A flexible paper based strain sensors drawn by pencil for low-cost pressure sensing applications

Mohd Norzaidi Mat Nawi, Jim Tze Ho Lau
Department of Physics, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, Tanjong Maim, Malaysia

Article Info

Article history:

Received Dec 7, 2023
Revised Jan 14, 2024
Accepted Feb 24, 2024

Keywords:

Flexible sensor
Paper and pencil
Paper based sensor
Pressure sensor
Strain sensor

ABSTRACT

Paper-based strain sensors, offering a cost-effective and environmentally friendly solution, are in demand for pressure sensing applications. Here, we present a simple sensor design comprising a piece of paper, a graphite pencil, and a copper plate. The proposed fabrication process is simple and eco-friendly. Beyond design and fabrication, our study explores the performance of paper-based sensors in effectively measuring and monitoring pressure changes induced by varying deflection angles. Our findings show that as the deflection angle increases, the sensor exhibits a proportional increase in the relative change in resistance. Furthermore, the practical applicability of the fabricated sensor is demonstrated through real-world testing on a human finger, considering different positions. In essence, our research positions paper-based strain sensors as a promising and practical choice for affordable, eco-friendly, and responsive pressure sensing.

Corresponding Author:

Mohd Norzaidi Mat Nawi
Department of Physics, Universiti Pendidikan Sultan Idris
Tanjong Malim, Malaysia
Email: norzaidi@fsmt.upsi.edu.my

1. INTRODUCTION

Flexible sensors play an important role in various applications, ranging from structural monitoring to the measurement of spine bending [1]–[4]. In structural monitoring applications, the raw data obtained from these sensors, typically in the form of voltage measurements, undergoes conversion into essential structural response values such as displacement, strain, and inclination [5]. Within the realm of spine monitoring, the measurement of bending proves invaluable for patients grappling with issues related to poor spinal conditions, encompassing abnormalities like kyphosis (excessive thoracic spine curvature), lordosis (inordinate inward curvature of the lumbar spine), or scoliosis (lateral curvature of the thoracic spine) [6]. Diverse methodologies exist for the measurement of strain or bend, including strain gauges [7], vibrating wire sensors [5], fiber Bragg gratings [8], [9], and Moiré grids [10]. However, these technologies often come with limitations in terms of cost, accessibility, and environmental impact. The pressure sensing also is crucial in various fields, and traditional sensors often pose challenges in terms of cost, accessibility, and environmental impact [11]. The demand for accessible, low-cost, and environmentally sustainable sensing solutions has driven research into alternative technologies. This paper presents a pioneering method utilizing common materials, namely paper and pencil, for the development of a low-cost and environmentally friendly pressure sensor.

Resistive flex sensors emerge as particularly attractive due to their lightweight nature, heightened sensitivity, low energy consumption, and user-friendly operation [12]–[14]. These sensors possess the unique ability to alter their electrical resistance in response to deflection. The flexibility of silicon substrates, achieved through processes like chemical-mechanical polishing reducing the substrate thickness to submicron levels, enhances the adaptability of such sensors [15]. Notably, paper, characterized by its softness, cost-effectiveness, and lightweight properties, has garnered considerable attention as an environmentally friendly substrate [16]–[18]. Previous research has explored paper-based sensors for various applications, including strain measurement, there remains a significant research gap in terms of leveraging common materials like paper and graphite to develop low-cost, environmentally sustainable sensors with enhanced performance characteristics. Due to economic considerations and environmental friendliness, there is a demand for integrating sensors using paper and pencil [19], [20]. Leveraging the conductivity of pencil graphite, there is a need to explore new sensor principles with simple fabrication techniques, making the sensor implementation accessible to everyone, especially for strain measurement applications. This paper explores the development and utilization of a paper-based sensor employing graphite from the pencil as a novel and cost-effective approach for strain measurement, investigating its performance characteristics and potential applications.

