Development of Capacitive Sensors to Detect and Quantify Fluids in the Adult Diaper

Muhammad Tanweer[1](✉), Raimo Sepponen[2], Ihsan Oguz Tanzer[1], and Kari A. Halonen[1]

[1] Department of Electronics and Nanoengineering, Aalto University, Espoo, Finland
{muhammad.tanweer,oguz.tanzer,kari.halonen}@aalto.fi
[2] Department of Automation and Electrical Engineering, Aalto University, Espoo, Finland
raimo.sepponen@aalto.fi

Abstract. In recent years the rapid technological development in printable electronics technology has made it possible to develop sensors and circuits for wearable medical devices using flexible substrate. In this paper a novel implementation of flexible capacitive sensors to detect and quantify human excreta inside adult diaper is explored. The flexible capacitive sensors are implemented in co-planar geometry by using conductive strips, paint and conductive fabric which are easily available in the market. The developed sensors are used to detect and quantify the fluid and concentration of electrolytes in-vitro (adult diaper and glass jar). An impedance analyzer is used to perform measurements from the sensor and collect necessary specifications in developing suitable printable sensors for a diaper.

Keywords: Wearable Medical Devices · Flexible Capacitive Sensors · Smart Diaper · Printed Sensors · Printed Electronics · Human Fluid Detection & Quantification

1 Introduction

There has been a rapid rise in the elderly population during few decades especially in Europe and Asia [1]. The percentage of elderly people in Europe in the total population is one of the highest, and recorded as the highest in Asia among global population [2]. The recent pandemic disease (COVID- 19) adversely impacted the elderly health worldwide [3]. Recent advances has made it possible to monitor and record physiological parameters using wearable medical devices [4]. Healthcare providers are now adapting to advanced and smart medical solutions provided by the wearable medical devices featured with the application of internet of things (IoT) to reduce the human resource need in medical care. A recent market research report has estimated the rise in global wearable medical device market size to grow from USD 27.2 billion in 2022 to USD 196.6 billion in 2030 [5].

The use of smart adult diapers elderly-care centres is expected to increase because the urine provides enormous biological data which is very helpful in clinical diagnosis

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of various diseases which is otherwise not feasible with the use of conventional diapers [6]. Information about urination frequency together with the urine quantity can be predictor of not only urological diseases like bladder inflammation and kidney function but also various other diseases such as prostatic hyperplasia, urinary track infection (UTI), cognitive deficit, arterial hypertension, diabetes mellitus, depression and many others when combined with other parameters [7].

Recently various fluid detection studies are performed by deploying capacitive sensors using conventional techniques [8, 9]. The advancement of printed electronics technology has brought the possibility to have low cost electronics production on flexible substrates using various biodegradable and environmentally friendly materials to enhance sustainability [10]. In this study, the capacitive sensors in coplanar geometry are developed on a flexible substrate by using printable and lowcost material for wearable usage. The developed sensors are used for detection of liquid and quantification of the volume of liquid inside adult diapers. In Sect. 2 the materials and methods used for the development of flexible sensors are discussed. Section 3 elaborates the measurement results recorded using developed sensors in different scenarios. Finally the Sect. 4 concludes the research work and discusses the possible applications for future developments.

2 Materials and Methods

The materials used in this research work are commercially available. Sensors are developed in Aalto University, Department of Electrical Engineering. Following subsections elaborate the material and methods in detail.

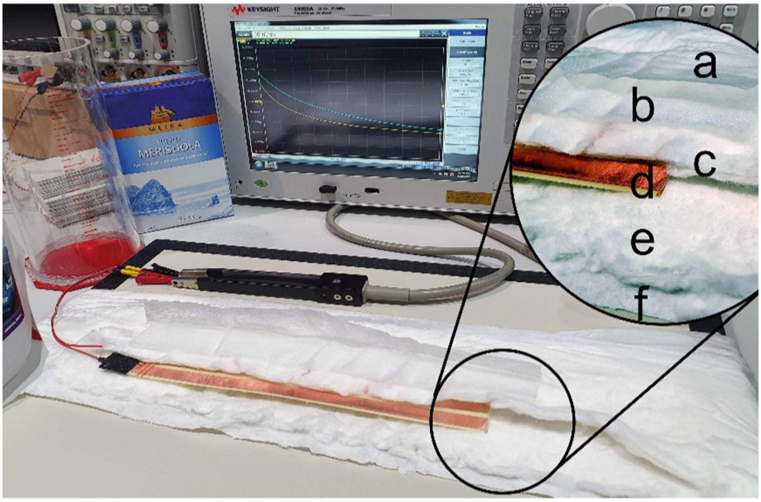

Fig. 1. Flexible capacitive sensor in adult diaper.

