diaper system consists of a disposable diaper with integrated passive carbon sensors printed on the back sheet of the diaper and a reusable driver strip, which contains a microcontroller for communication, driver circuits, and a flexible PCB to interface the electronics with the carbon sensor. Additionally, the small electronics box contains a triaxial accelerometer to record patient orientation and movement.

Signals are coupled capacitively to the sensing pattern printed on the diaper back sheet, by a flexible reusable polyimide coupling strip. The carbon-ink-printed moisture sensor, as recently designed and patented [26], consists of electrically conductive traces that are printed directly on the polyethylene (PE) sheet that is already present in a standard diaper, enabling mass manufacturing of smart diapers at an extremely small extra cost, compared to regular diapers. The traces are implemented using a single layer of Henkel Loctite

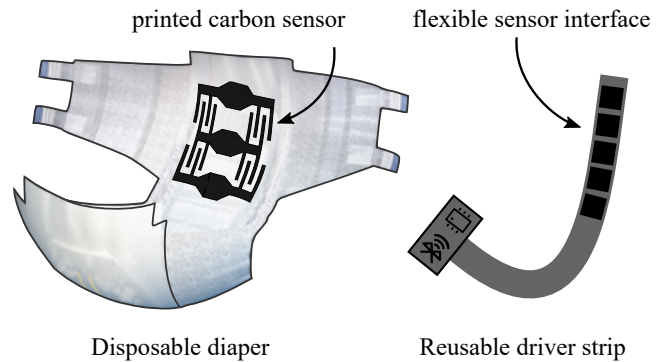


Fig. 1: Overview of the smart diaper system: a diaper with integrated carbon sensor printed on the backsheet and a flexible re-usable driver as sensor interface.

ECI7007 [37] conductive carbon ink, that is applied by means of roll-to-roll (R2R) flexography printing [38]. After curing, the printed ink’s sheet resistance is 1.1 kΩ/sq, resulting in conductive traces suitable for sensing applications. Although silver ink exhibits a higher conductivity, its disposal causes environmental problems due to its slow decomposition. Research has shown the harmful impact of silver nanoparticles to microorganisms that are essential for a sustainable future [39]. Furthermore, the sheer cost of silver ink and its cumbersome sintering process make its use economically infeasible for mass manufacturing of diapers.

A design choice was made to exploit capacitive coupling as the basis for contactless signal injection into the diaper, since this technique performs well, despite the limited conductivity of the carbon ink. In comparison, inductive coupling does not

work properly with carbon ink, since its conductivity is not high enough to generate sufficiently high currents into the printed structures.

The stack-up of the diaper with integrated sensing pattern is displayed in Figure 2. The top and bottom parts of the drawing correspond to the inside and outside of the diaper, respectively. From outside to inside, we see the external sensor, an adhesive layer, a soft non-woven hydrophobic polypropylene (PP) back sheet, a glue layer, a conductive ink layer on PE, a waterproof but breathable PE back sheet, a glue layer, a cellulose fluff and SAP moisture absorbing layer, a glue layer, an acquisition-distribution layer (ADL) made of polyester fibers, a glue layer, and a non-woven waterproof but breathable PE top sheet. Finally, the top blue lines are water resistant leakage barriers (non-woven cuff). A detailed view of the prototype

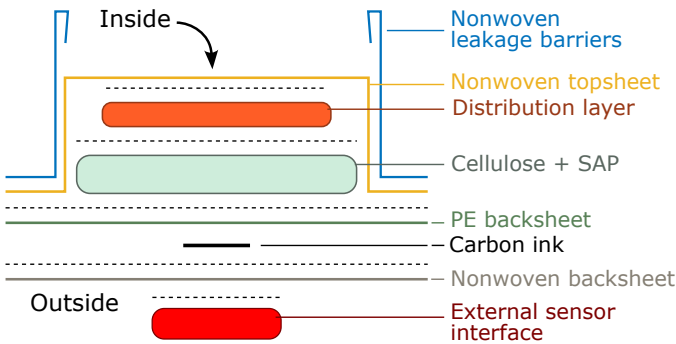


Fig. 2: Stack-up of a typical adult diaper with the proposed moisture sensor. Dashed lines indicate adhesive layers.