2. METHOD

2.1. Sensor design and principle

In this study, a novel paper-based sensor is crafted, leveraging graphite as the sensing element. The fabrication process involves the use of everyday materials such as standard paper, a regular pencil, a copper plate, and jumper wires. The sensor is assembled by depositing a conductive graphite trace onto the paper, creating a pattern designed to respond to applied pressure as shown in Figure 1(a). The integration of a copper plate enhances conductivity, while jumper wires facilitate electrical connections for seamless interfacing with measurement equipment. The sensor's response to applied pressure is governed by (1):

$$R = \frac{\rho L}{A} \tag{1}$$

where R represents resistance, ρ is resistivity, L is length, and A is the cross-sectional area. The underlying principle is straightforward: when pressure is exerted downward, the resistance increases. This behavior can be interpreted by the stretching of the graphite under pressure, altering the contact area (A). Figure 1(b) shows the graphite stretches, the physical separation between particles increases, impeding the free movement of electrons. Consequently, resistance rises proportionally to the applied force [21].

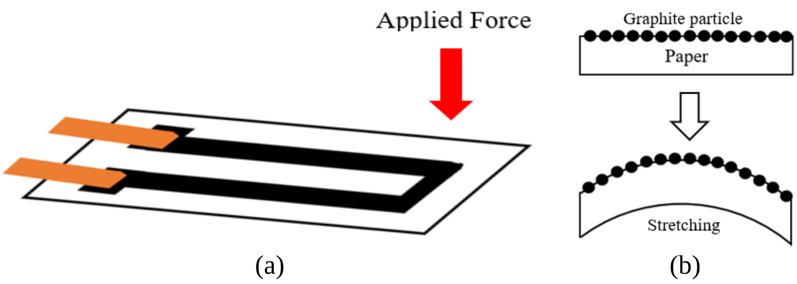

Figure 1. Sensor design: (a) sensor pattern which respond to applied force and (b) sensing mechanism of the sensor

2.2. Fabrication process

The fabrication begins with the use of a piece of paper (100gsm) dimension 7.5×2.0 cm, as illustrated in Figure 2(a). Using a 2B pencil, draw a thick and continuous line on the paper, ensuring uniformity and control over the graphite deposition. The drawing was repeated 10-15 times on the paper to ensure that the graphite layer is thick enough. The 2B pencil is chosen for its good performance in terms of hysteresis and sensitivity, as it readily responds to bending and stretching [20]. This step is depicted in Figure 2(b). After that, attach a rectangular copper plate as an electrode, accomplished by strategically placing the copper plate on the paper surface to ensure it comes into contact with the graphite trace. The copper plated is sealed using a piece of tape, as shown in Figure 2(c). Subsequently, the copper wire is soldered onto the surface of the copper plate, rendering the sensor prepared for measurement, as illustrated in Figure 2(d). Figure 2(e) provides a visual representation of the completed sensor. For the final step, conduct a simple test with continuity checks to ensure proper connections between the graphite trace, copper plate, and copper wire.

