Design, Fabrication, and Characterization of Paper-Based Flexible Sensor for Wearable Applications

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***Abstract*—This study presents the design, fabrication, and evaluation of a cost-effective paper-based flexible sensor for wearable applications, specifically motion detection. Utilizing filter paper as a substrate, the sensor is coated with graphite for conductivity and enhanced with sodium chloride (NaCl) to boost ionic dissociation and sensitivity. The fabrication process employs low-cost and sustainable materials and methods, yielding a sensor with high responsiveness, repeatability, and durability. Comparative analysis with commercial silicon-based sensors demonstrates the paper sensor's superior sensitivity to small angular changes, albeit with slightly lower stability. Optimal dimensions of 6 cm × 1 cm are identified by balancing sensitivity and mechanical stability. Integration with a microcontroller facilitates real-time data acquisition, showcasing the potential of assistive devices, gesture recognition, and healthcare monitoring. This work highlights the feasibility of paper-based sensors as accessible alternatives to conventional silicon-based technologies, aligning with environmental sustainability goals, and cost-effectiveness.**

***Index Terms*—Paper-based, Flex Sensor, Graphite-Coated Sensors, Sustainable Sensor, Wearable Technology.**

I. Introduction

Flex sensors have gained significant attention due to their ability to accurately measure bending or flexing in a structure, making them indispensable in various fields such as robotics, wearable technology, healthcare, and gesture-controlled systems. These sensors operate on the principle of changing resistance in response to physical deformation, enabling precise detection and quantification of angular or positional changes [1]. Despite their versatility and effectiveness, traditional flex sensors, often made from silicon or other synthetic materials, come with high manufacturing costs and environmental concerns related to material disposal. This has driven the demand for cost-effective and eco-friendly alternatives that retain or even enhance the performance of conventional flex sensors while addressing sustainability challenges. Developing such alternatives reduces environmental impact and makes this technology more accessible for broader applications, particularly in emerging markets and resource-limited settings.

Flex sensors have shown tremendous potential in applications requiring precise motion detection [2]. Their utility spans various domains, including robotics, wearable technology, medical devices, natural disaster detection, and other advanced technological sectors [2], [3]. By monitoring and measuring angular displacement, these sensors provide critical data essential for technological advancements and medical innovations [1].

In robotics, flex sensors are employed to observe and control the movement of robotic limbs and joints, enabling precise and smooth operations [4]. Wearable technology, enhances the functionality of smart clothing and devices, enabling accurate monitoring of body movements. This capability has improved the performance of fitness trackers and health-monitoring devices [5], [6], [7]. In the medical field, flex sensors play a pivotal role in applications such as prosthetics, where they provide critical feedback on limb positioning to develop responsive and functional artificial limbs [8], [9]. Additionally, they are integral to rehabilitation devices, allowing healthcare providers to monitor and optimize patient progress effectively.

Flex sensors are also gaining prominence in artificial intelligence-driven human-machine interface applications and human activity monitoring systems, such as breath and pulse monitoring [10]. These applications expand their utility to tasks like emotion recognition, knee motion monitoring, and human movement analysis, offering significant advancements in automation and data-driven decision-making [11], [12].

The effectiveness of flex sensors relies heavily on the materials used in their fabrication, as these must exhibit both flexibility and conductivity under bending stress, typically at the centimetre scale. Commonly employed materials include conductive polymers, metallic inks, and various metals such as copper (Cu), silver (Ag), gold (Au), platinum (Pt), aluminium (Al), chromium (Cr), nickel (Ni), magnesium (Mg), and molybdenum (Mo). These materials are chosen for their superior mechanical properties, high conductivity, and ability to maintain performance under repeated bending and flexing [3], [11].

Conductive polymers are desirable due to their inherent flexibility and lightweight nature, making them ideal for wearable and portable applications. Metallic inks, on the other hand, offer excellent conductivity and compatibility with advanced fabrication techniques like screen printing, enabling precise and scalable production. The metallic elements used in flex sensors, such as silver and gold, provide exceptional electrical conductivity and corrosion resistance, although their high cost can be a limiting factor in large-scale or cost-sensitive applications.

The choice of material directly impacts the sensor's durability, sensitivity, and overall performance, making material selection a critical factor in the design and development of reliable flex sensors. Continued advancements in materials science and fabrication techniques aim to address challenges such as cost reduction, environmental sustainability, and enhanced sensor performance, further broadening the scope of flex sensor applications across diverse industries [3], [11].

