Overall Additive Manufacturing of Capacitive Sensors Integrated into Textiles: A Preliminary Analysis on Contact Pressure Estimation

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Abstract: Printed electronics approaches in deploying sensors offers several advantages over traditional methods, including their capability to be integrated into flexible substrates, including textiles. Additionally, printed sensors can be manufactured at relatively low cost and overall include sustainable materials, making them a more accessible option for a wider range of applications. Utilizing additive manufacturing techniques like stereolithography and aerosol jet printing, this work focused on creating fully printed capacitive pressure sensors within textiles. The sensors were designed as planar capacitors with micro-structured dielectrics to enhance linearity and measurement range. Three devices, incorporating 3D pyramidal structures, were produced and characterized under varying loads; the dielectric part was realized by using stereolithography and directly incorporating fabric on the top/bottom sections, whereas carbon-based ink was then deposited to produce the conductive plates and connection pads. Results indicated primarily capacitive behavior up to 10 MHz, with tunable capacitance affected by surface areas and air/resin ratio; hysteresis was also observed, revealing inherent non-linear behavior. These main findings provide important insights into the feasibility of the design and the additive manufacturing process. This innovation holds promise for applications in a variety of fields, including safety and sports.

1 INTRODUCTION

In the context promoted by Industry 4.0 but also in sports, thanks to specific enabling technologies (i.e., Big Data, Internet of Things, Additive Manufacturing, and Cloud Computing), it is possible to constitute enhanced scenario composed by humans, servers equipped with AI-based algorithms, and a network of interconnected Smart Objects (SOs) (Kortuem et al., 2010; Munirathinam, 2020). Indeed, SOs can detect variations of specific physical quantities (i.e., temperature, humidity, mechanical deformations, etc.), while the presence of microcontrollers with devoted algorithms allows preliminary elaboration and transmission of the acquired data. Such a kind of device provides important added value by unlocking new functionalities like real-time monitoring, which can be declined in multiple ways depending on the context in which the SOs are placed. In the realm of sports technology, SOs can be devoted to continually monitor athletes' health, improve their performance, mitigate the risk of injury, and enhance overall engagement, particularly for youth and individuals with disabilities. Similarly, in the context of Industry 4.0, SOs strive to also enhance workers' safety and well-being, ultimately reducing the likelihood of injuries, lowering the overall risk; in this context, SOs

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can in fact monitor both the physiological and environmental conditions within the working area, highlighting variations of temperature and humidity (Borghetti et al., 2021; Saqlain et al., 2019; Perez-Alfaro et al., 2020).

Within these perspectives, contact pressure sensors can provide a fundamental function to SOs, which can be vital in many technological applications such as robotics or exoskeletons, but also in sports equipment or clothing. During the last years, different pressure transducers have been explored in the literature. Among those, the main used are piezoresistive, piezoelectric, capacitive, and optical (Mannsfeld et al., 2010; Pan et al., 2014; Persano et al., 2013; Ramuz et al., 2012). In particular, capacitive pressure sensors are interesting due to their high sensitivity, good repeatability, temperature independence, low power consumption and high spatial resolution (Chortos et al., 2016).

Thanks to its versatility, its ability of working with any kind of substrate material, and its customizability on possible patterns, printed electronics (PE) technologies represent a suitable solution for the fabrication of SOs including contact pressure sensors.

Among all the available printed electronics technologies that allow printing sensors over any surface, both planar or 3D, the contactless ones are the most attractive; among them, in particular, the Aerosol Jet Printing (AJP) represents the most actual state-of-the-art, since it enables to use a wide variety of functional inks and substrates, including non-planar and 3D ones (Almuslem et al., 2019; Gu et al., 2019; Horst et al., 2018; Fisher et al., 2023; Gramlich et al., 2023; Werum et al., 2022). Indeed, AJP together with advanced post-printing thermal treatments, such as Flash Lamp Annealing (FLA), or Intense Pulsed Light (IPL), open up to realize printed sensors even of sensible substrates, such as plastic and paper.

Considering this, the present work aims to propose the realization of contact pressure sensors for potential uses in sports and safety; the sensors were modeled as capacitive sensors and implemented within textiles using a fully additive manufacturing process. In this frame both stereolithography (SLA) and AJP and FLA were employed in order to produce both the mechanical and the electrical components needed to realize a hybrid combination of a polymeric matrix surrounded by fabric and enhanced with sensing functionality. The main hypothesis was that capacitive sensors for contact pressure estimation can be tuned by working on the dielectric flexible structure, while ensuring the integration within textiles, addressing wearable applications.