measurement device and its internal electronics is shown in Figure 3. This device interfaces with the diaper by exploiting capacitive coupling through the reusable flexible interfacing strip. In case the polyurethane (PU) coated strip were to get damaged or worn out, it can be easily replaced as it connects to the internal electronics by spring-loaded pogo-pins and is latched in place by the electronics' enclosure box. The PCB features an STM32WB55 microcontroller with Bluetooth Low Energy (BLE) capabilities using the manufacturer's recommended PCB antenna design and matching network. Furthermore, an LSM6DSL accelerometer and gyroscope IC is included to monitor the patient's orientation and movements. All electronics are powered by a 150 mAh, 3.7 V lithium polymer battery. One measurement cycle draws an average current of 13.6 mA for 125 ms, whereas a BLE transmission draws 21.8 mA for 125 ms and the idle current consumption remains below 5 mA. When performing five measurements over all sensing zones and transmitting their mean values every minute, as is the case in the latest firmware version, the expected battery life of the system is over 24 hours.

III. MEASUREMENT PRINCIPLE

The differential measurement principle relies on the properties of a capacitively coupled voltage divider, as illustrated in Figure 4. The parallel plate capacitors $C_{in/out}$ are formed by non-permanently gluing the sensing strip to the diaper. One plate of the capacitor is located on the polyimide sensing strip and the other plate is formed by a printed carbon ink area

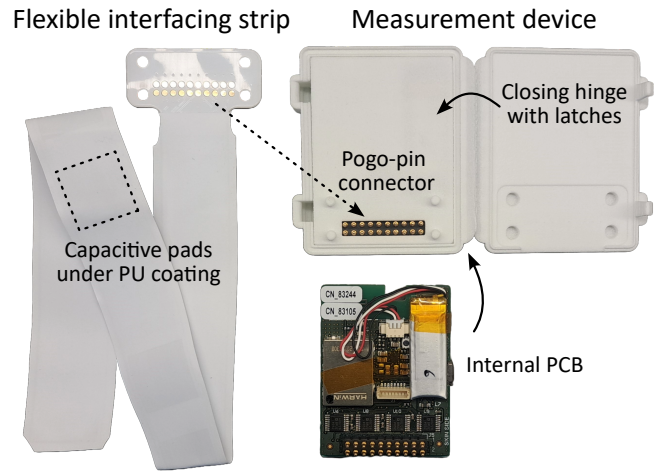


Fig. 3: Measurement device (top right) with internal PCB (bottom right) and flexible interfacing strip (left).

in the diaper. The dielectric for the capacitor is formed by a stack up of layers, being the sensing strip's coating, the adhesive layer, the soft non-woven outer diaper layer, another glue layer and the PE layer on which the sensing pattern is printed (see Figure 2).

The excitation voltage V_{in} on the left is generated directly by the microcontroller through two counter-phased square waves of 3.3 Volts peak-to-peak amplitude, which are filtered by LC low-pass filters with minor losses, resulting in two counter-phased sine waves, superimposed to yield a total AC excitation voltage of 3 Volts in amplitude. This small excitation voltage is completely harmless to the patient. Additionally, there is no direct electrical contact between the excitation voltage and the human body and, moreover, the current output of the hardware is also limited, resulting in a safe system.

The input coupling capacitors C_{in} and their series resistors R_s couple the signal into the diaper. The grey part in Figure 4 represents the carbon-ink sensor that is printed on the diaper, with the series resistors R_s , and parallel resistors R_p and $R_{moisture}$ forming a voltage divider. The latter resistor value decreases with a rising amount of urine in the diaper and is the basis for the measurement.

Note that $R_{moisture}$ is also capacitively coupled via $C_{moisture}$ because, on the plastic back sheet, the moisture is located on the side opposite to the carbon ink layer. However, the latter capacitors have a very low impedance at the measurement frequency, owing to the very thin back sheet operating as a dielectric. Therefore, they can be treated as lossless coupling capacitors, forwarding the AC signal as if there was a direct galvanic connection.

The voltage across the network is coupled to the detector circuit via series resistors R_s and the output coupling capacitors C_{out} , connecting the signal to the load resistor R_{load} on which the voltage V_{out} is generated. For the slope in the sensing characteristic to be in the most relevant urine resistance range for a smart diaper, this load resistor was selected to be 12 k Ω .