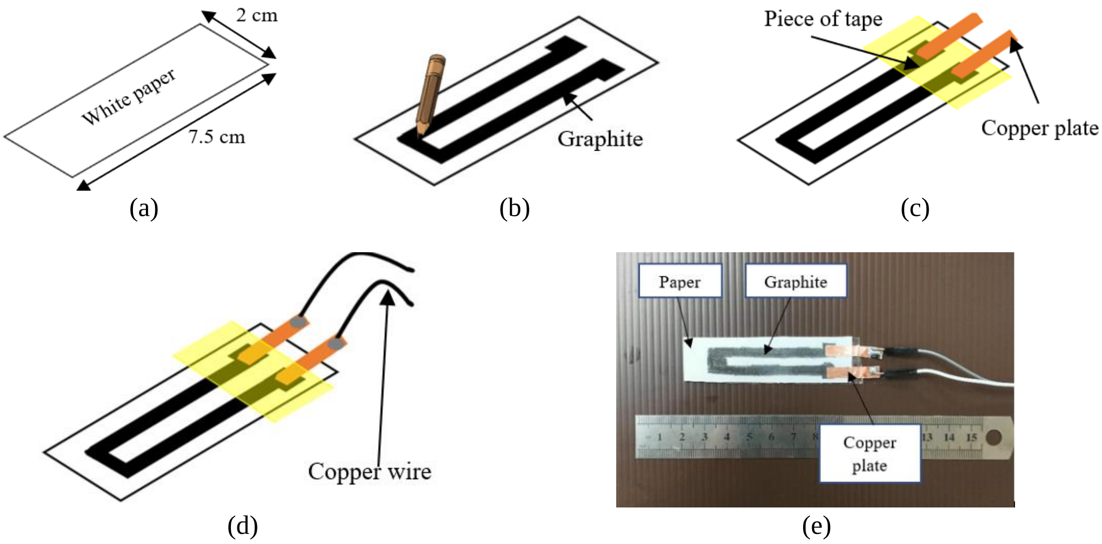

Figure 2. Sensor fabrication process: (a) starting from a piece of paper, (b) draw a thick and continuous line, (c) attach a copper plate, (d) copper wire is soldered onto the surface of copper plate, and (e) completed sensor fabrication

2.3. Experimental setup

Figure 3(a) shows the experimental setup for assessing the output response of the fabricated sensor. Precise evaluation and analysis of the sensor's output were conducted using an LCR meter (East Tester ET4410). The relationship between pressure and deflection has been discussed through analytical analysis. The experiment involved varying the angle of deflection (θ) from 0 to 60 degrees, with a protractor facilitating accurate angle measurements, as illustrated in Figure 3(b). The sensor's responses, recorded in terms of resistance, were systematically collected in triplicate to ensure robust data. An average response was computed for accuracy. Additionally, the sensor was attached to a finger to observe its behavior in diverse positions.

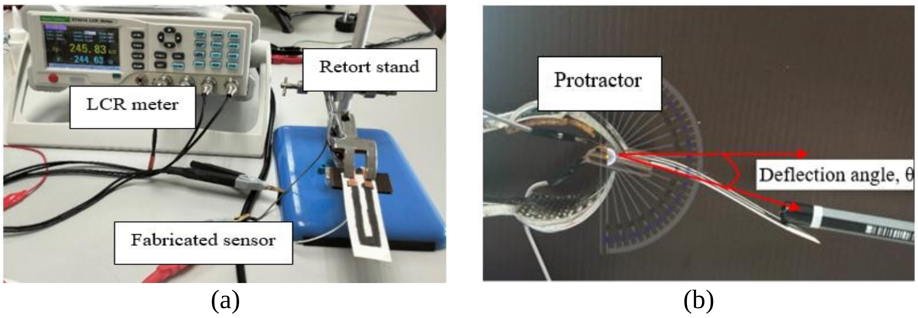

Figure 3. Experimental setup for the pressure measurement: (a) general setup and (b) varying the angle

3. RESULTS AND DISCUSSION

3.1. Relation between pressure and deflection

In this analytical analysis, we investigated the pressure-deflection relationship for a piece of paper configured as a cantilever beam. Clearly defining the cantilever's geometry and material properties, we applied the analytical bending equation derived from Euler-Bernoulli beam theory to express deflection (δ) and the angle of deflection (θ) as a function of applied pressure (P), Young's modulus (E), moment of inertia (I) and length of the beam [22].

$$\delta = \frac{PL^3}{3EI} \tag{2}$$

$$\theta = \frac{PL^2}{2EI} \tag{3}$$

The moment of inertia for the paper, which depends on the cross-sectional shape which rectangular cross section.

$$I = \frac{1}{12} bt^3 \quad (4)$$

Previous research indicates that the average Young's Modulus of A4 paper (100gsm) is 2.42 GPa [23]. Leveraging this established value, we anticipate the sensor's deflection under low applied pressure. This analytical approach reveals a linear relationship between pressure and deflection, as listed in Table 1 and plotted in Figure 4.