Despite their wide range of applications, conventional flex sensors have some major drawbacks:

- **Environmental Impact and Health Issues**: Commercially available flex sensors are manufactured using materials that harm human health for instance, certain conductive inks and polymers used in conventional flex sensors contain toxic substances that pose risks not only during manufacturing and handling but also in their disposal [7], [13]. In addition, they are not suitable for direct contact with the human body, making them unsafe for wearable or biomedical applications. These components make such sensors unsuitable for direct contact with the human body.
- **Production Costs**: The manufacturing processes involved in such sensors are usually complicated and expensive, requiring specialist equipment and clean room environments, which makes them unsuitable for low-cost applications.

Considering this issue, our research aims to develop flexible sensors made from paper as an alternative to harmful materials. This approach will make the sensors more environmentally friendly and cost-effective. We hope to create a new kind of innovative flex sensor that can be used in various applications, promoting sustainability and accessibility.

The rest of the paper is structured as follows, section I introduces the work. This is followed by section II, which talks about the sensor fabrication techniques and subsequent experiments with it.

II. Development and Experimental Testing of Paper Sensor

In this section, we have fabricated the sensor, and the detailed fabrication technique is described in Subsection A. In contrast, the experimental setup is described in the following Subsection B.

A. Sensor Devlopment

- **Material selection:**

Grade A filter paper, with a thickness ranging from 0.17 mm to 0.93 mm, was selected as the substrate for the flex sensor due to its lightweight, flexible, and porous structure. A 10B high-quality graphite pencil was used to coat the paper evenly, forming a conductive electrode. The thin copper tape was applied to both edges of the sensor, serving as a probe to facilitate electrical connections. To provide mechanical support, an old X-ray plate was repurposed as a flexible backing. Additionally, distilled water and sodium chloride (NaCl), commonly available as table salt, were employed during the fabrication process to enhance conductivity.

- **Chemical Properties**

The chemical properties of graphite and sodium chloride (NaCl) are integral to the sensor's enhanced performance:

(a) Graphite: Graphite, a crystalline form of carbon, is characterized by its excellent electrical conductivity, approximately 3×10^3 S/m. Its honeycomb-like layered structure consists of hexagonally arranged carbon atoms, where delocalized electrons move freely between layers, enabling efficient electrical conduction. This layered structure also imparts flexibility, making graphite suitable for applications requiring mechanical deformation, such as flex sensors [14], [15], [16], [17].

(b) Sodium Chloride (NaCl): When dissolved in distilled water, NaCl dissociates into sodium (Na^+) and chloride (Cl^-) ions, as represented by the dissociation equation:

$$\text{NaCl (s)} \xrightarrow{\text{H}_2\text{O}} \text{Na}^+(\text{aq}) + \text{Cl}^-(\text{aq})$$

These ions enhance the sensor's conductivity through ionic conduction, which complements the electronic conduction provided by graphite. This synergistic effect significantly improves the sensor's sensitivity and performance.

This process generates sodium (Na^+) and chloride (Cl^-) ions, enhancing the graphite-coated paper's electrical conductivity. These ions stabilize the electrical pathways, improving the sensor's sensitivity and responsiveness to mechanical deformations. The combination of graphite's conductive, layered structure and NaCl's ionic dissociation significantly enhances the sensor's overall performance across various applications [18].

- **Geometry selection:**

Then the outline structure of the sensor is drawn on the filter paper and the area is filled by the pencil graphite as shown in fig.1

- **Sensor fabrication:**

The sensor fabrication process begins by first outlining the sensor on a piece of white filter paper, as shown in Fig. 1. Step (i), measuring 6 cm × 1 cm. Once the outline is complete, the next step (ii) involves filling the designated area with graphite using a 10B graphite pencil. This step is crucial to create a consistent, even layer of graphite, which serves as the primary conductive element of the sensor.

