A Network Carbon Nanotube-Based Material Low-Power and Long-Range Wireless Sensor for Strain Sensing Applications

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Utilizing flexible electronics in device-engineering techniques has facilitated the production of inexpensive, lightweight, expandable, and foldable sensors. Although composites are effective in detecting signal stimulation according to the latest research, there is still room for improvement in the use of new flexible substances for low-power and low-range (LP-LR) Wireless Sensor Networks (WSN) in precision healthcare, structural health tracking, environmental detecting, wearables, and Internet of Things (IoT) usages. This article suggests using a portable strain-detecting node that utilizes nanocomposite made of Multiwall Carbon Nanotubes (MW-CNTs) and polypropylene (PP) for LP-LR communication networks with extensive interconnectivity. The sensor node, which has a nanostructured design and contains four weight percent of MW-CNTs, exhibits a significant level of sensitivity to piezoresistive effects, as shown by gage factors of about 4.5. A microcontroller unit is efficiently integrated with a portable LP-LR communication transceiver to enable flexible composites in a wireless nanostructured recognizing network. This integration includes an energy managing method that results in an LP-LR usage of 0.89 mW. The experimental findings of the MW-CNT/PP strain detecting node demonstrate the viability for a range of loT-WSN scenarios.

Keywords: Carbon Nanotube, Wireless Sensor, Strain Sensing, Low-Power and Long-Range.

1. Introduction

Traditional strain sensors, sometimes called metallic strain gauges, are limited to measuring stresses only on the structure's surface [1]. As a result, wires are necessary to collect data. Using many strain gauges on a big surface area, such as architectural health tracking or aircraft wings, will complicate the setup if cables are required. This implementation has other options, such as rotating elements or submerged structures. Wireless sensors have the advantage of removing wires, addressing conventional strain sensors' drawbacks [2]. Various industrial devices are designed to provide remote strain sensors using metal scales that rely on piezoresistivity to measure impedance changes caused by strain [3]. These sensors have several benefits, such as lower setup and upkeep costs, more adaptability, immediate data collection, ongoing monitoring, higher safety, and fewer risks associated with cabling. There are still restrictions in the form of possible interference, restricted communication spectrum, battery life, and more extraordinary starting expenses. Carbon Nanotubes (CNTs) are highly intriguing nanotechnology for strain sensors due to their exceptional mechanical and electrical capabilities [9].

CNTs have a large aspect ratio and extremely low density. Extensive research has shown the practicality of using thin films from CNTs for strain sensing in Low-Power and Low-Range (LP-LR) applications [13]. These films provide a distinctive physical system for detecting strain, which involves monitoring a shift in electrical conductivity caused by applied stress from friction [10]. This mechanism enables precise and dependable readings. When the CNT thin films experience applied strain stress, there is an apparent rise in the permeability of the film. The variation in electrical impedance is caused by a change in the bridging distance among the adjacent CNTs that constitute the conduction pathways [4].

Although reports suggest that flexible detectors based on CNTs could be a viable substitute for traditional electronic gadgets made of rigid materials, there is still an essential chance for advancing components that combine MW-CNTs and PP for sensing nodes with LP-LR capabilities. Recent investigations indicate that further advancements in stretchable and flexible electronics, along with integrating the IoT and WSN, are required to enhance the functionality of CNT/PP-based recognizing networks [12]. These advancements will improve LP-LR interaction and extend the system's battery life. These problems indirectly decrease the adherence of instruments and restrict the incorporation of extra sensing methods because of concerns about connection and power, particularly when expanding these systems to include self-strain monitoring and industrial uses [5].

The objective of this study is to utilize nanostructured substances to construct sensor nodes that are inexpensive, adaptable, portable, and have deficient power consumption. These sensor nodes will be integrated with wireless communication methods, enabling tracking and cloud data handling through Integrated electronic gadgets [7]. These involve examining and calculating an algebraic model for the MW-CNT/PP sensor metrics to rectify assessment inaccuracies caused by the nonlinear material reaction.

2. Materials and Methods

2.1 Materials

The strain MW-CNT/PP sensors were fabricated, an extrusion quality polypropylene from Taiwanese Plastics Co. This polypropylene has a melting factor of 5 g/10 min. These MW-CNTs were created by chemical-based vapor condensation. They had an interior diameter ranging from 4 to 12 nm, an outer diameter of around 35 nm, and a length dispersion spanning 1 and 7 μm, with an average length of 1.9 μm.

