

Pressure Sensing on Natural Leaf Scaffolds

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Abstract

Flexible and sustainable pressure sensors have received considerable focus recently for use in wearable electronics, biometric monitoring, and human-machine interfaces. This study introduces a cheap, flexible pressure sensor using a composite material made of graphene and metal oxide deposited on a natural leaf scaffold. The hierarchical structure provided by the leaf scaffold improves the mechanical flexibility and sensitivity of the sensor. On the other hand, the composite layer enhances electrical conductivity and the piezoresistive effect. The sensor works based on the change in resistance when subjected to external pressure and uses a microcontroller to acquire and process data in real-time. A coin is used to calibrate the system to produce consistent pressure from 0.11 to 2.20 kPa. Finally, linear regression analysis is performed to obtain a correlation equation between the output voltage and pressure. Using this correlation, the output voltage can be predicted accurately without further calibration of the sensor.

Keywords: Flexible Sensors, Leaf Scaffolds, Graphene Nanocomposite, Piezoresistive Sensing, Sustainable Electronics.

1. Introduction

Flexible and sensitive pressure sensors have received considerable interest because of their usage in wearable electronics, biometric sensing, robotics, and intelligent industrial processes. According to recent trends, pressure and strain sensors made of nanostructured materials with skin-like properties exhibit remarkable flexibility and electrical characteristics that facilitate successful human-machine interface and monitoring. Biodegradable and flexible

pressure sensors have also demonstrated great promise in eco-friendly technologies. Graphene strain and pressure sensors have been improved by the usage of graphene in strain and pressure sensors because of its high electrical conductance, strength, and sensitivity to detect low-pressure stimulus. Additionally, the integration of graphene with other functional materials enhances the piezo-resistivity and reliability of sensors. In addition to this, substrate engineering and flexible sensor structure contribute to the development of light, cost-effective, and conformable sensors.

The development of current pressure sensors depends heavily on sensing physics, material science, and instrumentation techniques. Micro- and nano-scale capacitive and piezoresistive sensors have better sensitivity and output stability. Iron oxide nanoparticles stand out among other materials due to their magnetic behavior, environmental stability, and compatibility with composites. They are used in conjunction with conductive materials such as graphene. For this research, a low-pressure sensor was developed by incorporating a graphene composite along with iron oxide, blue iron oxide, and zinc in the active part. An OSP sheet was employed as a substrate material for insulation purposes. Copper tapes served as electrodes in the sensor to provide a stable electrical path. The developed sensor utilizes the piezoresistive effect, which involves pressure-induced changes in resistances within the conductive paths.

The sensor output is connected to a microcontroller circuit to enable real-time monitoring, and signal conditioning is employed to enhance precision in measuring signals. A calibration process is carried out using a simple coin-loading system to provide a uniform level of pressure. Linear regression analysis is applied to create a correlation between the output voltage and the input force, leading to more precise predictions and eliminating the necessity for multiple calibration cycles.

In summary, the system showcases an inexpensive, efficient, and versatile concept by merging nanocomposites and microcontrollers for data collection and modelling to produce a mild-pressure detector. The novel sensor targets flexible, sensitive, and cost-effective construction through the integration of organic and synthetic materials. The leaf scaffold boosts the mechanical adaptation capability of the device, while the nanocomposite layer improves its electrical response. As a result, the sensor is capable of detecting mild pressure changes reliably despite undergoing bending and deformation.

2. Related Works

As the amount of research focused on using materials derived from plants and biomimetic approaches to make flexible, high performance, and sustainable sensing systems continues to grow, so has the focus of this research. The initial steps that laid the groundwork for this research were taken by Xu Ye et. al [10] analyzed the development of biomimetic sensors, which were inspired by naturally produced systems, and highlighted their unique ability to be adaptable, their hierarchical structures, and their ability to improve sensitivity. This review provided a conceptual framework for how biological structures could be used for designing sensors that can measure pressure, touch, or the environment. A number of studies have focused on exploring the use of plant-based materials to be used as sustainable substitutes for polymers from traditional sources.

Ahmed Elsayes et. al [2] created a newly designed capacitive pressure sensor from leaf veins and flowers where the leaf veins are the electrodes and the flowers are the dielectric layers; thus, demonstrating that constructs made from plants can be designed to be flexible and provide functional electrical capabilities. Other researchers include Klara Hänisch et. al [1] created biodegradable leaf-based scaffolds to design flexible pressure sensors that were much more sensitive than current sensors and had lower environmental impacts. Furthermore, Rakesh Rajendran Nair et. al proposed a concept termed "leaftronics", in detail, in which they developed an innovative method for using the venation network of leaves as bio-fractal scaffolds to manufacture electronics that produce minimal waste; this technique uses the naturally occurring hierarchy in leaves and the conductive pathways in leaves as the bio-fractal scaffold to produce the electronic devices [4], [6].