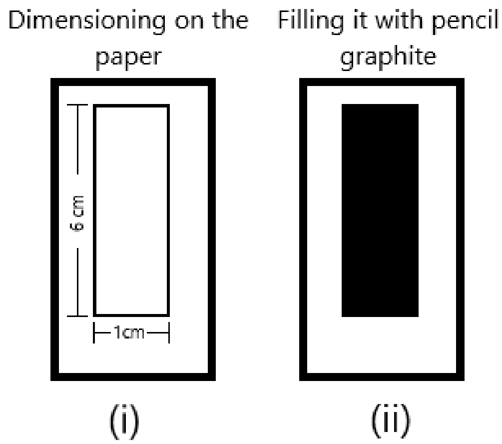

Fig. 1. Geometric dimensions of the sensor

Step (iii) after applying the graphite layer, a layer of sodium chloride (NaCl) solution is applied using a dropper on the surface of the sensor where graphite is deposited ensuring complete coverage as shown in Fig.2. This solution was prepared by dissolving 1 gram of common kitchen salt (NaCl) in 5 ml of distilled water (H_2O), achieving a solubility ratio of 1g/5ml. Then the paper is left to dry overnight under normal room conditions. This step enhances the electrical conductivity of the graphite by introducing ions from the NaCl solution, which improves the sensor's sensitivity.

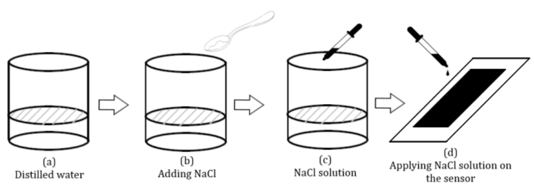

Fig. 2. Step (iii) (a-d) Schematic demonstration of NaCl solution preparation and application on the sensor.

Once the paper is completely dry, an X-ray plate is affixed to the backside, and copper tape is placed at both ends of the graphite-coated area to act as electrical probes. A transparent protective layer is then added to cover the graphite-coated portion, safeguarding it from physical damage and environmental interference while maintaining its flexibility as shown in fig.3 step (iv).

In the final fabrication stage, two wires are soldered to the copper tape at each end of the sensor. These wires provide the necessary electrical connections, allowing the sensor to be integrated into external circuits for testing and use, as illustrated in Fig.3 step (v) and Fig.4.

B. Data Collection setup

The paper-based flex sensor was interfaced with an ATmega328P microcontroller (Arduino UNO) through a voltage

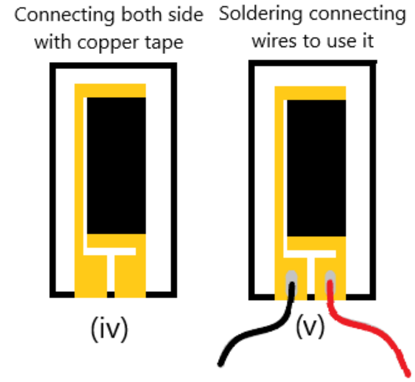

Fig. 3. The completely developed paper sensors.

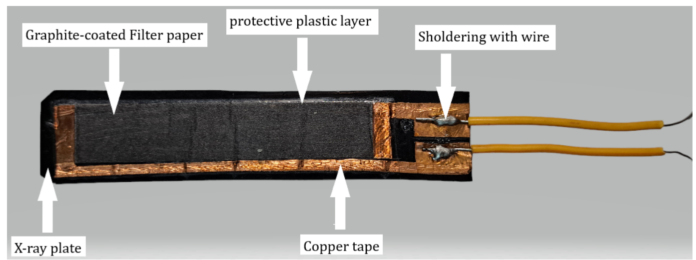

Fig. 4. Completely developed Paper-based Flex sensors.

divider circuit. The circuit consists of a fixed resistor R_1, with a resistance of 1Ω, and the paper sensor R_2, as a variable resistor. The output of the voltage divider is connected to an analogue A0 pin of the microcontroller. This particular microcontroller has a 10-bit ADC that produces values ranging between 0 and 1023 (1024 levels) [19], [20], [21]. An Arduino board is utilized to configure communication between the sensor and the computer [22]. The sensor data is observed through the serial monitor for continuous monitoring and the serial plotter for real-time graph display [20]. This configuration ensures optimal analogue-to-digital conversion (ADC) values, crucial to accurately detecting resistance changes in response to mechanical flexion as shown in Fig. 5.

The output voltage across R_2, denoted as V_{out} is given by the following voltage divider equation:

$$V_{\text{out}} = V_{\text{in}} \times \frac{R_2}{R_1 + R_2}$$

where V_{in} is the applied input voltage. As the sensor flexes, R_2 varies, producing a proportional change in V_{out}, which the ATmega328P interprets via its ADC. This method provides a reliable means of translating the sensor's mechanical response into measurable electrical data for analysis and characterization.