Electrically, the circuit is best analyzed as two cascaded voltage dividers, where the second divider loads the first one. Applying Thévenin's theorem to the first voltage divider

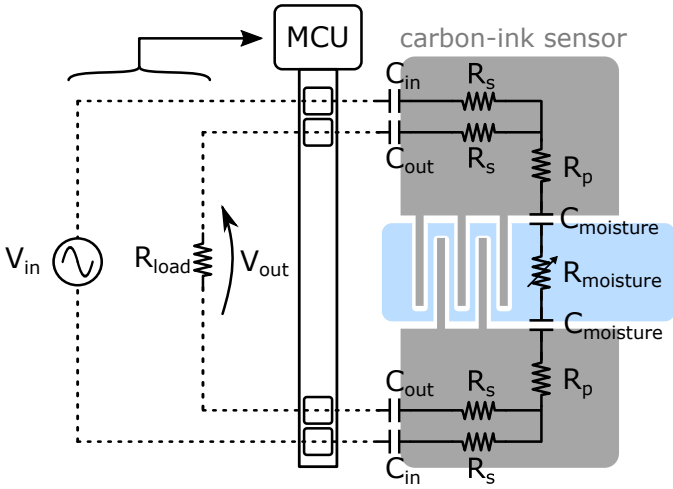


Fig. 4: Schematic representation of the carbon printed sensor. R_s represents the series resistance between input and output pad, R_p and $R_{moisture}$ represent the resistance in the sensing path originating from the carbon ink and the conductance due to the moisture, respectively, and $C_{in/out}$ represent each parallel plate capacitor to couple the signal in and out of the diaper. The signals are generated and measured by the microcontroller unit (MCU) in the reusable sensor interface.

yields an equivalent voltage source V_{Th} together with a series impedance Z_{Th} .

$$V_{Th} = V_{in} \cdot \frac{j\omega C_{in} (2R_p + R_{moisture})}{2 + j\omega C_{in} (2R_s + 2R_p + R_{moisture})} \quad (1)$$

$$Z_{Th} = \frac{2(2R_p + R_{moisture})(1 + j\omega C_{in} R_s)}{2 + j\omega C_{in} (2R_s + 2R_p + R_{moisture})} \quad (2)$$

The response of the second voltage divider leads to the following equation for the measured voltage amplitude:

$$V_{out} = V_{Th} \cdot \left| \frac{j\omega C_{out} R_{load}}{2 + j\omega C_{out} (2R_s + Z_{Th} + R_{load})} \right| \quad (3)$$

In lab measurements, the coupling capacitors have been determined to be $C_{in} = C_{out} = 20$ pF. A measurement frequency of 500 kHz was adopted as it achieved the highest signal strength with the developed driver electronics. The series resistors equal 250 Ω and the parallel resistors 1 k Ω . The amplitude of the output voltage is plotted in Figure 6, for R_{urine} ranging from 1 M Ω down to 1 k Ω .

Although the output voltages of the sensing system are directly within range of common analog-to-digital converters (ADC) integrated in modern microcontrollers, which typically exhibit an input range from 0 V to 3.3 V, our system first conditions the signals in the analog domain, enabling slower sampling and increased accuracy at a low power consumption. The complete output measurement schematic is shown in Figure 5. It consists of a first differential amplifier stage to increase the output voltage to better match the dynamic range of the microcontroller. Next, the 500 kHz signal difference voltage is fed into an active rectifier circuit to mitigate the diode's voltage drop. The circuit exploits the base-emitter

junction of a transistor to both rectify the signal while also amplifying its current. This current flows into a capacitor, thereby realizing a peak-detector. Finally, the rectified DC voltage is directly read out by the microcontroller's ADC. To save space on the PCB and to reduce idle power consumption, this measurement circuit is only implemented once. Hence, two analog ADG728 switch matrices are employed to sequentially read out the four differential sensing zones. Though