2.1 Capacitive Sensors

The capacitance of a conventional parallel plate capacitor is directly proportion to the geometry area (A) of conductors and permittivity (ε_r ε_0) of medium (dielectric) between the plates. The distance between conductor plates is inversely proportional to the capacitance as depicted in Eq. (1). The permittivity varies if there are different material used as dielectric for same geometry of capacitor.

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{1}$$

In this study, for the development of capacitive sensors, the conductive strips are rather deployed in coplanar geometry instead of parallel geometry. The capacitance model of sensor with two coplanar flat conductor is given in Eq. (2). Where as Fig. 2(b) presents the geometry of coplanar capacitive sensor where two conductive strips of equal width W and length L are separated by distance S on same plane.

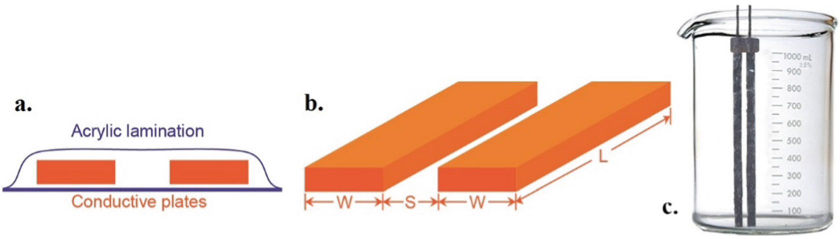

Fig. 2. a) Cross-section of acrylic laminated sensor. b) Geometry of coplanar capacitive sensor with two flat conductive strips. c) Sensor deployed in jar.

The thickness of the conductors is very small and assumed zero here. The flat conductor are assumed in a homogeneous medium with permittivity ($\varepsilon = \varepsilon_r$ ε_0) and permeability $\mu = \mu_0$. Where μ_0 is permeability of free space, ε_0 is the permittivity of air and v0 is speed of light [11].

$$C = \frac{\varepsilon_r L \, ln\left(-\frac{2}{\sqrt[4]{1-\frac{S^2}{(S+2W)^2}}-1}\left(\sqrt[4]{1-\frac{S^2}{(S+2W)^2}}+1\right)\right)}{377\pi v_0} \tag{2}$$

where $v_0 = \frac{1}{\sqrt{\mu\varepsilon_0}}$

The coplanar capacitive sensor is developed by using two equal flat strips of various conductive materials having width W = 10 mm and length L = 200 mm. Both strips are separated with a distance of S = 3 mm. Figure 2(a) depicts the cross section of developed flexible coplanar capacitive sensor. These strips are deployed on a flexible substrate and laminated with a thin transparent acrylic sheet to protect the conductors from corrosive chemical reactions while interacting with fluids. The permittivity of acrylic sheet ranges between 2 to 5 which adds it's effect on the capacitance of coplanar sensor. In free space, the capacitance of the sensors for the given materials with acrylic lamination sheet is calculated using Eq. (2) to be between 7.7 pF and 19.3 pF. When the capacitor is immersed in water, it is estimated that the capacitance of the sensor is supposed to rise about 40 fold assuming the permittivity of water to be 80.

In this study different conductive materials are used to develop a flexible capacitive sensor in coplanar geometry as shown in Fig. 3 in order to compare the capacitive behaviour for detection and quantification of liquid in an adult diaper.

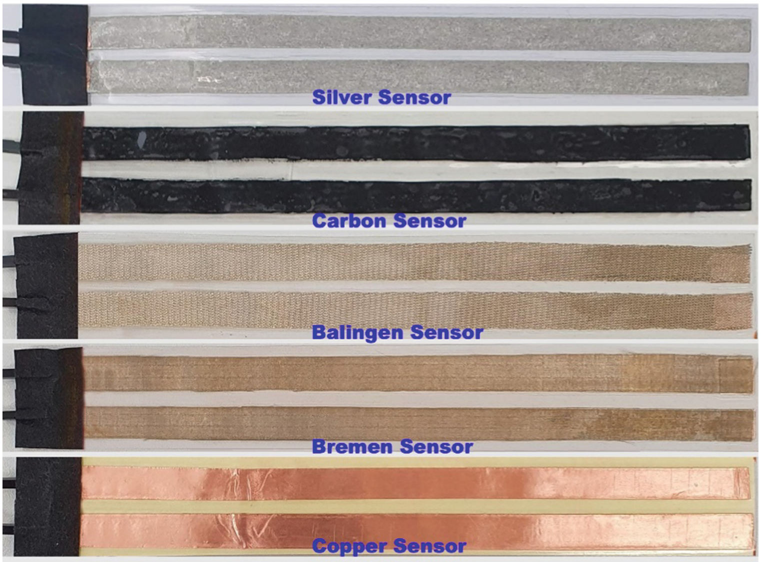

Fig. 3. The developed flexible coplanar capacitive sensors.