In our setup, the voltage divider circuit is configured with $R_1 = 1\,\Omega$, $R_2 = 34\,\Omega$, and $V_{\text{in}} = 5\,\text{V}$. The output voltage V_{out} across R_2 can be calculated as:

$$V_{\text{out}} = V_{\text{in}} \times \frac{R_2}{R_1 + R_2} = 5\,\text{V} \times \frac{34\,\Omega}{1\,\Omega + 34\,\Omega}$$

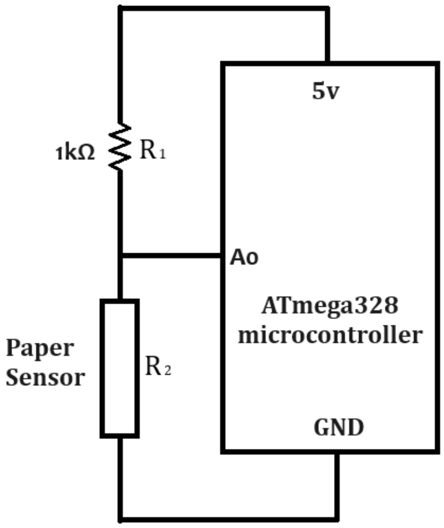

Fig. 5. The associated circuitry for data collection.

$$V_{\text{out}} = 5\,\text{V} \times \frac{34}{35} \approx 4.86\,\text{V}$$

The choice of a 1-ohm resistor R_1 is intentional to maximize the voltage drop across R_2, the paper-based flex sensor, which enhances the sensitivity of V_{out} changes R_2. This configuration ensures that even minor variations in the sensor resistance due to flexion produce a measurable change in output voltage, providing more accurate ADC values for precise data acquisition.

The sensor has two wires interfacing with the circuit, secured by paper clips at both ends. One side is fixed with a protractor to measure precise, error-free values according to the angle. This setup facilitates real-time monitoring of the sensor's performance shown in Fig. 6. During the experiment, raw data from the Arduino serial monitor were converted into voltage values using a specific equation.(1).

$$Voltage = ADCvalue \times \frac{5}{1023} \tag{1}$$

This conversion allowed for the precise measurement of voltage changes corresponding to the bending angles of the sensors.

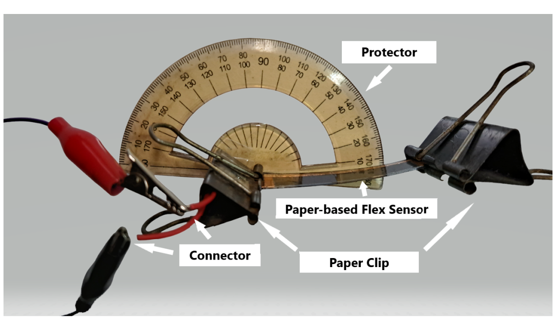

Fig. 6. Calibration setup.

- **Optimal Length and Dimension Selection**
  After the preparation of the sensors is completed, there was a need to ensure accurate measurements like the market-available flex sensor so it is created two types of paper-based flex sensors by systematically varying their physical characteristics as shown in Fig.7 First, it is adjusted the length of the sensors from 3 cm to 10 cm while maintaining a fixed width in table I. Second, it is altered the width of the sensors between 0.5 cm and 1.75 cm while keeping the length constant in table II. Each configuration's initial resistance R_0 is measured throughout this process to identify the most effective design compared to commercially available flex sensors.

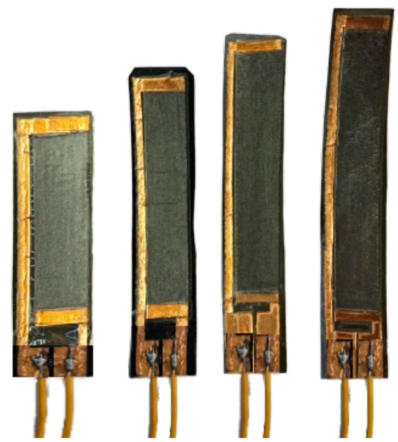

Fig. 7. Some examples of different dimensioned paper-based flex sensors.

The experiment was conducted by individually connecting each sensor of varying dimensions to a multimeter and measuring their internal Resistance (R_0) before using. The measured values shown in Tables I and II.