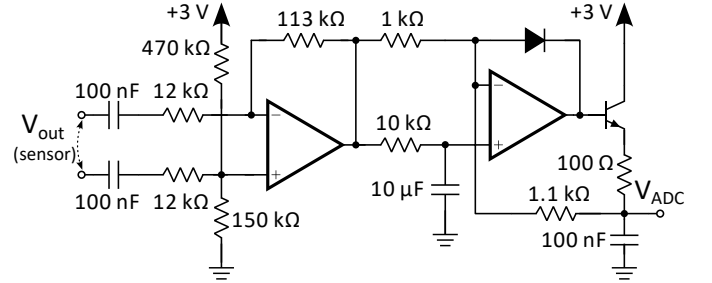


Fig. 5: Sensor output measurement circuit consisting of a differential amplifier and an active rectifier, featuring two MAX4453 rail-to-rail operational amplifiers fed by 3 V, a 1N4148W small-signal diode and a BC849C general-purpose transistor.

many smart diapers suffer from the influence of the human body and interference, this is largely reduced in the proposed system owing to its differential measurement method. The human body or a human-body-mimicking phantom presents a capacitive load to the measurement system. However, this load is insubstantial compared to the moisture in the diaper, which is orders of magnitude closer to the sensor. Furthermore, the proposed differential approach mitigates interfering signals through subtraction, while doubling useful signals in amplitude.

The measurement principle described above is valid for a single sensing zone. Since urine can flow across the length and width of the diaper, multiple such sensing zones created to guarantee timely detection.

IV. LAB TESTS

The smart diaper measurement principle was tested and optimized over several iterations to get a good compromise between reliability and dynamic range [40]. Afterwards, a production run was performed by Drylock Technologies, as illustrated by the prototype in Figure 7, where the diaper is stretched out in order to properly visualize the structure and dimensions of the sensing pattern. It visibly contains multiple sensing structures, where signals are coupled capacitively via the large black areas. The finger structures allow current to flow when the diaper becomes wet around these fingers. Of course, moisture in between the large black areas also directly contributes to the transmitted current, but the finger structure increases the surface area over which the sensor can perform detection.

Measurements were carried out with the diaper worn on a silicone test dummy representing the pelvis, the lower belly and the upper legs, as displayed in Figure 8. The weight of

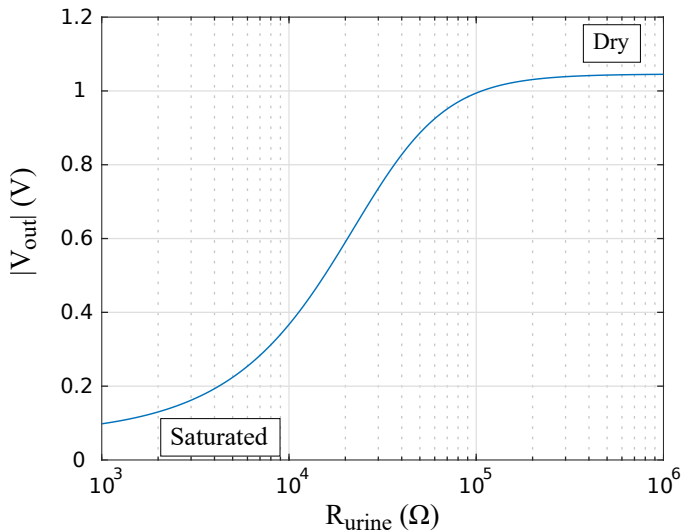


Fig. 6: Sensor response for a varying resistance caused by moisture content in the diaper.

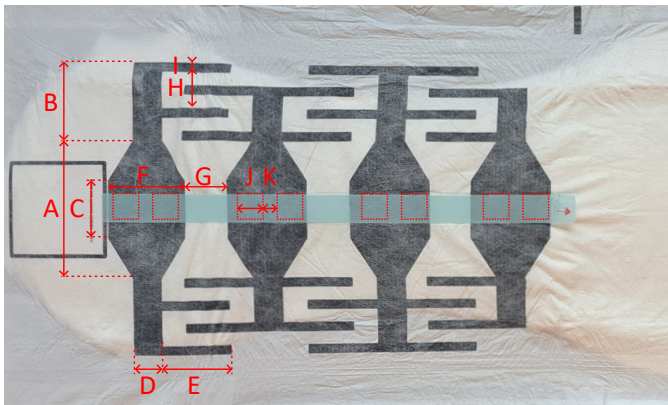


Fig. 7: Industrially manufactured smart diaper with printed carbon ink sensing pattern and pre-applied glue for interfacing strip. Dimensions of carbon ink pattern and capacitive pads: A=96 mm, B=54 mm, C=40 mm, D=20 mm, E=50 mm, F=56 mm, G=32 mm, H=26 mm, I=6 mm, J=18 mm, K=10 mm.

the test dummy is similar to the respective human body parts, causing significant and realistic pressure on the underlying diaper. In preliminary tests, both female and male test dummies were used. However, since the SAP mainly governs the moisture distribution within the diaper, gender showed to have an insignificant influence on the sensor response. Therefore, all of the presented lab tests in this manuscript were carried out using a female silicone dummy.