Wood-based materials as well as cellulose-based materials have been studied for sensing applications. In particular, Yi Ren et al. [5] reviewed wood-derived pressure and strain sensors that possess advantages in terms of mechanical strength, porosity control, and biodegradability. On the other hand, Ville Rissanen [3] has focused on cellulose nanofiber scaffolds derived from leaves and shown their capability for functional bioelectronics. Improvements in sensor performance are associated with advanced fabrication approaches.

Recent developments also include efforts towards enhancing the performance of sensors using high-performance fabricating technology and complete biomass-based sensing system. Jin, Yuan, Shen'ao Xue, and Yong He [7] proved the importance of the application of

3D printed microstructure in order to enhance the performance of pressure sensors in terms of sensitivity and tuneability by improving the surface morphology and stress distribution. Gu et al. [8] made use of fully biomass-based pressure sensors to analyze the gait, proving that the completely biomass-based sensors can offer satisfactory performance levels. Further, Huang et al. [9] created a 3D printed bio-inspired gradient adaptive piezoelectric scaffold.

However, there are still some challenges that need to be addressed, including the difficulty in fabrication, high cost, and poor stability. This study tries to solve these problems by using the graphene-metal oxide composite to create a cheap, flexible, and stable pressure sensor.

3. Proposed Work

The system under consideration is related to the development of a mild pressure sensor, which will be based on a graphene nanocomposite material (Figure 1). It means that the design will be aimed at creating a cost-effective and highly-sensitive flexible sensor. In order to improve electrical conductivity and increase piezo-resistivity of the device, graphene is used along with various oxides of metals, such as iron, blue iron, and zinc. Composite materials are placed on the OSP sheet, which serves as a flexible substrate and provides electrical insulation of sensors. Besides, copper tape electrodes are applied on both sides of the sensing layer to guarantee reliable connections between the sensor and the rest of the system. As soon as any external pressure impacts the material, a mechanical deformation occurs changing the properties of the conductive network. In other words, the resistance of the material depends on its strain, thus, it changes when it comes to deformation. Such changes can be detected through interfacing with a microcontroller-based system, which allows for the acquisition of the information in real time.

The loading process uses coins that provide controllable and reproducible force on the sensor surface during calibration. The output voltages associated with the various pressures are documented.

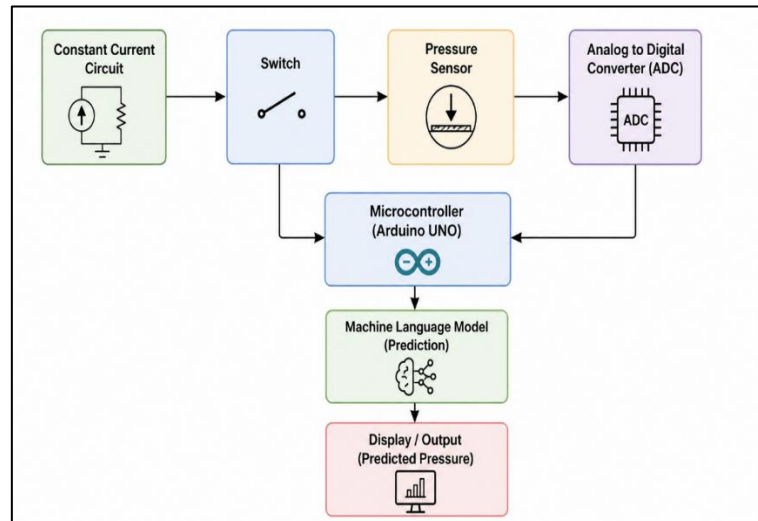


Figure 1. System Architecture

In order to determine the relation between the voltage and pressure, a linear regression analysis technique is adopted. This involves modeling a linear association between the measured voltage V and the applied pressure P , expressed as:

$$P = aV + bP$$

where:

- P = Predicted pressure (kPa)
- V = Sensor output voltage
- a = Slope (sensitivity coefficient)
- b = Intercept (offset value)

Values of a and b are found by using data from calibrations made under controlled load conditions (coin test method). Regression analysis works to minimize the errors in the difference between the actual and estimated pressures with the use of least squares approximation. The use of this model allows real-time prediction of pressure values.