TABLE I
CHANGE IN RESISTANCE WITH VARYING LENGTH BY KEEPING WIDTH 1 CM CONSTANT

Sl. No.	Dimension Length cm	Internal resistance R_0 (KΩ)
1	3	∼18
2	4	∼22
3	5	∼27
4	6	∼34
5	7	∼52
6	8	∼76
7	9	∼84
8	10	∼106

Our analysis revealed that the resistance of the paper-based flex sensor is directly proportional to its length as shown in table I and inversely proportional to its width according to table II, this is because a longer path for

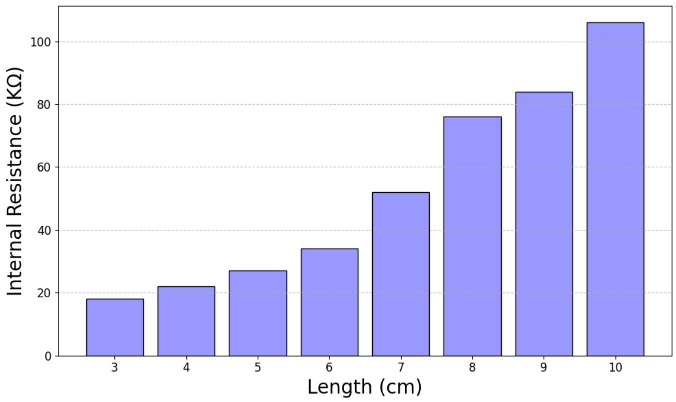

Fig. 8. Measured internal resistance (R_0) for Varied Lengths.

TABLE II
CHANGE IN RESISTANCE WITH VARYING WIDTH BY KEEPING LENGTH 6 CM CONSTANT

Sl. No.	Dimension Width cm	Internal resistance R_0 (KΩ)
1	0.5	$\sim$60
2	1	$\sim$34
3	1.25	$\sim$27
4	1.5	$\sim$19
5	1.75	$\sim$15

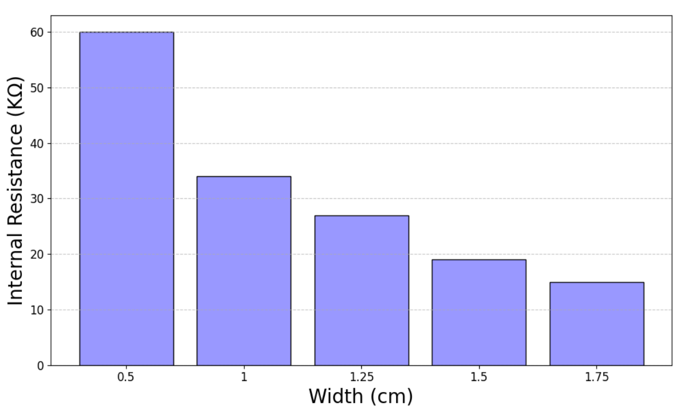

Fig. 9. Measured internal resistance(R_0) for Varied Widths.

the electric current results in more resistance due to the greater distance the current has to travel through the graphite-coated paper. Conversely, increasing the width of the paper decreases the resistance. A wider sensor provides a larger cross-sectional area for the current to pass through, reducing resistance. These findings are consistent with the principles of electrical resistance, where resistance R is given by the formula 2:

$$R = \rho \frac{L}{A} \tag{2}$$

where ρ is the material's resistivity, L is the length, and A is the cross-sectional area. In this context, increasing the length increases L, thus increasing R, while increasing the width increases A, thereby decreasing R [23].

III. RESULTS AND DISCUSSIONS

After analyzing all the data, it is determined that a sensor dimension of 6 cm × 1 cm provides a balanced initial resistance and demonstrates stability and responsiveness in multiple trials. These dimensions offer the ideal balance between sensitivity and durability, ensuring reliable performance for extended use. Additionally, this configuration is compatible with standard market flex sensors, allowing seamless integration into existing systems. The chosen dimensions effectively maximize the sensor's mechanical response while minimizing variability in initial resistance readings, making it highly suitable for applications.