A peristaltic pump is used to dose the synthetic urine in the diaper in a controlled way. The stepper-motor driven pump is software controlled and allows injection of liquid into the diaper, with sub-milliliter accuracy and a programmable speed to match the flow profile of typical excretion. The synthetic urine is composed of a 0.9% sodium chloride in water solution. Talens Ecoline 548 blue ink [41] is added, in order to visualize the flow inside the diaper. Note that the actual sodium content of human urine varies significantly, depending

on the food and liquid intake as well as the physical condition of the patient. However, the high electrical impedance of the measurement circuit reduces its effect on the measurement results, because the resistivity of the urine is quickly much smaller than the resistivity of the carbon ink traces. Therefore, a detection is also guaranteed with less conductive urine, albeit that the volume at which the alarm is triggered will be slightly higher.



Fig. 8: Lab measurement on test dummy, with smart diaper, measurement strip, connected hardware interface and synthetic urine.

Note that, although the sensor interface is equipped with BLE connectivity and an SD-card slot, the lab measurements employed a wired USB connection to directly log the data to the computer and keep the battery charged. Also in Figure 8, a mat with copper traces can be seen under the test dummy. This safety feature is not part of the smart diaper measurement system, but allows the automated lab setup to detect moisture from a potentially leaking diaper and instantly shut down the liquid supply in this event.

The combined results of lab measurements on 29 smart diapers, performed on the test dummy with peristaltic pump, are displayed in Figure 9, for moisture volumes in the diaper ranging from 0 to 750 milliliters. Sensor values are read for all sensing zones, their values summed, the constant offset subtracted and the result is finally normalized in order for the response for a dry diaper to be equal to one. The evolution of this normalized sum is evaluated for rising amounts of synthetic urine. Figure 9 presents the result of a statistical analysis of 29 different diapers, each gradually filled with 750 ml of synthetic urine. The displayed value is a saturation coefficient determined by adding the responses of all sensors and scaling the results by a common scaling factor for all measurements. The center line shows the average response for all 29 diapers, whereas the top and bottom lines show the

standard deviation from the average.

Although the sensing characteristics present the same monotonic trend for each diaper, with rising amounts of moisture always corresponding to rising sensor values, the standard deviation is fairly large. This phenomenon occurs due to the unpredictable flow of liquid in the diapers, because of the inhomogeneous distribution of the SAP across each diaper. Apart from this, the penetration of the liquid into the diaper is also unpredictable because of water's cohesion properties, causing moist zones to attract more moisture. Additionally, the attachment of the diaper to the test dummy is also slightly different each time, with varying tensile stress on certain areas, causing local variations of SAP compression. These three factors enlarge the uneven distribution of liquids into the diaper.

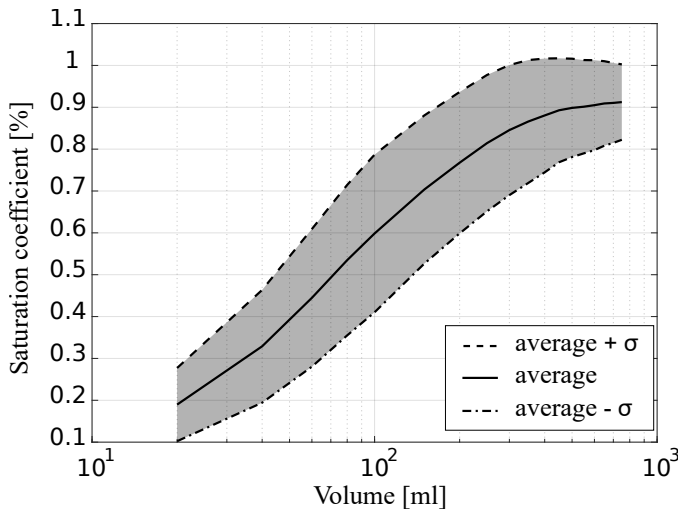


Fig. 9: Response of the smart diaper in lab tests.

