Journal of Techniques, ISSN: 2708-8383, Vol. 7, No. 1, 2025, Pages 19-27
DOI: https://doi.org/10.51173/jt.v7i1.2626

JOURNAL OF TECHNIQUES

Journal homepage: http://journal.mtu.edu.iq

RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

Development and Assessment of Highly Sensitive, Economically Viable, and Environmentally Sustainable Fabric-Based Flexible Capacitive Pressure Sensors

Subrata Pandey[1*], Soumitra Kumar Mandal[1]

[1]National Institute of Technical Teachers, Training and Research, Kolkata, India

[*] Corresponding author E-mail: subratapandey.ee@gmail.com

Article Info.

Article history:

Received
28 September 2024

Accepted
08 December 2024

Publishing
31 March 2025

Abstract

Flexible capacitive pressure sensors offer unparalleled benefits—malleability, stability, simplicity, low power consumption, and minimal sensitivity to temperature fluctuations. Yet, their expensive materials, complex, and environmentally detrimental manufacturing processes impede their widespread adoption. This study unveils a cost-effective, simple, and environmentally sustainable method to fabricate highly sensitive flexible capacitive pressure sensors that outperform costly sensors manufactured using unsustainable materials. By sandwiching a flexible polyurethane (PU) sheet between two silver-metallized fabrics (SMF) and securing them with polyethylene adhesive tape (PAT), we have eliminated the need for expensive and specialized equipment and methods. Crafting sensors of varying dimensions is now as simple as cutting fabric and PU sheets with everyday tools. The key to the sensor's performance lies in the exceptional deformability of the PU layer under applied pressure, resulting in an impressive sensitivity of 0.377358 kPa^{-1}.This surpasses the sensitivity of existing non-eco-friendly and expensive sensors reported in the literature. Additionally, the sensor exhibits excellent pressure resolution and high repeatability. Our sensor accurately detects intricate human movements like palm bends and taps, showcasing its potential across diverse applications—from robotic skins to smart wearables and seamless human-computer interactions. With a production cost as low as 0.34 USD per sensor — significantly lower than the costs of sensors reported in the literature—this study signals a significant advancement in flexible sensor technology, combining affordability, simplicity and sustainability with exceptional performance.

Publisher: Middle Technical University

Keywords: Capacitive Pressure Sensor; Flexible Pressure Sensor; Polyurethane; Silver Metalized Fabric; Robot Skin.

1. Introduction

With the increasing population, the importance of disease monitoring emerges as a notable societal issue. Governments, particularly in anticipation of future resource shortages exacerbated by crises such as the COVID-19 pandemic, are confronted with the imperative to address this issue. However, a beacon of hope emerges in the form of mobile wearable monitoring equipment, offering a promising solution to navigate this predicament. This innovative technology boasts the capability to meticulously observe and assess vital signs such as pulse rate, blood pressure, and sleep quality, empowering patients with early awareness of potential illnesses and pre-emptive measures against impending health crises [1-2] Beyond the realm of wearable devices, autonomous assistive medical robots emerge as indispensable allies in both patient care and support for healthcare professionals. However, these robots need vast environmental data to work safely in the presence of humans. Similar to human skin, a whole-body tactile sensor can fulfill this need. In this context, the integration of low-cost flexible pressure sensors emerges as a linchpin in both wearable monitoring equipment and the realm of robotic tactile sensing. These flexible sensors, serving as the core component of wearable devices, excel in capturing physical cues and detecting a spectrum of human movements, while also holding promise as human skin-like sensors for robots. Flexible pressure sensors encompass four primary types: capacitance-based, resistance-based, piezoelectric, and friction-based. Among these, capacitance-based flexible pressure sensors stand out as the optimal choice for wearable monitoring devices owing to their ability to measure both dynamic and static pressure, coupled with their simplicity, low power consumption, stability, flexibility and minimal susceptibility to temperature fluctuations [3]. A flexible pressure sensor based on capacitance typically comprises an elastic dielectric layer sandwiched between upper and lower electrodes. The viscoelastic properties and the elastic dielectric layer's modulus of elasticity play a pivotal function in determining the responsiveness and reaction time of the sensor [4]. Flexible pressure sensors have emerged as critical components in modern technology, enabling advancements in wearable devices, prosthetics, and human-machine interfaces. However, most sensors in the market are either prohibitively expensive or manufactured using non-eco-friendly materials, posing environmental challenges. This study addresses these limitations by designing a pressure sensor that is cost-effective, highly sensitive, and environmentally sustainable.

The primary objective of this research is to develop a sensor that outperforms traditional devices in sensitivity and affordability while maintaining eco-conscious production. The sensor's design is centered around a polyurethane (PU) layer, which offers remarkable deformability under applied pressure, ensuring superior performance.

Nomenclature & Symbols			
PU	Polyurethane	3×3 SLS-P	(3 × 3) cm Single PU Layer Sensors Fixated with Metal Pins
SMF	Silver-Metallized Fabrics	2×2 SLS-P	(2 × 2) cm Single PU Layer Sensors Fixated with Metal Pins
PAT	Polyethylene Adhesive Tape	3×3 SLS–T	(3 × 3) cm Single PU Layer Sensors Fixated with PAT
PRA	Poly-Synthetic Resin Adhesive	3×3 SLS-A	(3 × 3) cm Single PU Layer Sensors Fixated with PRA
VI	Virtual Instruments	3×3 DLS-A	(3 × 3) cm Dual PU Layer Sensors Fixated with PRA
2×2 SLS-A	(2 × 2) cm Single PU Layer Sensors Fixated with PRA	3×3 DLS-P	(3 × 3) cm Dual PU Layer Sensors Fixated with Metal Pins