Table 1. The deflection in cm due to applied pressure

Applied pressure (kPa)	Deflection (cm)	Deflection angle (°)
1	1.033	8.557
2	2.066	17.155
3	3.099	25.753
4	4.132	34.351
5	5.165	42.949
6	6.198	51.547
7	7.231	60.145
8	8.264	68.743
9	9.297	77.341
10	10.33	85.939

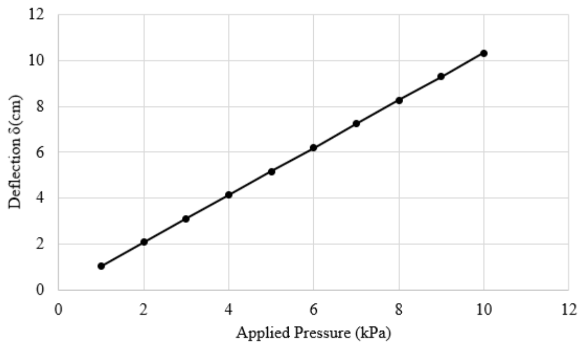

Figure 4. The pressure-defection relationship

3.2. Sensor response due to deflection

The evaluation of the fabricated sensor centered on assessing its linearity and sensitivity. Measurements were conducted by varying the deflection angle within a range of 0 to 60 degrees. The calculation of the relative change in resistance as shown in Table 2, reflecting sensor output variations from 0 to 0.05, was a key aspect of the analysis. As illustrated in Figure 5, the sensor's output response increases with the increasing deflection angle. This observed linearity is well-described by the linear fit equation.

$$y = 0.077x + 0.218$$

where y represents the relative change in resistance, and x denotes the deflection angle. The high goodness-of-fit is supported by a regression R^2 value of 0.991, affirming the proximity of the experimental data to the linear fit equation [24], [25]. The sensitivity sensor obtained is 0.077%.

Table 2. The relative change in resistance based on the deflection angle

Deflection angle (°)	Relative change in resistance, ΔR/R (%)			
	1st reading	2nd reading	3rd reading	Average
0	0.0000	0.0000	0.0000	0.0000
10	1.2448	1.2552	1.2511	1.2500
20	1.6597	2.0920	1.8764	1.8759
30	2.4896	2.2175	2.3547	2.3536
40	3.7344	3.1380	3.4363	3.4362
50	4.1493	3.3472	3.7273	3.7483
60	4.9792	4.6025	4.7914	4.7908

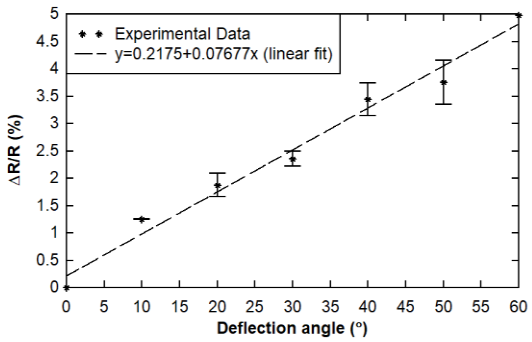

Figure 5. Relative change in resistance versus deflection angle with error bars

By using linear interpolation between the provided data in Table 1, the sensitivity of the sensor in terms of pressure can be calculated, which is equal to 0.64/kPa. From this experiment, we have demonstrated that, despite cost limitations and the use of eco-friendly materials, we can develop a simple sensor with the capability to detect low pressure. The sensitivity of our sensors was comparable to that of other similar paper-based sensors [26]. However, our sensor is specifically designed for pressure measurement applications.

3.2.1. Finger deflection response

During this phase, the sensor was affixed to the fingertip to investigate its response when situated on the finger. The finger underwent bending in three distinct positions, namely positions 1, 2, and 3, as depicted in Figure 6. This experiment delved into the analysis of hysteresis effects, wherein the finger underwent bending from position 1 (Figure 6(a)), position 2 (Figure 6(b)), and position 3 (Figure 6(c)) and subsequently returned to its original position, which is position 1. As we can see in Figure 7, the output increase as the finger is bend, and the maximum hysteresis which is 0.5% occur when the sensor is return to original position.