2.2 MW-CNT/PP Fabrication

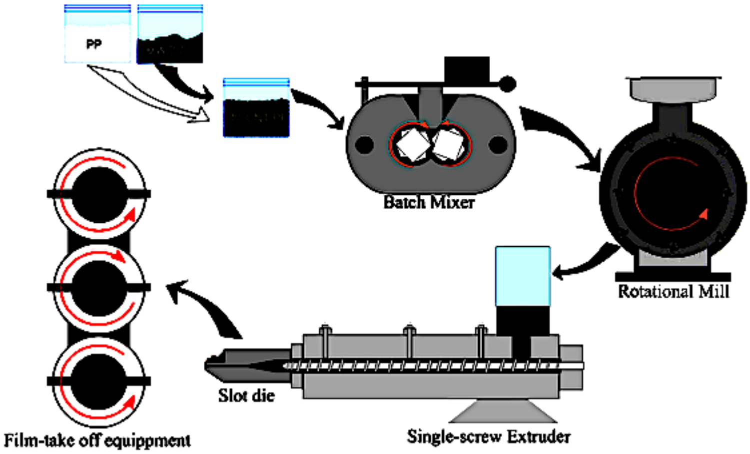

Fig. 1. Fabrication process of CNT

The MW-CNT/PP materials were synthesized using a two-step melting processing approach, as shown in Fig. 1. Before melting, a mixture is created by combining four weight percent of MW-CNTs with granulated polypropylene [6]. The mixture is melted-blending for 10 minutes at a rotational speed of 50 revolutions per minute using an automated mixer with three warming zones set to 200 °C. The MW-CNT/PP mix is pulverized using a rotary mill to achieve particles of millimeter size. The extruder is fitted with a slotted die adjusted to maintain a 250-um gap among the lips. The warming zones of both the extrusion and the die had been set to a temperature of 200 °C, while the screw rotation rate was set at 50 rpm. The nanocomposite is blown out into a flat sheet with a thickness of about 200 micrometers and a width of 15 centimeters [11]. Following the extrusion process, the nanocomposite is gathered and made uniform in thickness using a film-take-off three-roll equipment. The machine operates at a linear rate of 0.6 m and maintains a 250-um space among the wheels. The film's thickness was precisely regulated at 250 (± 25) um to produce a sensor with sufficient mechanical flexibility for detecting human movement and tactile sensation.

2.3 Energy Optimization

An energy-optimized technique is used to lower the power usage of the sensor node. The Texas Research was chosen for its exceptional energy efficiency, capacity to process analog and digital signals, 16-bit architecture, 512 KB of stable Random Access Memory, clock speed of up to 32 MHz, and voltage spanning 1.5 V to 3.4 V. The node has energy modes tuned for efficiency, namely sleep state and shut-down state, which correspondingly have usage levels of up to 0.5 μA and 0.3 μA. The active state of the machine consumes 450 μA of current in a standard 3.5 V device. The device requires a maximum of 5 μs to wake up from sleep and become functional. The node incorporates Low-Energy Acceleration (LEA), which provides rapid, effective, and energy-efficient vector math acceleration often used in Digital Signal Processing (DSP) workloads [8].

The energy managing technique maximizes energy use efficiency at the sensor nodes. Each sensor node collects 60 samples of the immediate electrical resistance reaction for the elasticity deformation caused by strain, following the normative for architectural health tracking. The piezoresistive data are calibrated using the suggested system classification concept and saved in the memory. They are processed using the weighting order statistics method. This technique is carried out on the microcontroller unit using the LEA module. It reduces energy usage in sensor nodes by reducing data transfer amounts without compromising accuracy. Only one projected strain value is sent as a consequence of the WOS computation of the 60 observations. The sensing node sends data and reverts to a dormant state, repeating this cycle every 5 minutes.

2.4 MW-CNT/PP Networks

The suggested network model consists of three primary components: i) the MW-CNT/PP sensing nodes incorporated as objects, ii) a gateway linked to the Internet to transmit the collected data to the clouds, and iii) an online interface with IoT applications that analyze and oversee the information gathered from each sensor node. The LoRa transceiver facilitates local interaction between sensor terminals and the gateway. The LoRaWAN-Class protocols work in the unregulated 916 MHz band and have a maximum transmission range of 3 km in line of vision or up to 25 km with directed antennae. A Raspberry Pi 3 gateway gets a one-byte data stream containing the anticipated strain from a sensing node utilizing the LoRaWAN technology. It transfers the details to the cloud via Wi-Fi. A User Datagram Protocol (UDP) socket facilitates the routing of packets from the LoRa sensing node to the gateways. The gateway enables the transmission of server Quality of Service (QoS) level 0 via transportation to the Broker and from the Broker to the website's application. Every sensor node in the system is issued an individual Sensor-ID to differentiate it from other gadgets. The gateway programs every node with a Node-ID. Upon receiving the information from the detector, the node proceeds to submit a message to the gateways. The RESTful Web Application Programming Interaction (API) participates in the sensing information, while a cloud-based repository is used to store the sensing information.