2. Literature Review

Various researchers have used different methods to fabricate highly sensitive flexible capacitive pressure sensors. In [5], the authors used a dielectric layer of polydimethylsiloxane (PDMS) with evenly spaced micro-pores to create a super-elastic, highly sensitive flexible capacitive pressure sensor with a quick response time and large sensing range. By employing sugar particles as a porogen and vacuum-assisted penetration of PDMS solution, the micro-pores were created. In [6], researchers developed a low-cost and mold-free technique wherein a vertical curing magnetic field induces the self-assembly of magnetically derived microneedles from a coating of curable magnetorheological fluid (CMRF). In [7], the researchers fabricated porous structures in a PDMS film with cone-shaped surface patterns using microwave irradiation to be used as the dielectric layer for a highly sensitive flexible capacitive pressure sensor. Prominently, methods such as photolithography and chemical etching have garnered considerable attention in fabricating regular microstructures. In a seminal study in 2010, researchers at Stanford University pioneered the enhancement of sensor sensitivity through the utilization of a dielectric layer adorned with regular pyramidal bumps, primarily employing photolithography for microstructure fabrication [8]. Subsequent endeavors, such as those by Lin et al., further refined this approach by leveraging photolithography to create micro-structured templates, leading to notable advancements in sensor sensitivity and response time [9]. Drawing inspiration from biomimicry, researchers have turned to natural templates, which possess intricate micro/nanostructures on their surfaces, as alternatives for fabricating environmentally friendly flexible pressure sensors. For instance, He et al. drew inspiration from the inner membrane structure of an eggshell to develop a capacitive pressure sensor with significantly heightened sensitivity, surpassing that of conventional flat sensors [10]. Similarly, Zhang et al. and Luo et al. utilized templates derived from natural sources, such as ginkgo leaves and rose petals, respectively, to craft micro-structured dielectric layers, resulting in sensors with enhanced sensitivity and response [11, 12]. However, the fabrication of all these works includes the use of photolithography and chemical etching. The reliance on these methods entails complexities, high costs, and environmental concerns. The field lacks a solution that seamlessly integrates affordability, simplicity, and high sensitivity with sustainable materials. This research aims to fill this gap by leveraging the unique properties of PU, a material that has been underexplored in this context.

By utilizing a common polyurethane (PU) sheet as the dielectric layer and silver-metallized fabric (SMF) electrodes as templates, this method offers simplicity, scalability, and environmental friendliness, aligning with the principles of green technology while also being cost-effective. Through systematic experimentation, involving variations in electrode dimensions, fixation methods, and dielectric layer configurations, the study evaluates the performance of seven distinct sensors. Following rigorous assessment, the most efficient flexible capacitive pressure sensor is identified for further exploration, with a focus on practical applications such as responding to diverse human movements, including finger pressing and fist-clenching, proving its effectiveness both in mobile wearable monitoring equipment and whole-body skin for robots.

3. Method

This section outlines the key components used for fabricating the flexible capacitive pressure sensor, including electrode and dielectric materials and the fabrication process that details the step-by-step method employed to assemble the sensor.

3.1. Materials

SMF was supplied by Statex Produktions- und Vertriebs GmbH, Berlin, Germany, and PU sheets were purchased from Gizga Essentials, Mumbai, India.

3.2. Fabrication process of the flexible capacitive pressure sensor

SMFs were cut into multiple pieces measuring 3 cm × 3 cm and 2 cm × 2 cm. PU sheets were also cut into multiple pieces measuring 4 cm × 4 cm and 3 cm × 3 cm to create flexible capacitors. A total of 7 sensors of 5 different types were created. Two sensors were created using two layers of dielectric PU sheets, and the rest of the five sensors with one layer of the PU dielectric sheet. Among these seven sensors, three were fixated with metal pins, three were fixated with PRA and one with PAT. In the PRA-based fixation method, PRA was applied to both sides of the insulator. The SMFs were then carefully placed on these PRA-coated sides. The 4 cm × 4 cm PU sheets were used for the 3 cm × 3 cm SMF electrodes, and the 3 cm × 3 cm PU sheets were used for the 2 cm × 2 cm SMF electrodes. The assembled components were left to dry for one hour before conducting tests. For the pin-based fixation method, the process involved placing a PU sheet as the bottom layer, followed by the placement of one of the SMF electrodes. Another PU sheet was then placed on top of that electrode, acting as the dielectric layer. Subsequently, the other SMF electrode was placed, and another PU sheet was added. Finally, the top and bottom PU layers were secured together using multiple metallic pins, ensuring no contact between the pins and the SMF electrodes. The size of the topmost and bottom layers matched the size of the dielectric layer. The top and bottom layers were used to aid in fixating different layers of the sensor together. In the PAT-based fixation method, the procedure began with placing one of the electrodes on top of the PU sheet, which was then affixed to the insulator using PAT. Similarly, the second SMF electrode was attached to the opposite side of the insulator in the same manner, using PAT. A total of 7 different sensors were fabricated with 5 different types. These sensors are:

- 3 cm × 3 cm Dual PU Layer Sensors Fixated with Metal Pins (3×3 DLS-P)
- 3 cm × 3 cm Single PU Layer Sensors Fixated with Metal Pins (3×3 SLS-P)
- 2 cm × 2 cm Single PU Layer Sensors Fixated with Metal Pins (2×2 SLS-P)

- 3 cm × 3 cm Single PU Layer Sensors Fixated with PAT (3×3 SLS–T)
- 3 cm × 3 cm Single PU Layer Sensors Fixated with PRA (3×3 SLS-A)
- 2 cm × 2 cm Single PU Layer Sensors Fixated with PRA (2×2 SLS-A)
- 3 cm × 3 cm Dual PU Layer Sensors Fixated with PRA (3×3 DLS-A)

An illustration is provided in Fig. 1.