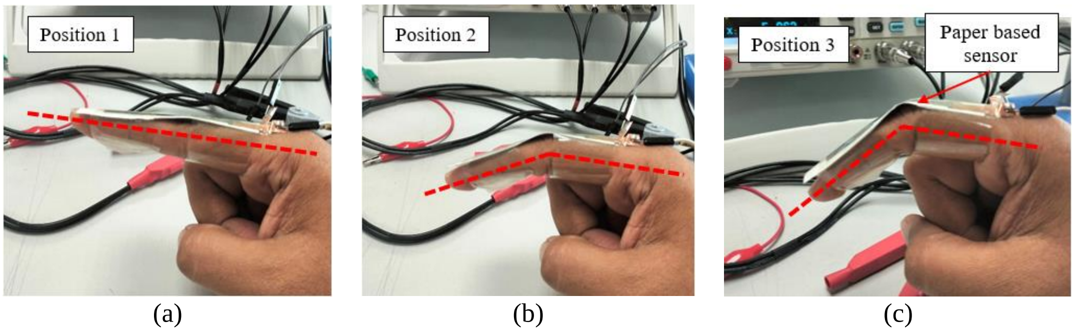

Figure 6. Three different positions of the finger: (a) position 1, (b) position 2, and (c) position 3

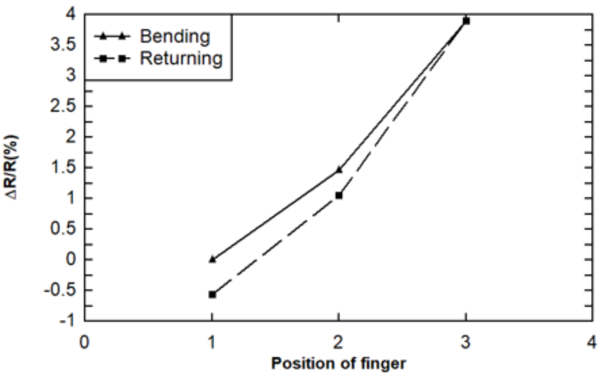

Figure 7. Sensor response due to finger bend

The occurrence of hysteresis in your paper-based sensor during a bending and return test can be attributed to various factors related to the materials and the mechanics of the system. Including, the bending and unbending of the sensor may alter the contact points between the graphite traces, affecting the overall resistance. Variations in contact resistance during deformation and relaxation can contribute to hysteresis. In conclusion, the experimental results demonstrate that the sensor fabricated by pencil drawing exhibits promising capabilities and possesses the potential to be utilized on flexible surfaces. This innovative approach holds significant promise in advancing the development of flexible and wearable sensing devices, as highlighted by previous research [27].

For the future work, it could focus on optimizing the sensor's material composition. Exploring alternative materials or coatings for the paper substrate may enhance conductivity and durability, broadening the sensor's applicability and environmental resilience. Simultaneously, there is a promising avenue for integration with smart systems or internet of things (IoT) platforms. Investigating methods to seamlessly incorporate paper-based sensors into connected networks could facilitate real-time data monitoring and communication, opening up possibilities for widespread deployment in various contexts.

4. CONCLUSION

Our research signifies a significant stride in the development of an affordable, eco-friendly, and responsive paper-based strain sensor through successful fabrication and testing. The sensor's simple design, involving paper, a graphite pencil, and a copper plate, emphasizes accessibility and environmental sustainability. Our investigation demonstrates the sensor's commendable performance in measuring pressure changes induced by deflection angles, showcasing a proportional increase in resistance with rising deflection angles. Real-world testing on a human finger further substantiates the sensor's practical applicability, confirming its responsiveness and adaptability across various positions. This innovative approach leverages low-cost and readily available materials, offering a cost-effective and accessible solution for sensor fabrication. By drawing upon previous research demonstrating the potential of pencil-drawn sensors. The use of graphite pencils as a tool for sensor fabrication may resonate with communities lacking access to specialized equipment or resources.

ACKNOWLEDGEMENTS

This research has been carried out under Fundamental Research Grants Scheme (FRGS/1/2021/STG07/UPSI/02/2) provided by Ministry of Education of Malaysia. The authors would like to extend their gratitude to UPSI that helped managed the grants. The authors also would like to thank all fellow research in the Faculty of Science and Mathematics, UPSI for their support and assistance throughout the work.