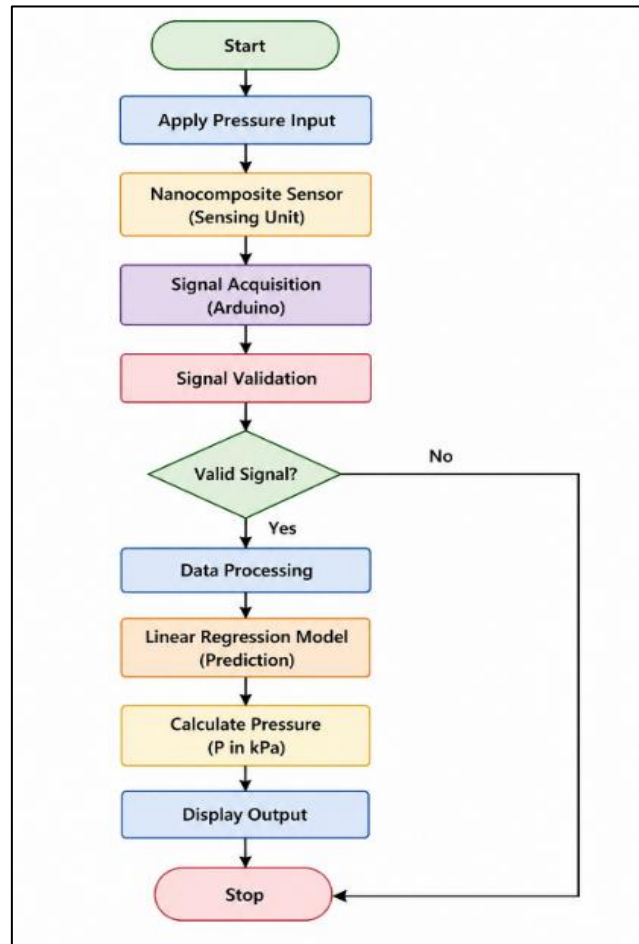


Figure 2. Work Flow of the Proposed System

Figure 2 shows the process of working of the pressure sensing system designed to conduct experiments. First, an external pressure signal is applied, sensed using nanocomposite pressure sensor built into a natural leaf scaffold which is a sensing element of the system. Natural leaf scaffolds increase sensitivity and flexibility of the device, allowing to effectively transform pressure to an electrical signal. Signal is transmitted to a microcontroller like Arduino and collected for further processing. Signal validation follows next in order to ensure that acquired signal is not erroneous. If the signal appears to be invalid, the process stops here, in order to avoid receiving incorrect data; otherwise, the process goes forward and proceeds to signal conditioning and formatting stage. Linear regression modeling is done for further prediction and calibration of pressure values based on the electric signal produced by the sensor. Pressure value in kilopascals (kPa) is calculated using the previously obtained regression equation and outputted to the user via interface. The process ends once all the calculations have been made and the final pressure value has been displayed to the user.

4. Results and Discussion

The performance of the proposed graphene-based pressure sensor was evaluated using a coin-based calibration method. Table 1 shows the simulation parameters used in this research work.

Table 1. Simulation Parameters

Parameter	Description
Sensor Type	Graphene-based piezoresistive sensor
Pressure Range	0.11 – 2.20 kPa
Substrate	OSP (Organic Solderability Preservative)
Sensing Material	Graphene + metal oxides composite
Electrode Material	Copper tape
Input Method	Coin-based loading
Output Parameter	Resistance / Voltage
Processing Unit	Microcontroller-based system
Calibration Method	Linear regression model

Different numbers of coins were placed on the sensor surface to apply known pressure values, as summarized in Table 2.

Table 2. Coins Placement and Pressure Values

Coins	Mass(g)	Pressure(kPa)
1 Coin	5.62 g	0.11 kPa
5 Coin	28.1 g	0.55 kPa
10 Coin	56.2 g	1.10 kPa
20 Coin	112.4 g	2.20 kPa

Where R_0 is the baseline resistance under no load and $R(P)$ is the resistance under applied pressure P . The relative resistance change is given by:

$$\Delta R/R_0 = kP$$

where k represents the pressure sensitivity coefficient of the nanocomposite. The applied pressure ranged from 0.11 kPa to 2.20 kPa, which corresponds to mild pressure levels suitable for touch-based and wearable sensing applications. Figure 3 shows the proteus implementation of the proposed model.