In this paper, chapter two present methods followed during design, fabrication and performed tests, while chapter three shows the preliminary results obtained during the validation and characterization of the devices; chapter four will summarize the preliminary results achieved, with future perspective of this application.

2 MATERIAL AND METHODS

2.1 Sensor Design

A capacitive pressure sensor can be at first modeled as a planar capacitor whose capacitance (C) can be estimated as in equation (1), in which ε_r depicts the relative permittivity of the insulating layer, ε_0 the vacuum permittivity, A is the surface of the plates of the device and d is the distance between them.

$$C = (\varepsilon_0 \varepsilon_r A)/d \tag{1}$$

This model is acceptable when referring to devices with uniform dielectrics. However, the use of micro-structured dielectrics is widely used in order to improve the linearity and better tune the measurement range of the device. In this work, a modular dielectric approach is proposed. Each single cell can be modeled in 3D as the combination of four 3D pyramidal structures. In Figure 1(c) the white side represents the air space (2 pyramids), and the combination of the 4 light blue sides of the dielectric also composes 2 pyramidal structures. In this configuration, the relative permittivity can be expressed as the weighted average of the two materials (air and dielectric) as per equation (2), where ε_{ra} and ε_{rb} are the relative permittivity of air and where α and ß represent the percentage of the single cell area covered by air and material, respectively.

$$\varepsilon_r = \varepsilon_{ra}\, \alpha + \varepsilon_{rb}\, \beta \tag{2}$$

In order to evaluate both the selected material and geometries three different kinds of devices were produced. A first set of 10 x 10 x 2 mm completely filled (*Sample A*) was proposed in order to evaluate the electrical characteristics of the selected resin, while two different geometries (10 x 10 x 2 mm and 20 x 20 x 3 mm, both with honeycomb filling, named respectively *Sample B* and *Sample C*) were proposed to evaluate the effect of the different geometry.

2.2 Sensor Fabrication

The devices were fabricated using a multi-step approach. First, a textile substrate (cotton, with dimensions of 100 mm x 50 mm x 1 mm) was attached to the building plate of a stereolithographic printer (Photon Mono M5s, Anycubic). The dielectric part of the capacitive pressure sensor was printed on the surface of the textile using a flexible resin (3D materials SuperFlex); after printing, the excess of resin was washed of using ethanol anhydrous (Sigma Aldrich) and post cured inside an UV chamber for 20 min at room temperature. As further step, an additional layer of the same textile was placed on top of the printed structures and secured with the polymeric resin; the devices were then cured in a UV bath at 60 °C for 20 minutes in order to achieve proper mechanical stability. After that, a carbon-based ink EXP 2652-8 (Creative Materials Inc.) was deposed by AJP system (AJ300, Optomec) on both the textile faces in order to produce the conductive plates that compose the capacitor, as well as to produce a set of connection pads to ease the interconnection of the devices to the frontend electronics. Prior to printing, the tool path was designed by using a CAD platform (AutoCAD 2021, Autodesk). Each layer was composed by two crossed paths in order to obtain a complete fill of the plate. A total number of 10 depositions per plate was performed, considering as process parameters: a) sheath gas flow equal to 110 SCCM; b) atomizer gas flow equal to 770 SCCM; c) exhaust gas flow equal to 750 SCCM, with a printing speed of 3 mm/s. The positioning plate of the AJ300 was set at a temperature of 70 °C. The samples were left to dry overnight at room temperature and then cured using FLA solution (Pulseforge, Novacentrix), setting voltage and pulse duration at 230 V and 1750 µs, respectively. After that, the connection pads were reinforced via drop-casting a carbon nanotube paste in order to improve their resistance to scratch and wear. Figure 1(a) presents the block diagram of the overall production process, while Figure 1(b) and Figure 1(d) show the bare photopolymer printed onto textile substrate and the complete capacitive sensor, respectively.