V. FIELD TESTS

A field measurement campaign was organized in a home for the elderly and supervised by the SKINT department of Ghent University Hospital. Nine patients participated in the field tests, all incontinent and bedridden. Among the participants were eight women and one man, where it should be noted that preliminary tests showed an insignificant influence of gender on the sensor response. Patients with dementia were excluded from the study in order to avoid unwanted diaper manipulation. Patients with a pacemaker were excluded too. Although interference is considered unlikely, this choice was made to fully eliminate such a risk.

The smart diaper system was tested for a full week and handled by the care-giving personnel only. No engineering staff was present at the setting. Data were recorded automatically on the wearable unit's flash cards and analyzed after the end of the field tests. The personnel monitored the diapers through an experimental Bluetooth application and filled in logbooks with the recorded time of diaper changes, the weight of the diaper after removal and the presence of leakage or stool. The data from the logbook were then compared to the results obtained from the measurements performed by the smart diaper system during the post processing stage.

The system has been further developed for more practical on-site ergonomics, including a smartphone app that couples to the smart diaper system via Bluetooth and shows three color-coded alert levels. Green means a dry or almost dry diaper, orange denotes slightly wet and red indicates that the diaper is quite saturated and needs to be changed as soon as possible. These alarm colors were also added to the log book during the field trials.

An annotated example of the raw measurements, as recorded in the field tests, is displayed in Figure 10. The two synchronous plots illustrate the raw output of four moisture sensing zones ($S1$ through $S4$) in the top figure as well as the triaxial acceleration ($AccX$, $AccY$ and $AccZ$) on the same time axis in the bottom figure. The moisture sensors output a voltage expressed in millivolts (mV). Compared to the basic measurement principle shown earlier in Figure 6, the signals have been amplified and rectified before sampling, which causes a fixed gain and offset factor on the signal. The output of a dry, well-connected moisture sensing zone can be as high as 2000 mV, whereas a moisture-saturated sensing zone typically outputs about 1000 mV. The acceleration is measured along three orthogonal axes and is expressed in m/s^2 . From the measured accelerations, the patient's movements and orientation can be analyzed. This measurement is based on the accelerometers tracking the Earth's gravity. Therefore, depending on the orientation of the accelerometer's axes, values from $-9.81 m/s^2$ up to $9.81 m/s^2$ can be obtained, even while the patient is not moving. Accelerations caused by movements are superimposed on this acceleration caused by gravity. In the graph, orientation changes correspond to sudden larger changes in acceleration, whereas patient movements cause quick small variations on the acceleration values.

Analyzing the measurement starting at 0 minutes, we notice the attachment of the diaper to the patient, while the measurement has already started. Patient orientation changes are visible in the beginning of the measurements, corresponding to some degree of sensor signal variation. This is mainly caused by varying pressure on the diaper and the measurement strip glued to it, and to a lesser degree, the result of the changing influence of the human body. After 20 minutes, the patient is laying still and accelerations stabilize. The recorded moisture sensor values indicate a dry diaper with the sensing strip well attached, although with sensing zones $S3$ and $S4$ coupled better than zones $S1$ and $S2$. Some variability is possible due to inaccurate strip positioning. However, this causes a scaling factor that remains constant during the full measurement. Hence, this factor can be assessed automatically from the first measured values after attaching the strip.

Although a small urine disposal is visible on $S3$ and $S4$ after about 90 minutes, a first significant amount of urine is detected around 130 minutes, this time predominantly on $S1$ and $S3$. In the meantime, the acceleration measurements show an orientation change, probably influencing the urine flow towards a different sensing zone. A second large urine disposal is recorded around 270 minutes, saturating zone $S1$, and with the distribution of the moisture in the diaper's SAP, affecting all sensing zones, albeit to varying degrees. After the second large urine disposal, no additional urine flows into