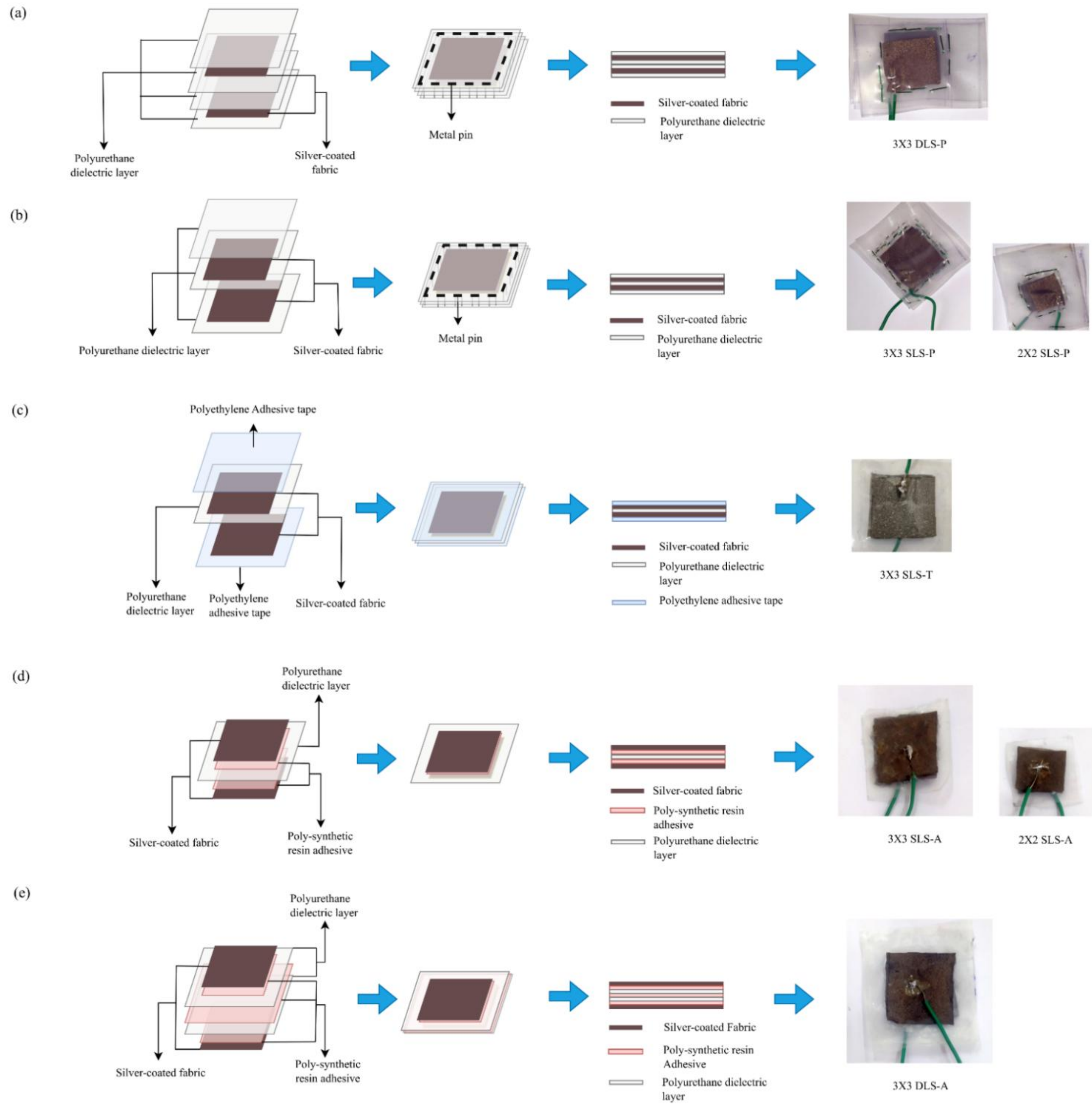

Fig. 1. The fabrication method of the flexible capacitive pressure sensors: (a) 3×3 DLS-P, (b) 3×3 SLS-P and 2×2 SLS-P, (c) 3×3 SLS-T, (d) 3×3 SLS-A and 2×2 SLS-A, (e) 3×3 DLS-A

3.3. Methodology

To evaluate the capacitive sensitivity of the sensors, they were placed on a flat surface, and then standard weights of values 50 gm, 100 gm, 200 gm, 500 gm, and 1 kg were placed on top of the sensors in different combinations to determine their capacitance. Its capacitance was measured using a Digital Multimeter. Forces exerted on the sensors were determined by multiplying the mass values with gravity. These force values were then divided by the surface area of the masses to determine their resultant pressures.

For evaluating the voltage sensitivity of the sensor, a 240 Ω resistance was connected in series with the sensors on top of a breadboard to create a voltage divider circuit. The digital-to-analog converter (DAC) of the MyRIO-1900 device by National Instruments was used to generate an AC signal of 40 kHz. Then, the signal was passed through the voltage divider circuit. The voltage signal transduced across the resistor was then inputted into the analog-to-digital converter (ADC) integrated within the MyRIO-1900 platform, facilitating subsequent computation.

After offset removal, the signal was passed through a Hanning window to reduce the effect of spectral leakage. Then, the Fast Fourier Transform (FFT) of the windowed signal was determined. The voltage magnitude of the FFT for the 40 kHz frequency was measured for different combinations of the masses and then the pressure exerted by these masses was calculated. LabVIEW by National Instruments was used to program the Field Programmable Gate Array (FPGA) of the MyRIO-1900 device for performing real-time signal processing, data acquisition and real-time visualization. The block diagram of the circuit, along with the picture of the connection and a circuit diagram, is provided in Fig. 2(a), (b), and (c). The virtual instruments (VI) used in LabVIEW for programming the FPGA part of the MyRIO-1900 device are shown in Fig. 3(a). The VI used for the data acquisition and real-time visualization is exhibited in Fig. 3 (b).

After collecting the data using LabVIEW, the sensitivity (S) was determined using the below equations:

$$S = \frac{\frac{\Delta C}{C_0}}{\Delta P} \tag{1}$$

$$\Delta C = C - C_0 \tag{2}$$

$$C = \frac{\epsilon_0 \epsilon_R A}{D} \tag{3}$$

$$\Delta P = \frac{mg}{a} \tag{4}$$

$$\Delta V = V - V_0 \tag{5}$$

ΔC and ΔP represent the initial capacitance of the sensor, the change of capacitance (2) and pressure applied on the capacitor (4) respectively. As the sensor sensitivity is primarily related to ΔC, (3) can specify the eventual capacitance of the sensor (C) [13-15], here, ε_0 signifies the space dielectric constant, ε_r represents the comparative dielectric constant of the dielectric layer, A denotes the proportional area of the PU dielectric layer, d stands for the spacing between the two SMF electrodes of the sensor, m represent the mass of the object place on the sensor, and g is the acceleration due to gravity, respectively. In (5) ΔV is the change in voltage which is a difference between the voltage value V when pressure is applied and V_0 is the voltage when no pressure was applied on the sensor. The capacitance (C) is determined by A, ε_r and d. The varying parameters for the sensors are A and d in the PAT-based and pin-based fixation methods. In the case of PRA based fixation method, permittivity is also varying because of the presence of a layer of PRA in between the two PU dielectric layers (in the case of 3×3 DLS-A) and in between the SMF electrodes and the PU dielectric layer (in case of all three PRA fixated sensors).