Conductive Foil Tape: Copper foil with conductive adhesive (3M, StPaul, Minnesota, USA) having electrical resistance of 0.005 Ω / □is used to develop the flexible capacitive sensor. Named as copper sensor in this article.

Conductive Paint: Off the shelf electrically conductive paints are used on unwoven cotton fabric to contain develop the flexible capacitive sensor.

– Silver based conductive paint (Kemo-Electronic GmbH) having electrical resistance of 0.02 Ω- 0.1 Ω / □is soaked in the fabric to develop the sensor. Named as silver sensor in this article.
– Carbon based conductive paint having electrical resistance of 0.1 Ω – 4 Ω / □is soaked in the fabric to develop the sensor. Named as carbon sensor in this article.

Conductive Fabric: General purpose electrically conductive knitted fabric from the market is used to develop the flexible capacitive sensors.

- 99% pure silver plated polyamide fabric by Bremen having electrical resistance of 0.3 $\Omega/\square$is used to develop the sensor named as bremen sensor in this article.
- 99% pure silver plated polyamide fabric by Balingen having electrical resistance of 0.6 $\Omega/\square$is used to develop the sensor named as balingen sensor in this article.

2.2 Fluids

The fluids used for this study is off the shelf distilled water by Wurth and tap water from the research lab. Table salt (NaCl) is used to introduce the sodium and chloride electrolytes in the fluid with different concentrations. A 60 mmol/l salt solution is prepared in-rd house to mimic the urine to use in-diaper fluid detection and measurements.

2.3 Adult Diapers

The adult diapers of Caroli brand (by W. Pelz GmbH & Co. KG) are procured for this study work. A cross section of the adult diaper is presented in Fig. 1. The upper hydrophilic layer (a) which absorbs the fluids quickly and maintains the dryness around skin. The distribution layer (b) transfers the fluids evenly to lower absorbent layer. The absorption core is made of fluff and hydrogel (c, e) which is a super absorbent polymer (SAP). A non-woven hydrophobic back-sheet (f) prevents the fluids leakage.

2.4 Lab Measurement Equipment

Laboratory precision scale and beaker is used to prepare and measure the fluids. An impedance analyzer by Keysight Technologies Inc (US) E4990A is used with fixture HP16664A to measure and record the real-time capacitance of sensors. A sweep of 900 kHz on 100 kHz−1 MHz span is run to record the sensor behaviour on wide span for an earlier developed custom front-end electronics interface. The recorded measurements are further analyzed using Matlab to compile the results.

2.5 Measurement Setup

First measurement setup is prepared using a liter jar with flexible capacitive sensor attached vertically to the inner wall of jar as shown in Fig. 2(c) Distilled water, tap water, salt solutions and sugar solutions of various concentrations are used to study the response of capacitive sensor. In the second measurement setup the flexible capacitive sensors are deployed inside absorption core of adult diaper under the distribution layer as depicted in the Fig. 1 to ensure the close contact of sensor with fluids absorbed by hydro-gel. A series of fluid introduction scenarios are performed to study the behaviour of developed sensors inside diaper.

3 Measurements Results

In the first scenario the distilled water is used as fluid for detection and quantification. A quantity of one liter of liquid is poured in jar setup with increment of 100 ml for each measurement. The Fig. 4 presents the fluid quantity detection from all sensors.

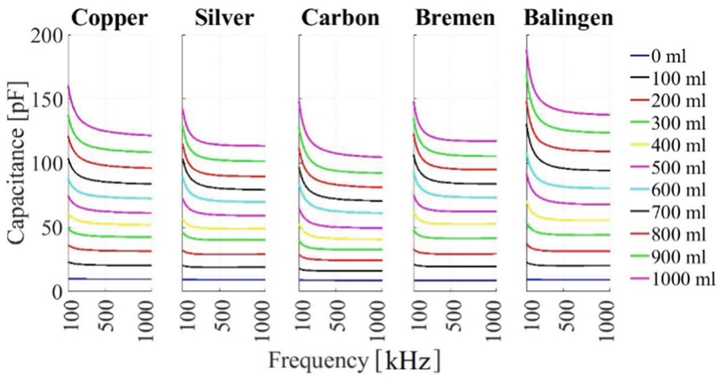

Fig. 4. In jar fluid detection and quantification results compared.