A. *Scheme of the proposed sensor*

The operation of the graphite-based paper sensor under bending conditions can be understood through the following sequential process Fig.10 The molecular distance between

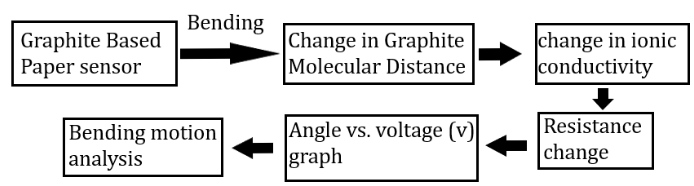

Fig. 10. Schematic block diagram of bending motion.

the graphite particles changes when the graphite-coated paper sensor is bent. This alteration in molecular spacing directly affects the sensor's ionic conductivity, for that reason, the closer or farther positioning of graphite molecules influences the movement of ions across the material.

This molecular adjustment causes a change in the sensor's electrical resistance. This resistance variation is a critical indicator of the sensor's response to bending. Subsequently, the sensor's output can be visualized through an angle vs. voltage (V) graph, capturing the voltage response as a function of the bending angle.

Finally, the bending motion of the sensor is analyzed based on this graph, enabling the characterization of the sensor's performance in terms of sensitivity and reliability. This process highlights the ability of the graphite-based paper sensor to detect bending motions through resistance changes, providing valuable information for applications that require flexible sensors.

B. *Comparison of Paper-Based and Silicon-Based Flex Sensors*

The performance comparison between a paper-based flex sensor and a commercially available silicon-based flex sensor, both having an internal resistance of approximately $R_0 \sim$

$34\,\mathrm{k\Omega}$, is illustrated in Fig. 11. The relationship between the bending angle and the corresponding output voltage for each sensor is presented in Fig. 12, demonstrating their respective performance characteristics.

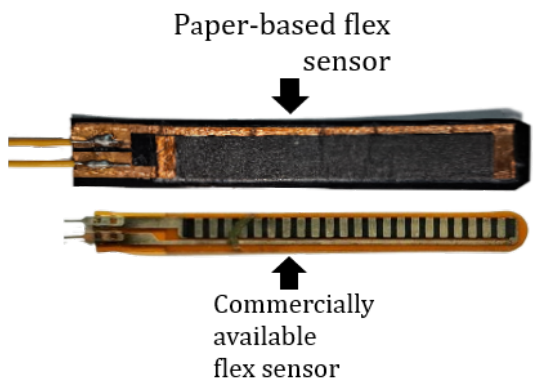

Fig. 11. Commercial silicon-based flex sensor and paper-based flex sensor.

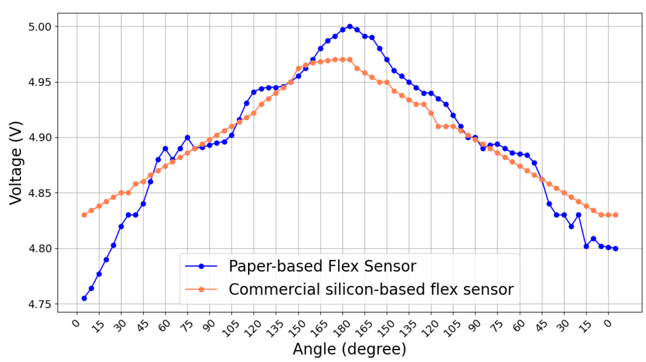

Fig. 12. characteristic curve between commercial silicon-based flex sensor and paper-based flex sensor.

1) **Sensitivity:**
The sensitivity of both sensors was measured by calculating the upward and downward slopes of the graph using the following formula:

$$m = \frac{\Delta \text{Voltage}}{\Delta \text{Angle}}$$

TABLE III
CHANGE IN SLOPE BETWEEN PAPER-BASED FLEX SENSOR AND COMMERCIAL SILICON-BASED FLEX SENSOR

Slope	Paper-based flex sensor	Commercial silicon-based flex sensor
Up	0.0022	0.0007
Down	0.0012	0.0009
Difference	0.001	-0.0002

As shown in Table III, the difference between the upslope and downslope for the paper-based sensor is 0.001, while for the commercially available silicon-based sensor, it is -0.0002. These results demonstrate that the sensitivity of the silicon-based sensor is slightly superior to that of the paper-based sensor.

2) **Trend Analysis:**
In fig. 12 the paper-based flex sensor (represented by the blue line) begins with a lower voltage value at an initial angle of 0° than the commercial sensor. This suggests the paper-based sensor has a relatively higher initial resistance or is less sensitive to small angular changes at the start. As the angle increases, the serial value for both sensors increases, peaking between 90° and 120°. It then gradually declines symmetrically as the angle returns to 0°.
The silicon flex sensor (orange line) demonstrates a smoother, more linear increase in voltage value as the angle increases, in contrast to the paper-based sensor, which shows steeper fluctuations. This highlights that the silicon sensor has more consistent responses to varying angles, while the paper sensor is more variable in its sensitivity.