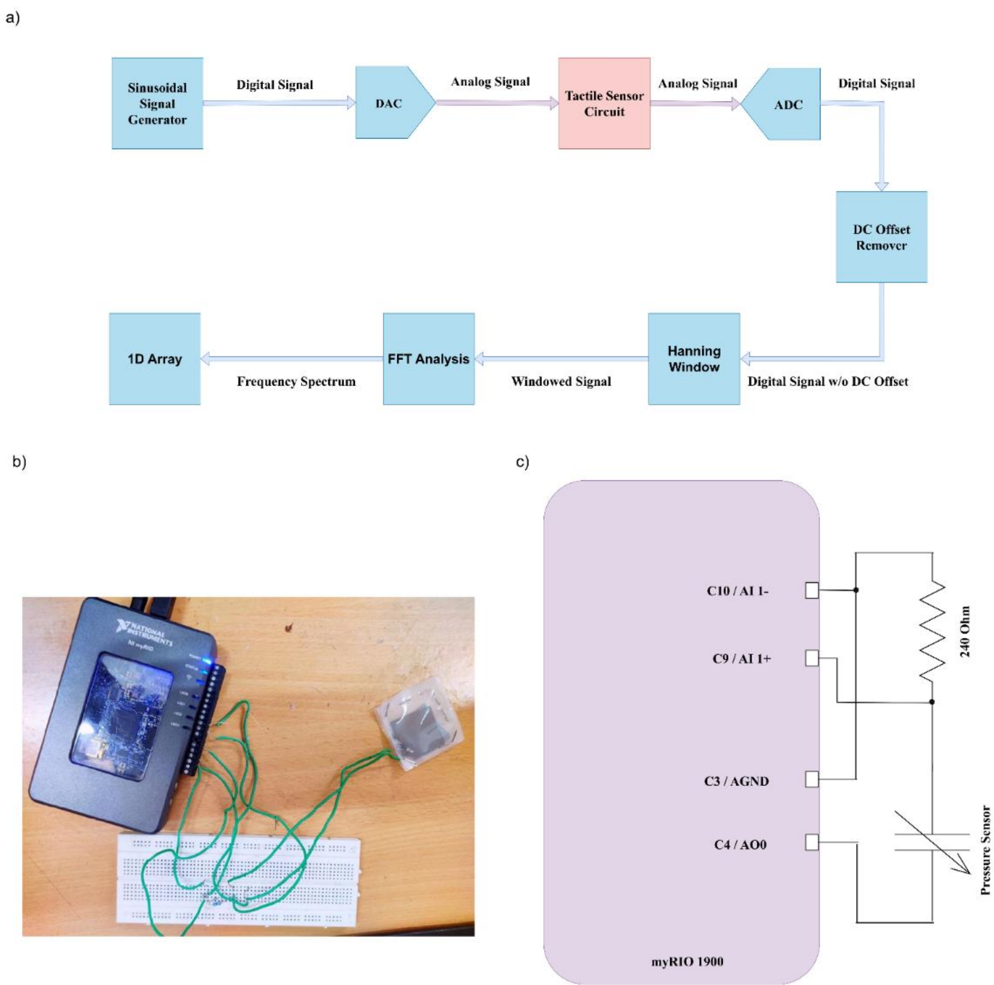

Fig. 2. (a) Block diagram of FFT-based sensor data communication system, (b) Picture of the sensor data acquisition system circuit, (c) Circuit diagram of sensor data communication system circuit

(a)

(b)

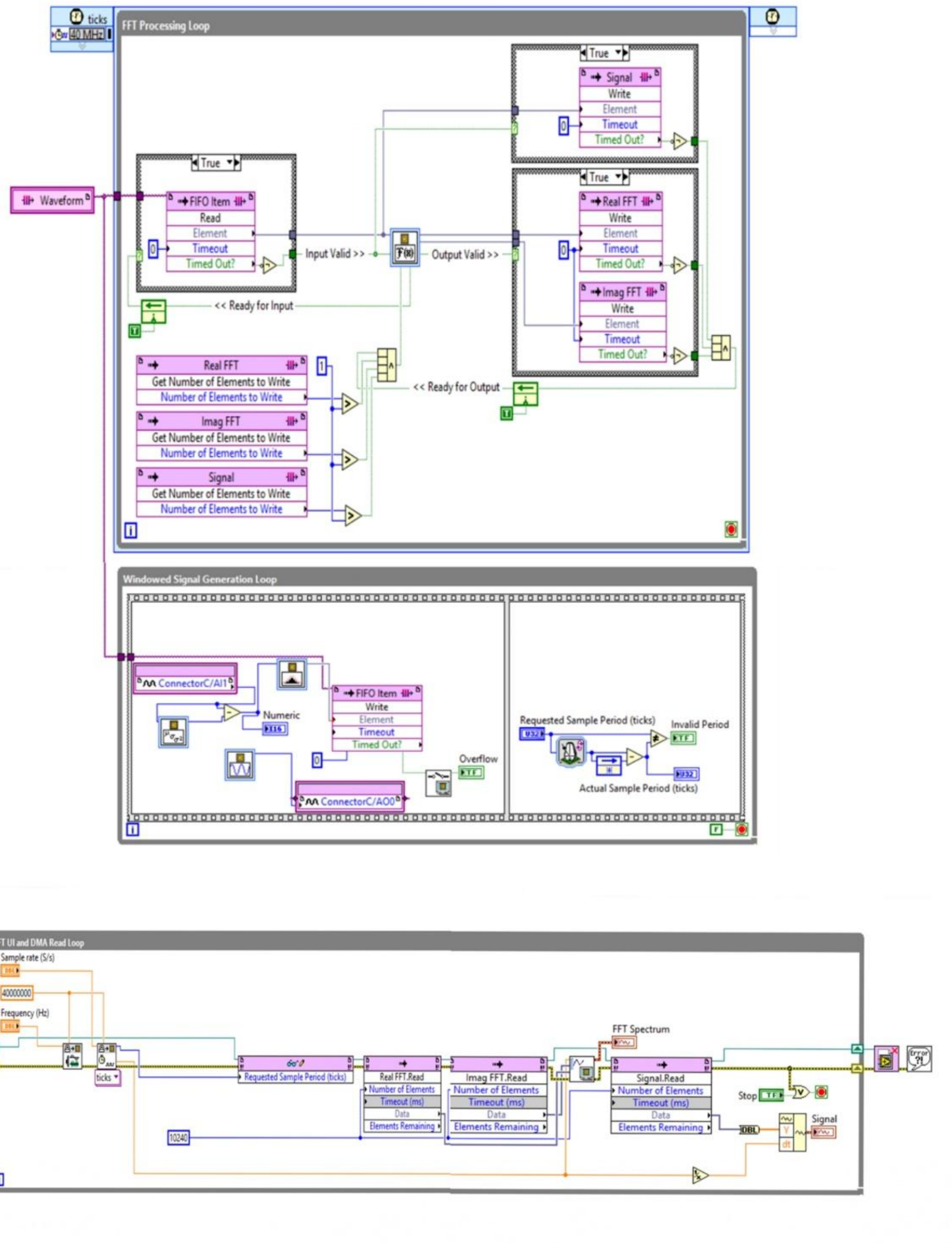

Fig. 3. LabVIEW VIs for; (a) programming the FPGA of the MyRIO-1900 Device for real-time signal processing, (b) data acquisition and visualization of the signal