In the second scenario sugar and salt electrolyte concentration in distilled water is measured in the jar using all the sensor types. Figure 5 depicts the comparison of the measured results with silver sensor in three concentration levels of distilled water at level of 500 ml. A change in capacitance is observed with respect to the change in concentration of electrolytes in the liquid affecting the dielectric permittivity. High capacitive behavior of fluid is observed for salt based electrolytes as compared to distilled water. Whereas Fig. 6 shows the capacitive curve of silver sensor for fluid quantification.

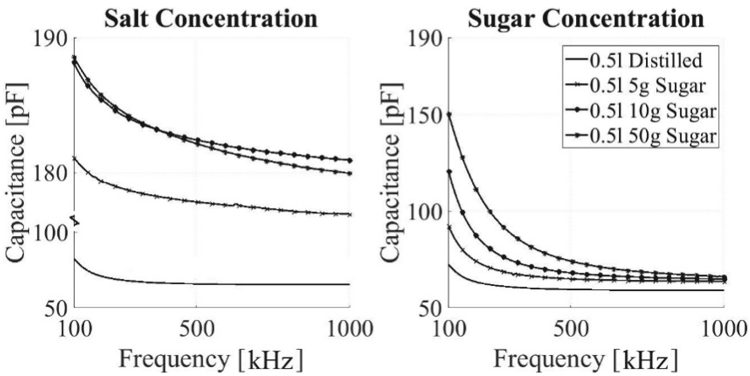

Fig. 5. In jar sensor sugar and salt electrolyte concentration comparison with distilled water.

For sensor measurements inside diaper it is assumed that an adult holds around 400 ml to 600 ml of urine in bladder normally [12]. A pseudo urine is prepared in lab with 60 mmol/l sodium chloride electrolyte concentration. In the third scenario an amount of 600 ml pseudo urine is used to make the diapers wet. Figure 7 shows the measurement results for dry and wet diapers. All sensors have produced promising results for liquid detection.

The fourth scenario is prepared for liquid volume quantification in diaper. For each measurement an amount of 600 ml tap water and pseudo urine is poured into diaper with

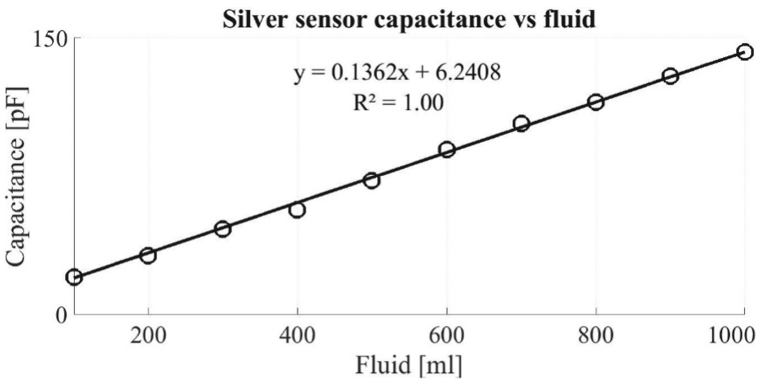

Fig. 6. Capacitive curve of Silver sensor for liquid quantification.

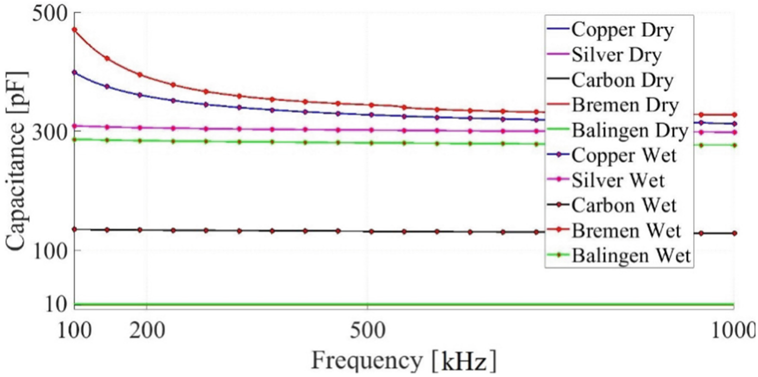

Fig. 7. In diaper sensor dry and wet results compared.

increment of 100 ml at rate of 15 ml/s which is an average urine flow-rate in adults [13] An absorption waiting time of 60 s is introduced before each measurement. Figure 8 and Fig. 9 presents the results of tap water and pseudo urine quantification in silver and copper sensors respectively. It is observed that the increase in capacitance is not linear with respect to liquid volume. We also believe that the liquid volume quantification precision would be enhanced if an artificial intelligence (AI) based algorithm would be used.