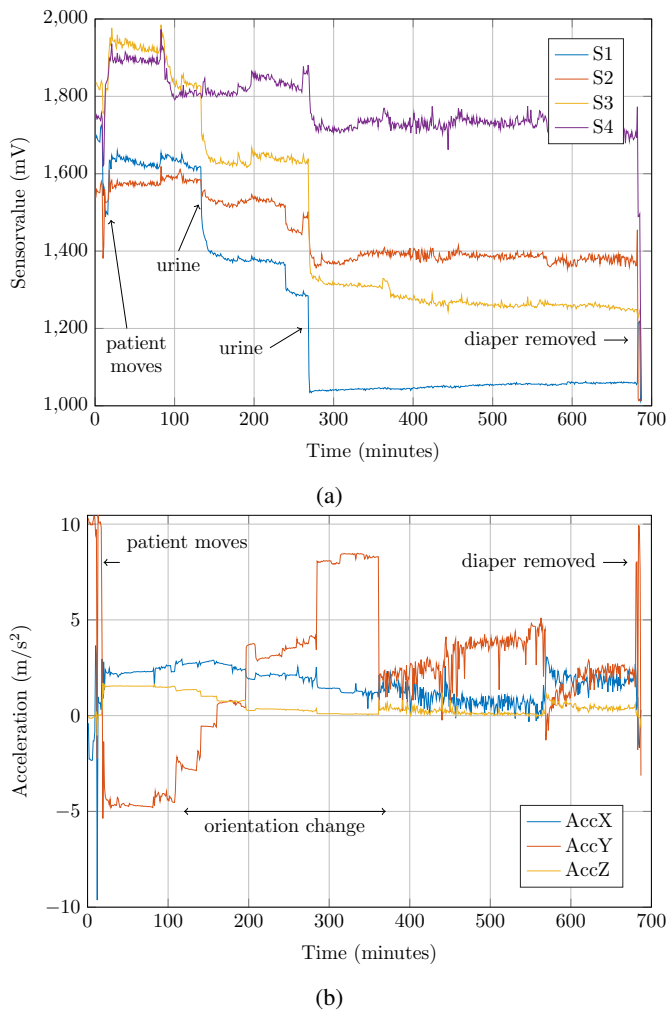


Fig. 10: Moisture and movement detection from field test.

the diaper for the remaining time of the measurement. Note how the sensing values remain constant, despite the significant orientation changes and movement of the patient shown in the acceleration graphs. This illustrates the stability of the measurement once the diaper is wet. At the very end of the graph, a sudden large movement and orientation change is detected. This corresponds to removing the diaper from the patient and then also detaching the measurement strip from the diaper, resulting in an abrupt drop of the sensor signals. After removal, the diaper was weighed by the caregiver and its weight of 400 grams recorded in the log book, minus the dry diaper weight of 102 grams, which corresponds to a urine content of 298 grams.

During 5 of the 145 field tests, also stool was noticed by the nurses and reported in the logbooks. In all of these cases, an increase of sensor values could be observed, in contrast to the decreasing values when moisture is added. This may be a result of the pressure that the feces introduce on the diaper, effectively reducing the gap of parallel plate capacitors $C_{in/out}$ in Equation 3. However, with only five samples, the data are too limited for an accurate assessment of this claim and the reliability of this method in the presence of urine remains unknown. Therefore, this paper solely focuses on the detection

of urine. Note that, a multi-sensor approach [42], employing a VOC sensor, chemical indicators or a compact pressure and temperature sensor [20], may improve the reliability of a stool detection mechanism in the future.

VI. SMART DIAPER ALERTS

The preceding sections described the performance of the smart diaper moisture sensing system in lab and field conditions. The field tests should be seen as a proof of concept, demonstrating the smart diaper's functionality in real-life situations. The sensing method remained unharmed by the presence of the human body or by movements made by the test persons. However, for determining a procedure to generate alerts, the number of field measurements was limited and also the exact conditions were too variable to represent a systematic approach that is required to design an alert system.

Therefore, the alert decision algorithm was based on the systematic lab measurement of the diapers. On the one hand, as documented earlier, the properties of each diaper cause an unpredictable flow of liquid. Given the four sensing zones present in the smart diaper, it is hence random which sensing zones will saturate first, or how uneven the distribution of liquid will be. It is possible that moisture remains predominantly on one side of the diaper. Therefore, the four sensing zones are complementary to guarantee a timely detection of urine. On the other hand, a detection should also not happen too early. If detection occurs from the slightest amount of moisture, then an alert will be produced under conditions where a diaper change is preliminary. This should of course be avoided.

The analysis of the measurements and the sensing behavior led to the following straightforward rule to generate an alert: as soon as two or more sensing zones are saturated enough for the signal to be reduced to 73% or less of their initial values, an alert is immediately triggered.