3. Results

An experimental investigation was performed utilizing real-time metrics, system simulation, and strain estimates in a LoRa network with an IoT connection.

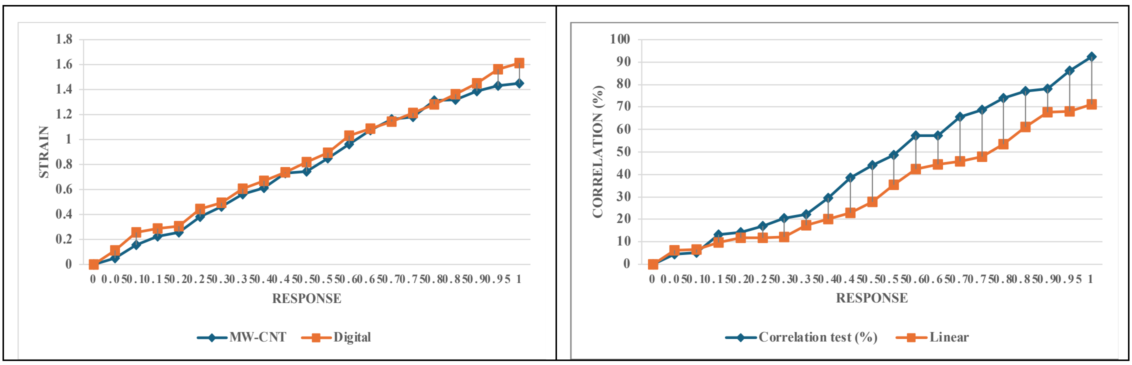

Fig. 2(a). Strain analysis and 2(b). Correlation analysis

Fig. 2(a) displays the piezoresistive responsive curves, which reflect the strain readings and the digital signal analysis. The regularization outcomes of the parameterized system recognition response were evaluated by calculating the mean square faults. The sensor response exhibits excellent stability and consistency and negligible hysteresis. Fig. 2(b) illustrates the response after 50 cycles of loading. Compensating methods are used to account for repetition in practical applications. The probabilistic method was used to establish a quantitative system simulation method that enhances process dependability, streamlines sensor handling, and minimizes sensor repeatability.

The energy-optimized approach allows the microcontroller unit to collect 60 readings over 5 seconds, resulting in a power usage of 9.2 milliwatts. The system recognition concept acquires and processes each data point for 8.4 milliseconds. A brief sleep period of 90.21 milliseconds is added. A frequency of 12 Hz is the optimal interval for collecting data to assess deformation degrees in architectural health surveillance situations. Following data collection, the font end is unplugged, and the microcontroller computes the WOS categorization within 5.1 milliseconds.

The energy usage determined by the WOS is 6.8 mW, lower than during data collection. This difference is attributed to using the LEA unit and its arrangement. The LoRa transmitter is operational and will transmit the predicted distortion level for 602 milliseconds, with a maximum power output of 212 milliwatts. Although the suggested strain MW-CNT/PP sensor node reaches a high power level, its mean power usage is 0.89 mW.

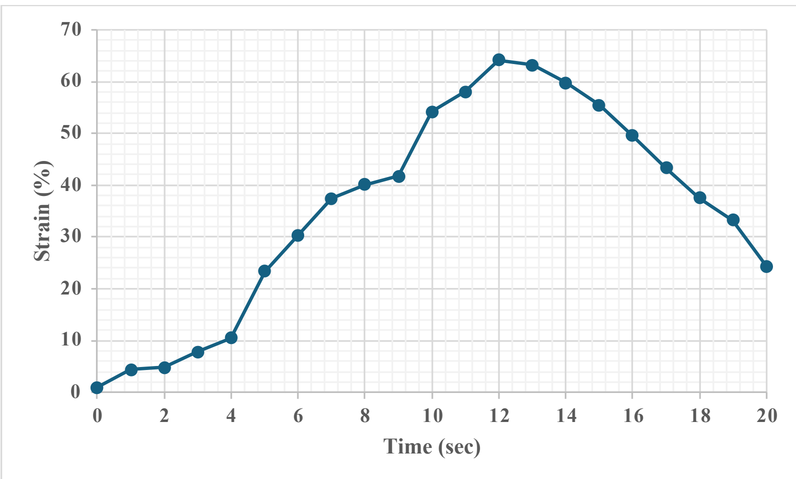

Fig. 3. Strain analysis over time

They are using web technology to supervise and display the measured information, and an online strain visualization method was created. Fig. 3 illustrates the predicted strain curve over time for a uniaxial longitudinal strain-loading experiment conducted on the MW-CNT/PP sensor node. The website application lets users choose the preferred LoRa sensing node. This technique allows the consumer to study the behavior of architectural health surveillance using the MW-CNT/PP-based sensing nodes. All of the data is saved inside the cloud.