2.3 Experimental Setup

In order to evaluate the behavior of the produced devices a dynamometer (ESM1500, MARK 10) was used to control the displacement applied to the plates of the printed devices. In order to apply an even force on all the surfaces of the plates and thus ensure a uniform displacement, a set of 3D-printed adapters in the form of trapezoidal prims were realized via additive manufacturing. The devices under test (DUTs) were then connected to an impedance analyzer (HP4194A, HP) to measure their main electrical characteristics. All the samples were measured after a set of fixed displacements applied in increasing/decreasing steps; in fact, after the first compression part, the sensor was unloaded again. In each configuration, the impedance/phase spectrum of the impedance were estimated. Figure 2 presents the schematic representation of the experimental setup.

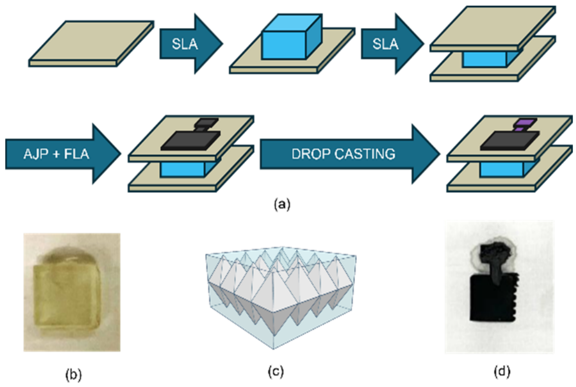

Figure 1: (a) Block diagram of the sensors production steps. The textile substrate is represented in ocher color, the photopolymer in light-blue, the carbon plates of the capacitor in black, carbon nanotubes in purple. (b) Picture of the printed photopolymer. (c) Schematic visualization of the selected 3D structure of the honeycomb dielectric. (d) Final layout of the printed sensors.

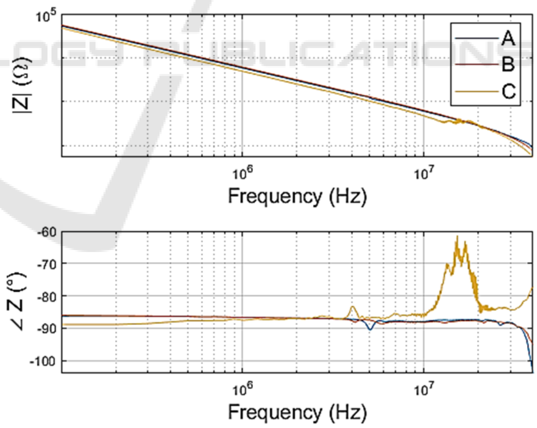

Figure 2: Impedance spectrum of the three different devices taken into consideration.

3 PRELIMINARY RESULTS

The electrical characterization of the devices started analyzing the impedance of the three devices at no load (Figure 3).

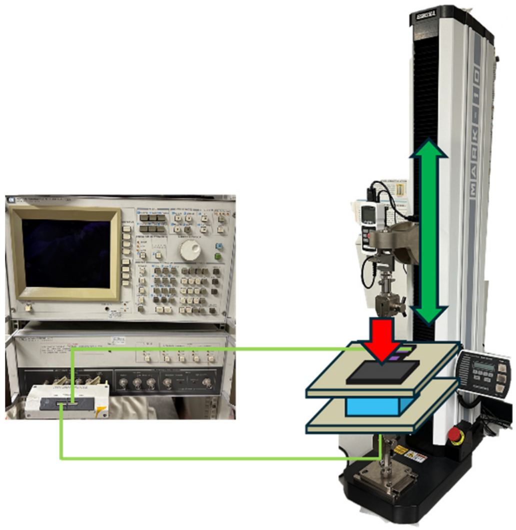

Figure 3: Schematic representation of the experimental setup.

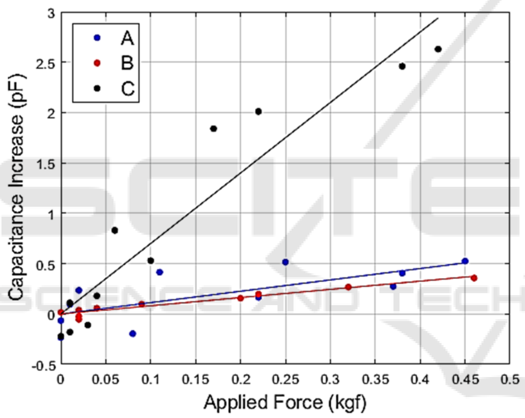

Figure 4: Increase of the three device's capacitance due to the applied force. Solid circles depict the experimental data, while the lines are the respective fitting lines.