The result of this approach for the 29 diapers filled up to 750 ml in the lab is displayed as a histogram in Figure 11. The average urine content at which an alert is triggered equals 169 ml, with a standard deviation of 74 ml. Alerts were never triggered at urine contents below 80 ml or above 400 ml. Therefore, we can conclude that for dry or slightly moist diapers, no unnecessary alerts are generated. The maximum amount of urine at which an alert was triggered still corresponds to an unsaturated diaper, with ample margin before leakage is expected to occur. With the current SAP content, adult diapers can hold up to 1 liter of urine. Hence, owing to the smart diaper system, the amount of SAP can certainly be reduced. Note that the straightforward rule can be directly implemented on low-cost and low-power microcontroller-based systems for real-time alert generation. Despite the simplicity of the rule, its effectiveness is not only clear from the results in Figure 11 but can be directly understood. Indeed, on the one hand, for larger volumes of moisture, the rule will always trigger an alert, as it is impossible to have a large volume of liquid influencing less than two out of four available sensing zones. On the other hand, very small amounts of urine, which should not trigger an alert yet, only have a local influence on one sensing zone, which is not enough to trigger a alert. Based

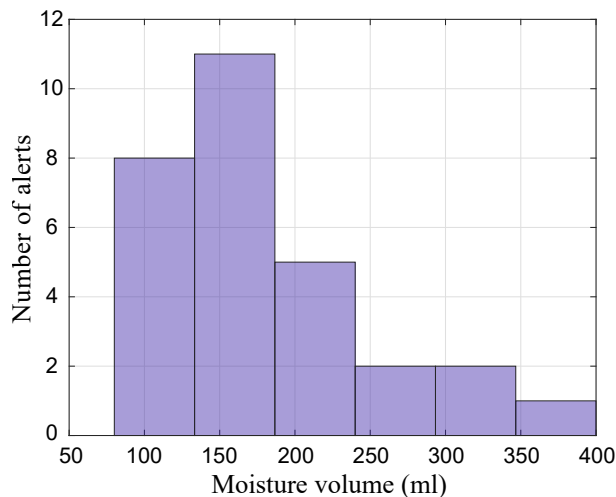


Fig. 11: Histogram of alert levels for 29 diapers in the lab. Rule: two or more zones under 73% of initial signal level.

on these principles, alerts are expected to always occur within an appropriate range of moisture levels.

VII. CONCLUSION

The smart diaper system documented in this paper was designed, developed, manufactured and tested in the lab as well as in the field. The patented main principle of the sensing system leverages a contactless, capacitively coupled, differential transmission measurement based on a carbon ink printed structure inside the diaper. Compared to an impedance measurement, a transmission measurement has advantages in terms of reliability and it additionally allows a dry reference measurement to be performed. The capacitive coupling is performed by a reusable polyimide measurement strip glued on the outside of the diaper, coupling with the carbon print on the inside.

The lab measurements confirmed the reproducible response to rising moisture levels in the diapers, however with a significant spread on the values, due to SAP inhomogeneity, which is inevitable. Multiple sensing zones are implemented to mitigate the effects of the random flow of moisture. The field tests illustrated the continued usefulness of the moisture detecting system in the presence of the human body, with clothing on top of the diaper and patient movements. Orientation changes and other movements were recorded by a triaxial accelerometer in the measurement unit, proving that the moisture sensing functionality remains unharmed by them. An alert-generation procedure is proposed and tested, exploiting the complementarity of the different sensing zones and obtaining reliable and timely urine alerts. The average alert is triggered at a synthetic urine content of 169 ml, with a standard deviation of 74 ml, a minimum level of 80 ml and a maximum level of 400 ml over 29 smart diapers filled up to 750 ml in the lab.

The latter results prove that no unnecessary alerts are triggered for dry or only slightly moist diapers, whereas at the same time an alert is always triggered more than soon enough to avoid diaper leakage. Hence, the comfort of the elderly is improved by eliminating unnecessary diaper

changes or leakages, reducing also the workload of care-giving personnel. Importantly, the smart diaper system is expected to enable the use of adult diapers with significantly reduced SAP content, potentially down to 50% of what is currently used, drastically reducing the environmental load caused by SAP waste products.

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