4. Results and Discussion

This section investigates how the sensitivity of pliable capacitance-based pressure sensors is influenced by various factors such as different numbers of dielectric PU layers, electrode dimensions, and fixation methods. Also, the 3×3 SLS-T sensor's repeatability, voltage change response, and its response under different types of pressure have been investigated. Additionally, the 3×3 SLS-T sensor's sensitivity has been determined for comparison. According to (1), the sensitivity of the sensors can be characterized by plotting the curve of $\Delta C/C0$ versus pressure change (ΔP). However, as initially the pressure on the sensor is zero, sensitivity can be characterized by plotting the curve of $\Delta C/C0$ versus pressure (P). Essentially, the gradient of this curve indicates the sensitivity of various sensors, as illustrated in Fig. 4(a) [16-18]. Table 1 displays the sensitivity of the sensors as determined by the gradient of their respective curves across various pressure intervals.

According to the measurement, the sensitivity of the 3×3 SLS-T is the highest, reaching 0.377358 kPa^{-1} within the range of 0-5 kPa. Notably, this sensitivity is 67 times greater than that of the sensor with the lowest sensitivity, which includes both the 2×2 SLS-A and 3×3 SLS-A. In Fig. 4(a), the flexible capacitive sensors exhibit varying sensitivities across different pressure levels. As pressure increases, the sensitivity of all sensors decreases. This trend suggests that as a sensor undergoes low-pressure loading, it generates a larger ΔC and higher sensitivity can be achieved for the sensors in the range of 0–5 kPa. With the gradual increase of pressure loading, compression of the PU layer becomes the main factor affecting ΔC. Overall, the sensitivity of sensor configurations varied significantly depending on the fixation method employed. Configurations utilizing the PAT fixation method demonstrated the highest sensitivity, while those with the pin fixation method showed medium sensitivity, and those with the PRA fixation method exhibited the lowest sensitivity. This disparity can be attributed to several factors. With the PRA fixation method, the drying PRA forms a hardened layer that increases the distance between the electrodes and reduces the sensor flexibility, thereby reducing overall sensitivity. Although, the dielectric property of the PRA contributes to the increased overall capacitance of the sensor. In contrast, sensors fixed with pins displayed lower sensitivity due to the presence of layers of PU dielectric sheets atop both the anode and cathode. This compressible layer dampens pressure application on the sensor, resulting in reduced sensitivity. However, it in turn enhances the sensitivity gradient compared to other sensors in higher ranges, particularly evident in the last two data points of all sensors. PAT-based fixation, though flexible, lacks compressibility of the PAT material, which is the top and bottommost layer of the sensor, leading to higher sensitivity output in the lower ranges but lowered sensitivity in the higher ranges, compared to the metal pin-based fixation method. Sensor size also played a role, with larger sizes generally exhibiting higher sensitivity due to increased electrode area. However, the influence of sensor size varies depending on other factors such as PU dielectric configuration and fixation method. For instance, 3×3 SLS-T, 3×3 SLS-P, and 3×3 DLS-P configurations showed higher sensitivity compared to 2×2 SLS-P and 2×2 SLS-A. However, the presence of a hardened PRA layer in PRA-fixed sensors, including 3×3 configurations, resulted in minimum sensitivity compared to others, even lower than 2×2-SLS-T and 2×2 SLS-P sensors. Moreover, 3×3 DLS-P exhibited less sensitivity than 3×3 SLS-T due to the additional layer of PU dielectric sheets in pin-based fixation, which reduced sensitivity. Conversely, 3×3 DLS-P showed higher sensitivity compared to 3×3 SLS-P and 2×2 SLS-P, which is attributed to the higher dielectric thickness. Despite this, they showed more sensitivity compared to the PRA-based fixation method. The 3×3 SLS-T sensor stands out with the highest sensitivity among the seven flexible sensors, registering at 0.377358 kPa^{-1} in the 0–5 kPa range and 0.024826 kPa^{-1} in the 5–40 kPa range. Consequently, the 3×3 SLS-T sensor is chosen as the optimal candidate for further analysis. Moreover, the sensitivities of the three 3×3 SLS-T sensor samples were evaluated to discern any performance discrepancies among them, as depicted in Fig. 4(b). The findings indicate that each sensor's capacitance response remains relatively stable around the average value under identical pressure conditions, implying enhanced reliability. Additionally, the sensor's repeatability was assessed by subjecting it to three cycles of loading and unloading at the same pressure (1.06 kPa). As illustrated in Fig. 4(c), the collected output signal remains consistent across the three cycles, indicating a consistent response from the sensor. Fig. 4(d) shows voltage sensitivity when the sensor is gradually loaded with weights producing equivalent pressure of 1.06 kPa and 5.3 kPa. A 30-second data was collected. The voltage sensitivity remained stable for a given load. Therefore, the sensor exhibits its steady, consistent, and trustworthy real- time response capability. In Fig. 4(e), the sensor is positioned at the bottom left corner of a mouse. Each mouse click occurs at intervals of approximately 2.5 seconds. With the appearance of each distinct peak, representing a sharp increase and decrease in the $\boldsymbol{\Delta C/C_0}$ value, corresponding to a click action, it is evident that the sensor can accurately detect both the magnitude and frequency of pressure when the index finger clicks the mouse. Moving forward, the sensor was affixed to the palm to monitor the pressure exerted by the fingers after making a fist. Each peak in the $\boldsymbol{\Delta C/C_0}$ value reflects the increase in pressure when a finger clenches, and the number of peaks corresponds to the number of fist-clenching actions. The results demonstrate the sensor's ability to detect each action accurately, confirming its potential application in the realm of limb movement monitoring [refer to Fig. 4(f)]. The forces applied during the palm bending action were approximately the same, resulting in a similar magnitude of voltage output accurately, confirming its potential application in the realm of limb movement monitoring [refer to Fig. 4(f)]. The forces applied during the palm bending action were approximately same resulting in a similar magnitude of voltage output.