3) Peak and Slope Behavior:
The peak voltage for the paper-based sensor is approximately 5v, while the silicon sensor reaches a lower peak of around 4.97v. The sharper and steeper slopes observed in the paper-based sensor data indicate more dramatic changes in resistance in response to flexing, especially in the middle range of angles. This suggests that the paper sensor may offer greater sensitivity to bending but at the cost of reduced smoothness in its response curve. Conversely, the silicon sensor shows a more gradual incline and decline, highlighting its stability and consistency across a broader range of motion. This makes it more suited for applications where uniform and predictable sensor responses are critical.

4) Responsiveness:
The paper-based sensor is more responsive to small changes in angle, particularly in the ranges of 0°-40° and 140°-180°, where it shows steeper slopes compared to the silicon sensor. This heightened sensitivity could make the paper sensor a better choice for tasks requiring fine detection of angular changes, though it might result in more noise in environments where stability is needed. On the other hand, the silicon sensor demonstrates more consistent and smoother changes in serial value, suggesting it would perform better in applications requiring gradual and predictable transitions.

C. High Sensitivity to Angle Changes according to dimension wise

The paper-based flex sensor demonstrated high sensitivity to small angle changes. This sensitivity is a significant advantage, as it allows for detecting minute flexion, making the sensor suitable for applications requiring precise angle measurements.

The high sensitivity can be attributed to the fine and responsive nature of the graphite-coated paper, which changes resistance with minimal bending. In our case, the best sensing results are 6 cm x 1 cm.

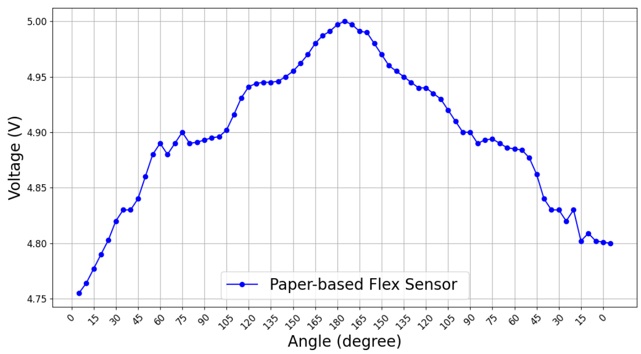

Fig. 13. Sensitivity according to dimension

In the sensor of dimension 6 cm x 1 cm, the sensitivity for each degree bending is 0.0107526882 volt as shown in Fig.13.

D. Sensors Repeatability, durability and consistency test

A comparison of the voltage responses of the paper-based flex sensor between its first and twentieth uses, as shown in Fig. 14, demonstrates the sensor's reliability and stability under repeated bending. The voltage response curves for both tests were closely aligned, highlighting the ability of the sensor to maintain consistent performance across multiple cycles. Both curves exhibit similar patterns over the entire angular range (0°–180°), indicating that the sensor's sensitivity to angle changes remains largely unaffected by repeated use.

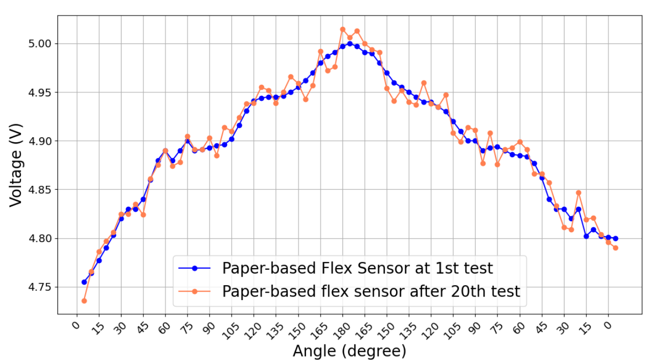

Fig. 14. Repeatability test of same sensor at 1st use and in 20th use.

In terms of peak voltage, the sensor consistently reached a maximum value of approximately 5V for both tests. This consistency suggests that the graphite coating retains its conductive properties and the sensor maintains its electrical integrity despite multiple bending cycles. While minor deviations were observed in certain regions of the curve, particularly between angles of 60° and 120°, these variations were subtle and could be attributed to slight changes in the graphite coating or the inherent flexibility of the paper substrate. Importantly, these discrepancies did not significantly affect the overall performance or the accuracy of the sensor.