The behavior of all the devices is mainly capacitive, up to 10 MHz. At higher frequencies, in *Sample C*, other phenomena related to different effects, such as parasitic ones, are evident. From those measurements, it is possible to underline how the biggest value of capacitance corresponded to *Sample C*, which in fact presented the bigger surface area. On the other hand *Sample A* presented a bigger capacitance value with respect to *Sample B* thanks to the higher ratio of resin in the dielectric part of the device. In Figure 4, the increase of the device capacitance related to the applied force is underlined; in fact, in this figure, it is possible to observe the huge difference in terms of sensitivity introduced by the geometrical form factor. Again, as expected, *Sample A* presented a higher value of sensitivity with respect to *Sample C*, while normalizing for the surface area of the plates thanks to the bigger permittivity of the resin compared to the one of air. The achieved coefficient of determination is around 0.9. This may be explained by considering the non-linear behavior as highlighted by the hysteresis (Figure 5); the main differences between the compression and the releasing parts are related to the viscoelasticity of the used dielectric resin as well as to the effect of compression in the internal microstructure of the dielectric part that introduces non-linearity in the behavior of the overall device.

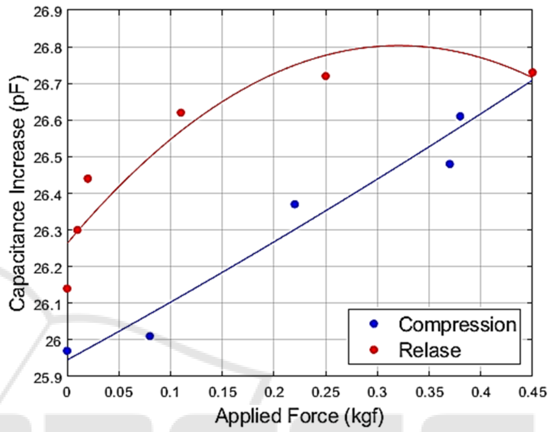

Figure 5: An example of the achieved data where the phenomenon of hysteresis is underlined. In blue it is shown the compression part of the experiment, while the red points were the ones achieved while releasing the force in steps.

4 DISCUSSION AND CONCLUSIONS

In this work, a set of pressure sensors on textiles were produced using only the possibilities of additive manufacturing such as stereolithography and aerosol jet printing. Three different devices were produced to underline the main differences introduced by the dielectric structure both in terms of internal filling (honeycomb versus filled structures) and plates' size (10 x 10 mm versus 20 x 20 mm). The achieved preliminary results, in terms of variation in capacitance and sensitivity, showed an increased sensitivity due to the increase of the plate size (6.998 pF / kgf for *Sample C*) as well as considering the filled structure (1.1278 pF / kgf for *Sample A*) versus the honeycomb (0.814 pF / kgf); these findings allowed us to verify the design assumptions as well as to assess the feasibility of the proposed approach.

Comparing the proposed approach with respect to the most recent research on flexible capacitive pressure sensors, we found several studies, which were specifically focused on the fabrication, characterization, and sensitivity enhancement of this kind of sensor. In fact, Zhao et al. presented an interesting approach concerning the use rapid prototyping of flexible capacitive pressure sensors based on porous electrodes (Zhao et al., 2023) whereas He et al. and Yang et al. described a capacitive pressure sensor with enhanced sensitivity and fast response to dynamic interaction (He et al., 2018) . Interestingly, Ye et al. reported the possibility of realizing all-fabric-based flexible capacitive sensors, underling the tremendous interest for healthcare monitoring, soft robotics, and human−computer interface (Ye et al., 2022). Furthermore, the sensitivity-optimized flexible capacitive pressure sensor microstructured dielectrics represented a promising approach in the optimization of the range of measurement and overall sensitivity optimization (Hua et al., 2023; Li et al., 2021; Ma et al., 2023; Pignanelli et al., 2019) . Indeed, these studies emphasized aspects such as sensitivity, range of measurement, response time, and novel fabrication techniques.

In general, the results of our study align with the ongoing research efforts to enhance the overall characteristics of flexible capacitive pressure sensors. By comparing our findings with the existing literature, we can further validate the significance of our research and identify potential areas for future development and improvement. However, further work is still needed in order to tune the device mechanical and electrical characteristics in order to improve their performance, such as increasing the maximum working range, reduce hysteresis and adapt them to the specific application field.

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