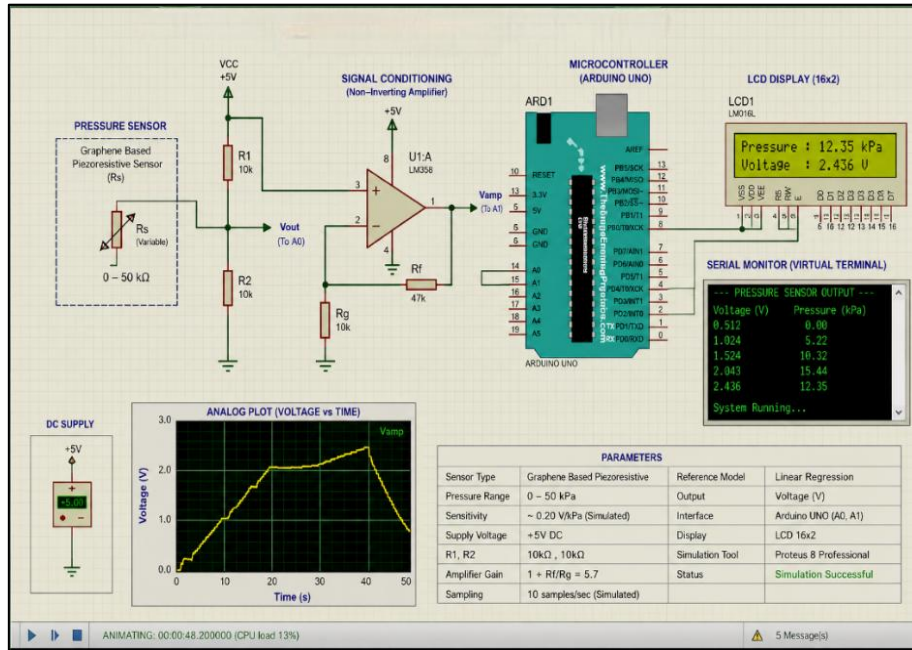


Figure 3. Proteus Implementation and Analysis

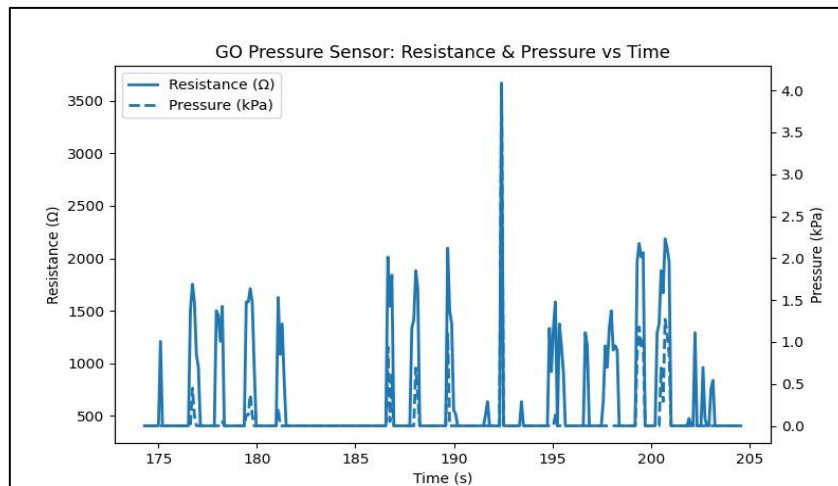


Figure 4. Resistance and Pressure vs Time Chart

Figure 4 shows the variation of sensor resistance and calculated pressure with respect to time. When pressure was applied, a noticeable change in resistance was observed due to the piezoresistive behaviour of the sensing layer. As the applied pressure increased, the resistance

value showed a sharp and repeatable variation, indicating high sensitivity of the sensor. When the pressure was removed, the resistance returned close to its initial value, demonstrating good recovery characteristics. The maximum values of resistance in the graph represent the application of varying loads of coins on the sensor, whereas the straight portions represent zero pressure conditions. The sensor has demonstrated consistency throughout the loading and unloading processes. Small variations in the resistance pattern can be linked with differences in manual loading and external interference. The data obtained was then used for fitting the output voltage against applied pressure using linear regression to find out their relationship. It has been found from the regression analysis that the output voltage of the sensor is linearly related to pressure applied in the selected range. Thus, it confirms the suitability of the sensor for detecting mild pressures. The developed sensor does not require recalibration due to the use of regression analysis for finding out the relationship between pressure and output voltage.

5. Conclusion

The current research discusses the development of a flexible sensor for detecting mild pressure using a graphene nanocomposite coupled with metal oxides. This sensor is based on the principle of piezo-resistance and exhibits good sensitivity, stability, and repeatability in the case of low-pressure sensing. The employment of a flexible substrate along with conductive composite materials makes the device capable of sensing pressure variations while remaining flexible. The inclusion of a microcontroller-based acquisition system makes it possible to perform real-time measurements as well as accurate processing of signals. Also, a regression-based calibration technique helps to increase accuracy and minimize the need for manual recalibration of the sensor. Advantages of this type of sensors include the fact that they can be made at relatively low costs and are easy to fabricate and integrate into electronic systems.

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