To compare the performance of the existing flexible capacitive pressure sensors in the literature, a comparison between the sensitivity and the pressure range of the created sensors and similar capacitive sensors in the literature is shown in Table 2. The analysis demonstrates that the developed sensor exhibits outstanding performance, particularly in sensitivity, pressure detection range, and repeatability, as evidenced by references [8], [19-24]. Competitive sensitivity is demonstrated by the sensors created in this work, especially in the low-pressure range (0–5 kPa). Because of the customized structure of the 3×3 SLS-T design, the sensor in 3×3 SLS-T notably has the highest sensitivity (0.377 kPa−1) of all the sensors examined, surpassing even sensors in [21-24] in this range. Sensor in 3X3 SLS-T is perfect for applications needing accurate detection of minute pressure changes because of its exceptional sensitivity. The sensitivity of the produced sensors declines in the higher-pressure range (4–30 kPa), as demonstrated by sensors 3X3 SLS-A (0.0036 kPa^{-1}) and 2X2 SLS-A (0.0036 kPa^{-1}), which are lower than those of sensors in [22] (0.0125 kPa^{-1}) and [24] (0.015 kPa^{-1}). However, dual-layered PU and 3 cm ×3 cm structural topologies, which enhance electrode contact and pressure distribution, allow sensors 3X3 DLS-P (0.0172 kPa^{-1}) and 3X3 SLS-T (0.0248 kPa^{-1}) to perform better. The sensors that have been developed are ideal for applications involving low to moderate pressure (0–30 kPa). In contrast to literature sensors such as [22] and [23], which function well in broad pressure ranges (<360 kPa), the pressure range of sensors fabricated in this work is more limited. However, in situations where severe pressures are not commonly encountered, such as wearable electronics, this narrow range is beneficial. The most optimal designs are the 3×3 DLS-P and 3×3 SLS-T, which combine a functional pressure range and excellent sensitivity. By increasing electrode uniformity and dielectric responsiveness, structured designs such as SLS-T improve performance and outperform literature sensors like sensor in [21] (0.055 kPa^{-1}) and sensor in [23] (0.0077 kPa^{-1}) in terms of low-pressure sensitivity. However, 2×2 SLS-A and 3×3 SLS-A are examples of designs that exhibit limited sensitivity, suggesting that they require additional refining to match the sensitivity of high-performing literature sensors, such as sensors in [20] in the low-pressure range and sensor in [24] in the higher range.

Table 1. The sensitivity of sensors across varying pressure intervals based on their compositions

Sl. No.	Sensor Name	Pressure Range (kPa)	Sensitivity (kPa^{-1})
1	3×3 SLS-A	0-5, 5-30	0.005602, 0.003581
2	3×3 DLS-A	0-5, 5-30	0.030189, 0.006289
3	2×2 SLS-A	0-5, 5-30	0.005602, 0.003581
4	3×3 SLS-P	0-5, 5-30	0.212264, 0.012775
5	3×3 DLS-P	0-5, 5-30	0.332434, 0.017221
6	2×2 SLS-P	0-5, 5-30	0.157232, 0.018781
7	3×3 SLS-T	0-5, 5-30	0.377358, 0.024826