REFERENCES

[1] B. Zazoum, K. M. Batoo, and M. A. A. Khan, "Recent advances in flexible sensors and their applications," *Sensors*, vol. 22, no. 12, p. 4653, Jun. 2022, doi: 10.3390/s22124653.
[2] T. P. Huynh and H. Haick, "Autonomous flexible sensors for health monitoring," *Advanced Materials*, vol. 30, no. 50, Dec. 2018, doi: 10.1002/adma.201802337.
[3] A. Nag, S. C. Mukhopadhyay, and J. Kosel, "Wearable flexible sensors: A review," *IEEE Sensors Journal*, vol. 17, no. 13, pp. 949–3960, 2017, doi: 10.1109/JSEN.2017.2700078.
[4] J. L. T. Ho, M. N. M. Nawi, and M. F. A. Rahman, "Analytical analysis of flexible microfluidic based pressure sensor based on triple-channel design," *EMITTER International Journal of Engineering Technology*, vol. 11, no. 2, pp. 234–245, Dec. 2023, doi: 10.24003/emitter.v11i2.798.
[5] H. S. Park, Y. Shin, S. W. Choi, and Y. Kim, "An integrative structural health monitoring system for the local/global responses of a large-scale irregular building under construction," *Sensors (Basel, Switzerland)*, vol. 13, no. 7, pp. 9085–9103, Jul. 2013, doi: 10.3390/s130709085.
[6] P. R. Croft, G. J. Macfarlane, A. C. Papageorgiou, E. Thomas, and A. J. Silman, "Outcome of low back pain in general practice: A prospective study," *British Medical Journal*, vol. 316, no. 7141, pp. 1356–1359, 1998, doi: 10.1136/bmj.316.7141.1356.
[7] X. W. Ye, Y. Q. Ni, K. Y. Wong, and J. M. Ko, "Statistical analysis of stress spectra for fatigue life assessment of steel bridges with structural health monitoring data," *Engineering Structures*, vol. 45, pp. 166–176, 2012, doi: 10.1016/j.engstruct.2012.06.016.
[8] M. A. Zawawi, S. O'Keeffe, and E. Lewis, "Plastic optical fibre sensor for spine bending monitoring with power fluctuation compensation," *Sensors (Switzerland)*, vol. 13, no. 11, pp. 14466–14483, Oct. 2013, doi: 10.3390/s131114466.
[9] Z. Ma and X. Chen, "Fiber bragg gratings sensors for aircraft wing shape measurement: Recent applications and technical analysis," *Sensors (Switzerland)*, vol. 19, no. 1, 2019, doi: 10.3390/s19010055.
[10] C. S. Lynch, "Strain measurement," *Mechanical Variables Measurement-Solid, Fluid, and Thermal*, pp. 1–3, 2023.
[11] Y. Huang, X. Fan, S. C. Chen, and N. Zhao, "Emerging technologies of flexible pressure sensors: Materials, modeling, devices, and manufacturing," *Advanced Functional Materials*, vol. 29, no. 12, Mar. 2019, doi: 10.1002/adfm.201808509.
[12] G. Saggio, F. Riillo, L. Sbernini, and L. R. Quitadamo, "Resistive flex sensors: A survey," *Smart Materials and Structures*, vol. 25, no. 1, pp. 2–31, 2015, doi: 10.1088/0964-1726/25/1/013001.