The stability of the shape and alignment of the voltage response curves reinforces the repeatability of sensor measurements. The sensor demonstrated a reliable response during both upward and downward sweeps of the angle, ensuring accurate and consistent measurements across repeated tests. The paper substrate's resilience and the graphite coating's robustness emphasize the sensor's durability, making it a strong candidate for applications that involve frequent and repetitive bending.

A comparison with commercially available sensors showed that the paper-based flex sensors performed better. Notably, a 50-rupee commercial flex sensor begins to show instability after repeated cycles, often producing inaccurate readings due to wear and a loss of sensitivity in its conductive layer. In contrast, the paper-based flex sensor remained functional and delivered accurate measurements, albeit with minor noise. The paper-based sensor's ability to maintain reliable performance in conditions where the commercial sensor fails underscores its robustness and superior durability. This ensures that even in high-frequency use or extended testing scenarios, the sensor continues to provide dependable results.

Overall, the comparison between the first and twentieth uses highlights the durability, repeatability, and stability of paper-based flex sensors. Its ability to maintain consistent peak voltage values and voltage response behaviour across multiple bending cycles validates its potential for long-term use in various practical applications.

IV. Potential Application

The innovative paper-based flex sensor developed in this research addresses several pressing challenges across diverse fields. Its high sensitivity, cost-effectiveness, and user-friendliness make it an ideal candidate for solving problems in assistive technology, interactive gaming, and product development. Below are three significant applications that utilize the unique capabilities of the sensor:

A. Assistive Glove for Disability Support

The paper-based flex sensor can be used effectively in the development of an assistive glove that aims to improve accessibility for individuals with physical disabilities [1]. Current assistive devices, such as gesture-controlled wheelchairs or smart home systems, often rely on expensive silicon-based sensors, making them less accessible to a broader audience [11]. By integrating the paper-based flex sensor into a glove, finger movements can be accurately detected as resistance changes and translated into gestures for controlling devices. This approach not only reduces the cost and weight of such systems but also provides an environmentally friendly alternative, offering a practical solution to enhance the independence and quality of life for users.

B. Use in Modern Gesture-Based Gaming industry

In the gaming industry, the paper-based flex sensor offers a cost-effective and sensitive option to create gesture-based controllers. Advanced gesture-control devices used in gaming are typically expensive, restricting their availability. The paper-based flex sensor, due to its high sensitivity and affordability, can be embedded in wearable gaming controllers to track finger and hand movements for an immersive gaming experience. This application democratizes gesture-based gaming by making it more accessible to a wider audience while reducing existing technologies' environmental footprint.

C. Bending Angle Detection in Products

The paper-based flex sensor has immense potential in robotics and other applications requiring precise bending angle detection. Robotic limbs and joints depend on accurate feedback to enable smooth, controlled movements. Conventional bending angle sensors are often costly and environmentally harmful, making them less viable for scalable or sustainable designs. The paper-based flex sensor, with its high sensitivity to angular changes, can be integrated into robotic systems to monitor and control movement effectively.

V. Conclusion

The paper-based flex sensor developed in this research significantly advances sustainable, user-friendly, and cost-effective sensing technology. Its construction, using a graphite-coated grade 1 filter paper enhanced with sodium chloride, provides a compelling alternative to conventional silicon-based flex sensors, which often face challenges related to high production costs and environmental concerns. The fabricated sensor exhibited high sensitivity, repeatability, and durability during testing, making it suitable for a variety of applications. The optimal dimensions of 6 cm × 1 cm ensured a balance between sensitivity and mechanical stability, proving its potential for integration into real-world systems.

Hand-made sensors are susceptible to human error, particularly in the concentration of graphite applied [24]. To mitigate this issue and improve accuracy, a CNC plotter can be utilized. The CNC plotter ensures precise control over the application of graphite, thereby reducing human error and enhancing the consistency and reliability of the sensors. [25].

The versatility of the sensor was highlighted through potential applications, including assistive gloves for individuals with disabilities, gesture-based controllers for gaming, and bending angle detection in robotics and smart textiles. These examples illustrate the sensor's ability to solve real-world problems while promoting sustainability and accessibility.

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