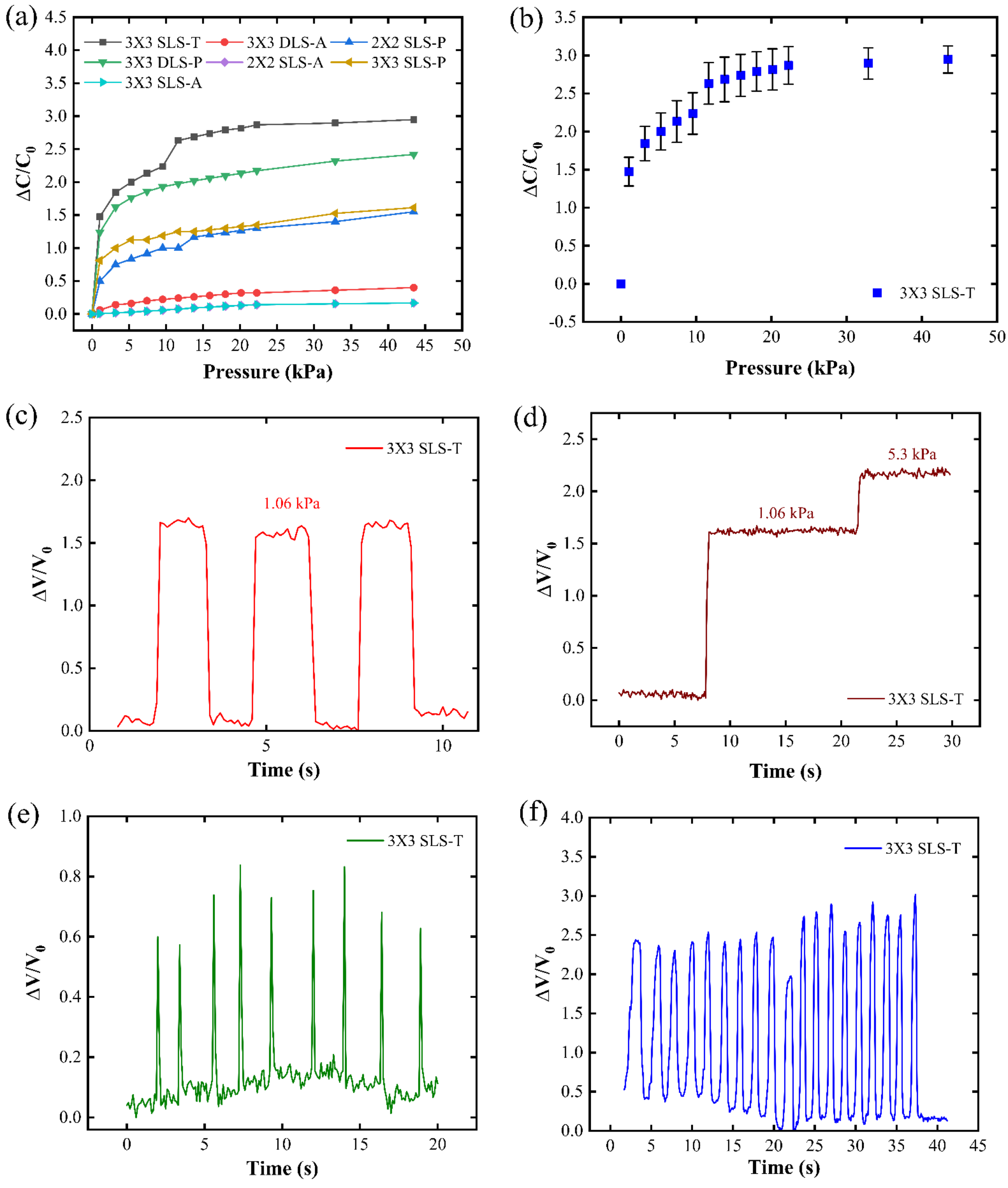

Fig. 4. (a) Relative capacitance responses of the sensors with different configurations, (b) Relative capacitance curve of three independently structured 3X3 SLS-T sensors, (c) Repeatability of the 3×3 SLS-T sensor under the same load (1.06 kPa), (d) Voltage change rate responses of the 3×3 SLS-T sensor under different pressure loadings (1.06 and 5.3 kPa), (e) Quick tapping responses of the 3×3 SLS-T pressure sensor, (f) Palm bending responses of the 3×3 SLS-T pressure sensor

The price of different sensors in USD is presented in Table 3. It can be seen clearly that the price of all the sensors is around 50 cents. The pressure sensor with the highest sensitivity, 3×3 SLS-T, costs only about 30 cents.

In summary, the findings unequivocally demonstrate the sensor's ability to be effectively utilized across a range of applications, particularly in wearable monitoring devices and in whole-body skin for robots.

Table 2. Comparative analysis of the sensing properties of notable works utilizing the pliable capacitance-based sensor

Sl. No.	Electrode	Dielectric Layer	Pressure Range (kPa)	Sensitivity (kPa^{-1})	Ref. No. / Sensor Name
1	ITO	PDMS	0.2-2,2-7	0.55, 0.15	8
2	Au	PDMS	<1.5, 5-20	0.42, 0.04	19
3	AgNWS	CPI	<2, 2-15	1.194, 0.077	20
4	ITO	PDMS	0.5-10	0.055	21
5	Ag	Ecoflex	<16, 16-360	0.0224, 0.0125	22
6	PEDOT and PSS	Ecoflex	0-10, 10-20	0.0077, 0.0015	23
7	Woven conductive cloth	TPU	0-5, 5-10, 10-40	0.182, 0.077, 0.015	24
8	SMF	PU	0-5, 4-30	0.005601887, 0.003580975	3X3 SLS-A
9	SMF	PU	0-5, 4-30	0.030189, 0.006289	3X3 DLS-A
10	SMF	PU	0-5, 4-30	0.005602, 0.003581	2X2 SLS-A
11	SMF	PU	0-5, 4-30	0.212264, 0.012775	3X3 SLS-P
12	SMF	PU	0-5, 4-30	0.332434, 0.017221	3X3 DLS-P
13	SMF	PU	0-5, 4-30	0.157232, 0.018781	2X2 SLS-P
14	SMF	PU	0-5, 4-30	0.377358, 0.024826	3X3 SLS-T

Table 3. Comparison of prices of the fabricated sensors

Sl. No.	Sensor Name	Per Piece Total Price (USD)
1	3X3 SLS-A	0.30
2	3X3 DLS-A	0.39
3	2X2 SLS-A	0.13
4	3X3 SLS-P	0.48
5	3X3 DLS-P	0.57
6	2X2 SLS-P	0.15
7	3X3 SLS-T	0.30

5. Conclusion and Limitation

In essence, this study introduces an environmentally friendly, cost-effective, and direct method for fabricating a pliable and exceptionally responsive capacitive pressure sensor that outperforms the costly, unsustainable, and complex-to-manufacture flexible capacitive pressure sensors mentioned in the literature. Utilizing SMF as electrodes and PU as a dielectric template, we explored various flexible electrode dimensions, numbers of PU layers, and fixation methods to identify optimal parameter values. Seven sensors were fabricated with different parameters, among which the sensor featuring a 3 cm × 3 cm area, a single PU dielectric layer, and PAT-based fixation emerged as the most sensitive, boasting a sensitivity of 0.377358 kPa^{-1} compared to the other sensors. Conversely, the lowest sensitivity was observed in sensors employing PRA-based fixation methods, with electrode areas of both 3 cm × 3 cm and 2 cm × 2 cm, and a single layer of PU dielectric material. Sensors employing a metal pin-based fixation method exhibited moderate sensitivity in lower ranges, yet they demonstrated the capacity to measure higher ranges in comparison to other sensors. Furthermore, the selected sensor exhibits stability, repeatability, and quick response times, underscoring its advantages. Finally, we exhibited the real-world applications of the sensor featuring a single PU dielectric layer and fixated on PAT in discerning human actions like fist clenching and mouse clicking. Consequently, the sensor holds promise for integration into wearable monitoring devices and robot skin while offering both sustainability and cost-effectiveness. Future work should explore the impact of porous polyurethane and other similar flexible dielectric layers on the sensitivity of the sensors.

Acknowledgment

The authors express their deepest gratitude to the National Institute of Technical Teachers' Training and Research, Kolkata for its generous financial support, which was instrumental in making this project a reality. Their invaluable contribution ensured the resources necessary for the successful execution and completion of this work.

References

[1] Y.-L. Tai and Z.-G. Yang, "Flexible pressure sensing film based on ultra-sensitive SWCNT/PDMS spheres for monitoring human pulse signals," J. Mater. Chem. B, vol. 3, no. 27, pp. 5436–5441, 2015, doi: 10.1039/c5tb00653h.

[2] A. Kumar, "Flexible and wearable capacitive pressure sensor for blood pressure monitoring," Sens. Bio-Sens. Res., vol. 33, Aug. 2021, Art. no. 100434, doi: 10.1016/j.sbsr.2021.100434.

[3] Y. Peng, N. Yang, Q. Xu, Y. Dai, and Z. Wang, "Recent advances in flexible tactile sensors for intelligent systems," Sensors, vol. 21, no. 16, p. 5392, Aug. 2021, doi: 10.3390/s21165392.