[13] Z. Lou, L. Wang, and G. Shen, "Recent advances in smart wearable sensing systems," *Advanced Materials Technologies*, vol. 3, no. 12, 2018, doi: 10.1002/admt.201800444.
[14] K. Xu, Y. Lu, and K. Takei, "Multifunctional skin-inspired flexible sensor systems for wearable electronics," *Advanced Materials Technologies*, vol. 4, no. 3, 2019, doi: 10.1002/admt.201800628.
[15] J. L. Tanner, D. Mousadakos, P. Broutas, S. Chatzandroulis, Y. S. Raptis, and D. Tsoukalas, "Nanoparticle strain sensor," *Procedia Engineering*, vol. 25, pp. 635–638, 2011, doi: 10.1016/j.proeng.2011.12.158.
[16] S. M. Khan, J. M. Nassar, and M. M. Hussain, "Paper as a substrate and an active material in paper electronics," *ACS Applied Electronic Materials*, vol. 3, no. 1, pp. 30–52, 2021, doi: 10.1021/acsaelm.0c00484.
[17] C. Zhang *et al.*, "Batch fabrication of paper-based waterproof flexible pressure sensors enabled by roll-to-roll lamination," *ACS Applied Materials and Interfaces*, vol. 15, no. 35, pp. 41950–41960, 2023, doi: 10.1021/acsami.3c09587.
[18] H. Xiang *et al.*, "Enabling a paper-based flexible sensor to work under water with exceptional long-term durability through biomimetic reassembling of nanomaterials from natural wood," *ACS Sustainable Chemistry and Engineering*, vol. 11, no. 23, pp. 8667–8674, 2023, doi: 10.1021/acssuschemeng.3c01870.
[19] Y. Liu, H. Wang, W. Zhao, M. Zhang, and H. Qin, "Pencil-on-paper flexible electronics for daily sensing applications," *Circuit World*, vol. 45, no. 4, pp. 189–195, 2019, doi: 10.1108/CW-05-2018-0037.
[20] S. K. Mahadeva, K. Walus, and B. Stoeber, "Paper as a platform for sensing applications and other devices: A review," *ACS Applied Materials and Interfaces*, vol. 7, no. 16, pp. 8345–8362, 2015, doi: 10.1021/acsami.5b00373.
[21] A. S. Kurian, V. B. Mohan, H. Souri, J. Leng, and D. Bhattacharyya, "Multifunctional flexible and stretchable graphite-silicone rubber composites," *Journal of Materials Research and Technology*, vol. 9, no. 6, pp. 15621–15630, 2020, doi: 10.1016/j.jmrt.2020.11.021.
[22] K. J. Rawson and E. C. Tupper, *Basic ship theory volume 1*, vol. 1. Butterworth-Heineman, 2001.
[23] R. Munir, H. D. Rahmayanti, N. Amalia, F. D. Utami, S. Viridi, and M. Abdullah, "Investigation of mechanical properties for non-homogeneous by image tracking method," *Materials Today: Proceedings*, vol. 44, pp. 3415–3419, 2020, doi: 10.1016/j.matpr.2020.12.1158.
[24] C. Hagquist and M. Stenbeck, "Goodness of fit in regression analysis-R2 and G2 reconsidered," *Quality and Quantity*, vol. 32, no. 3, pp. 229–245, 1998, doi: 10.1023/A:1004328601205.
[25] P. Allison, "What's the best R-squared for logistic regression," *Statistical Horizons*, vol. 13, 2023.
[26] C. W. Lin, Z. Zhao, J. Kim, and J. Huang, "Pencil drawn strain gauges and chemiresistors on paper," *Scientific Reports*, vol. 4, no. 1, p. 3812, 2014, doi: 10.1038/srep03812.
[27] X. Liao *et al.*, "Flexible and highly sensitive strain sensors fabricated by pencil drawn for wearable monitor," *Advanced Functional Materials*, vol. 25, no. 16, pp. 2395–2401, 2015, doi: 10.1002/adfm.201500094.

BIOGRAPHIES OF AUTHORS

Mohd Norzaidi Mat Nawi received his B.Eng. degree in Mechatronic Engineering and Ph.D. degree in Electrical and Electronic Engineering from Universiti Sains Malaysia, Nibong Tebal, Malaysia, in 2010 and 2015, respectively. His research focuses on liquid-based capacitive and resistive types of sensors. He can be contacted at email: norzaidi@fsmt.upsi.edu.my.

Jim Tze Ho Lau received his B.Ed. degree in Physics Education from Universiti Pendidikan Sultan Idris in 2021. He is currently pursuing his M.Sc. degree in Physics, with his primary focus on liquid based flexible pressure sensors. He can be contacted at m20211002714@siswa.upsi.edu.my.