In the sixth scenario 600 ml pseudo urine is poured into diaper and sensor capacitance is measured after every 5 min up to 30 min to study the hydro-gel absorption effect on the sensor capacitance. It is observed that there is a slight decrease in capacitance over the time followed by initial rapid reduction in first 5 min. It is because the hydro-gel in edges of diaper takes sometime to uniformly absorb the liquid in overall diaper. Finally an amount of 100ml liquid is poured into diaper after 30 min to observe the effect on sensor capacitance. Figure 10 depicts the gradual capacitance reduction overtime and rapid increase when 100ml liquid is poured after 30 min. The results shows the capability of the sensor to detect intermittent liquid introduction in diaper.

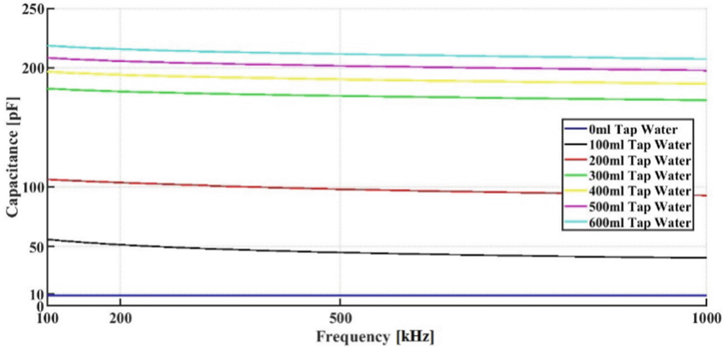

Fig. 8. In diaper silver sensor tap water detection and quantification.

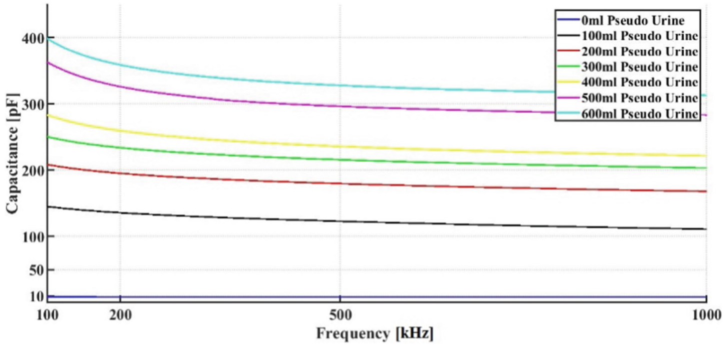

Fig. 9. In diaper copper sensor pseudo urine detection and quantification.

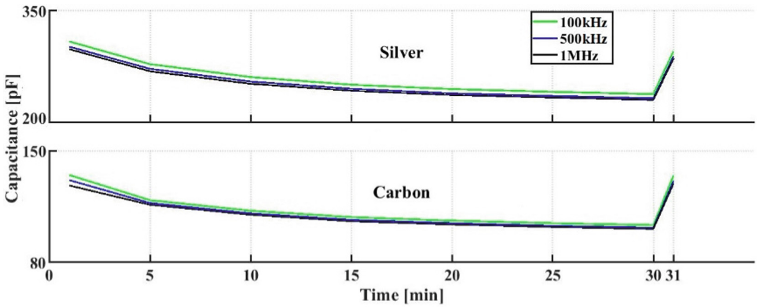

Fig. 10. Hydro-gel absorption trend for all sensors over 30 min time.

4 Conclusion

In this study a series of flexible capacitive sensors are developed using conductive foils, conductive paints and conductive fabrics to detect and quantify the fluids in adult diaper. Several in-vitro measurement scenarios are executed to validate the proof of concept by using impedance analyzer. The measurement results show not only the fluid detection but also a good resolution of fluid volume detection for 100 ml fluid in a diaper. The absorption trend of hydro-gel is also measured for precise volume quantification during frequent urination which brings the possibility to detect bladder inflammation. The frequency sweep results of artificial urine has shown a reduction in dielectric constant for increased salinity over higher frequencies. The proposed implementation of flexible capacitive sensors and front end electronics on flexible substrate using state-of-the-art printable materials along with artificial intelligence based data analysis could enable smart, economical and environmentally friendly adult diapers.

5 Acknowledment

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