[4] R. Li et al., "Research progress of flexible capacitive pressure sensor for sensitivity enhancement approaches," Sens. Actuators A, Phys., vol. 321, Apr. 2021, Art. no. 112425, doi: 10.1016/j.sna.2020.112425.

[5] S. Li, K. Dong, R. Li, X. Huang, T. Chen, and X. Xiao, “Capacitive pressure sensor inlaid a porous dielectric layer of super elastic polydimethylsiloxane in conductive fabrics for detection of human motions,” Sens. Actuators A, Phys., vol. 312, Sep. 2020, Art. no. 112106, doi: 10.1016/j.sna.2020.112106.

[6] W. Asghar et al., “Piezo capacitive flexible E-skin pressure sensors having magnetically grown microstructures,” Adv. Mater. Tech- nol., vol. 5, no. 2, Feb. 2020, Art. no. 1900934, doi: 10.1002/admt.201900934.

[7] Y. Kim, H. Yang, and J. H. Oh, “Simple fabrication of highly sensitive capacitive pressure sensors using a porous dielectric layer with cone- shaped patterns,” Mater. Des., vol. 197, Jan. 2021, Art. no. 109203, doi: 10.1016/j.matdes.2020.109203.

[8] S. C. Mannsfeld et al., “Highly sensitive flexible pressure sensors with micro structured rubber dielectric layers,” Nature Mater., vol. 9, no. 10, pp. 859–864, Oct. 2010, doi: 10.1038/nmat2834.

[9] M.-F. Lin, C. Cheng, C.-C. Yang, W.-T. Hsiao, and C.-R. Yang, “A wearable and highly sensitive capacitive pressure sensor integrated a dual-layer dielectric layer of PDMS microcylinder array and PVDF elec-trospun fiber,” Organic Electron., vol. 98, Nov. 2021, Art. no. 106290, doi: 10.1016/j.orgel.2021.106290.

[10] X. He et al., “Microstructured capacitive sensor with broad detection range and long-term stability for human activity detection,” npj Flexible Electron., vol. 5, no. 1, pp. 1–9, Dec. 2021, doi: 10.1038/s41528-021-00114-y.

[11] P. Zhang, J. Zhang, Y. Li, and L. Huang, “Flexible and high sensitive capacitive pressure sensor with micro structured electrode inspired by ginkgo leaf,” J. Phys. D, Appl. Phys., vol. 54, no. 46, Nov. 2021, Art. no. 465401, doi: 10.1088/1361-6463/ac1ddc.

[12] Z. Luo et al., “Flexible capacitive pressure sensor based on an embedded-rib fabric with a bionic sloping petal structure,” IEEE Sensors J.,vol. 21, no. 18, pp. 20119–20128, Sep. 2021, doi: 10.1109/JSEN.2021.3097349.

[13] P. Zhao et al., “Shape-designable and reconfigurable all-paper sensor through the sandwich architecture for pressure/proximity detection,” ACS Appl. Mater. Interfaces, vol. 13, no. 41, pp. 49085–49095, Oct. 2021, doi: 10.1021/acsami.1c14523.

[14] Z. Liu, Z. Yin, J. Wang, and Q. Zheng, “Polyelectrolyte dielectrics for flexible low-voltage organic thin-film transistors in highly sensitive pressure sensing,” Adv. Funct. Mater., vol. 29, no. 1, Jan. 2019, Art. no. 1806092, doi: 10.1002/adfm.201806092.

[15] R. Li, K. Dong, M. Panahi-Sarmad, S. Li, and X. Xiao, “Three- dimensional printing of a flexible capacitive pressure sensor array in the assembly network of carbon fiber electrodes and interlayer of a porous polyurethane dielectric,” ACS Appl. Electron. Mater., vol. 3, no. 9, pp. 3999–4008, Sep. 2021, doi: 10.1021/acsaelm.1c00534.

[16] B. Ji, Q. Zhou, B. Hu, J. Zhong, J. Zhou, and B. Zhou, “Bio-inspired hybrid dielectric for capacitive and triboelectric tactile sensors with high sensitivity and ultrawide linearity range,” Adv. Mater., vol. 33, no. 27, Jul. 2021, Art. no. 2100859, doi: 10.1002/adma.202100859.

[17] N. Bai et al., “Graded intrafillable architecture-based iontronic pressure sensor with ultra-broad-range high sensitivity,” Nature Commun., vol. 11, no. 1, p. 209, Jan. 2020, doi: 10.1038/s41467-019-14054-9.

[18] S. Sharma et al., “Hydrogen-bond-triggered hybrid nanofibrous membrane-based wearable pressure sensor with ultrahigh sensitivity over a broad pressure range,” ACS Nano, vol. 15, no. 3, pp. 4380–4393, Mar. 2021, doi: 10.1021/acsnano.0c07847.

[19] Y. Luo et al., “Flexible capacitive pressure sensor enhanced by tilted micropillar arrays,” ACS Appl. Mater. Interfaces, vol. 11, no. 19, pp. 17796–17803, May 2019, doi: 10.1021/acsami.9b03718.

[20] Y. Wan et al., “A highly sensitive flexible capacitive tactile sensor with sparse and high-aspect-ratio microstructures,” Adv. Sci., vol. 4, no. 4, 2018, Art. no. 1700586, doi: 10.1002/aelm.201700586.

[21] C. Mahata, H. Algadi, J. Lee, S. Kim, and T. Lee, “Biomimetic- inspired micro-nano hierarchical structures for capacitive pressure sensor applications,” Measurement, vol. 151, Feb. 2020, Art. no. 107095, doi: 10.1016/j.measurement.2019.107095.

[22] Q. Hua et al., “Skin-inspired highly stretchable and conformable matrix networks for multifunctional sensing,” Nature Commun., vol. 9, no. 1, p. 244, 2018, doi: 10.1038/s41467-017-02685-9.

[23] H. Shi et al., “Screen-printed soft capacitive sensors for spatial mapping of both positive and negative pressures,” Adv. Funct. Mater., vol. 29, no. 23, Jun. 2019, Art. no. 1903020, doi: 10.1002/adfm.201903020.

[24] Cao, R. Li, M. Panahi-Sarmad, T. Chen, and X. Xiao, “A Flexible and Highly Sensitive Capacitive Pressure Sensor with Micro structured Dielectric TPU Layer Based on Mesh Fabric as Template,” IEEE Sensors Journal, vol. 22, no. 21, pp. 20276–20284, Nov. 2022, doi: https://doi.org/10.1109/jsen.2022.3207005.