4. Conclusion and findings

The proposal involves developing a movable node for strain detecting, which utilizes MW-CNT/PP nanocomposites. A sensor node with LP-LR was developed and evaluated for mobile networks with IoT connections. The node was equipped with a web-based supervisory system allowing real-time viewing of strain measurement data. The MW-CNT/PP strain sensing was first designed using the parameterized system recognition approach, resulting in enhanced process dependability, simplified sensor interaction, and reduced sensor node management. The WOS categorization method calculates the strain value on a percentage scale, minimizing communications from the sensing nodes to the LP-LR gateways. The energy-optimized technique achieved a compromise between energy consumption and precision by using strain monitoring and extending battery life. The periods are modified to various step sizes, allowing for a trade-off between strain-sensing precision and energy conservation. It is feasible to have sleep intervals that are less than 5 minutes to enhance data accuracy but at the cost of increased energy usage. The MW-CNT/PP sensing node, when combined with an energy-optimized method, is used to address various real-time issues related to human motion identification, adaptable electronics, wearable devices, and structural healthcare tracking.

References

1. Chen, H., Zhuo, F., Zhou, J., Liu, Y., Zhang, J., Dong, S., ... & Fu, Y. (2023). Advances in graphene-based flexible and wearable strain sensors. Chemical Engineering Journal, 464, 142576.
2. Jamshed, M. A., Ali, K., Abbasi, Q. H., Imran, M. A., & Ur-Rehman, M. (2022). Challenges, applications, and future of wireless sensors in Internet of Things: A review. IEEE Sensors Journal, 22(6), 5482-5494.
3. Rajesh, D., Giji Kiruba, D., & Ramesh, D. (2023). Energy Proficient Secure Clustered Protocol in Mobile Wireless Sensor Network Utilizing Blue Brain Technology. Indian Journal of Information Sources and Services, 13(2), 30–38.
4. Negri, V., Pacheco-Torres, J., Calle, D., & López-Larrubia, P. (2020). Carbon nanotubes in biomedicine. Surface-modified nanobiomaterials for Electrochemical and Biomedicine Applications, 177-217.
5. Rosa, C., Wayky, A.L.N., Jesús, M.V., Carlos, M.A.S., Alcides, M.O., & César, A.F.T. (2024). Integrating Novel Machine Learning for Big Data Analytics and IoT Technology in Intelligent Database Management Systems. Journal of Internet Services and Information Security, 14(1), 206-218.
6. Dobránsky, J., Pollák, M., Běhálek, L., & Svetlík, J. (2021). Implementation of a recycled Polypropylene homopolymer material for use in Additive Manufacturing: Sustainability, 13(9), 4990.
7. Jara, A.J., Zamora, M.A., & Gómez-Skarmeta, A.F. (2010). An Initial Approach to Support Mobility in Hospital Wireless Sensor Networks based on 6LoWPAN (HWSN6). Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 1(2/3), 107-122.
8. SHAIK, SADULLA. "A coplanar wave guide fed compact antenna for navigational applications." National Journal Of Antennas and Propagation 2.1 (2020): 7-12.
9. Yu, W., Patros, P., Young, B., Klinac, E., & Walmsley, T. G. (2022). Energy digital twin

technology for industrial energy management: Classification, challenges, and future. Renewable and Sustainable Energy Reviews, 161, 112407.

10. Shoukat, R., & Khan, M. I. (2021). Carbon nanotubes: A review on properties, synthesis methods and applications in micro and nanotechnology. Microsystem Technologies, 1-10.
11. Bobir, A.O., Askariy, M., Otabek, Y.Y., Nodir, R.K., Rakhima, A., Zukhra, Z.Y., Sherzod, A.A. (2024). Utilizing Deep Learning and the Internet of Things to Monitor the Health of Aquatic Ecosystems to Conserve Biodiversity. Natural and Engineering Sciences, 9(1), 72-83.
12. Omanović-Mikličanin, E., Badnjević, A., Kazlagić, A., & Hajlovac, M. (2020). Nanocomposites: A brief review. Health and Technology, 10(1), 51-59.
13. Mukti, I.Z., Khan, E.R., & Biswas, K.K. (2024). 1.8-V Low Power, High-Resolution, High-Speed Comparator with Low Offset Voltage Implemented in 45nm CMOS Technology. Journal of VLSI Circuits and Systems, 6(1), 19-24.
14. Almurisi, N., & Tadisetty, S. (2022). Cloud-based virtualization environment for iot-based wsn: solutions, approaches and challenges. Journal of Ambient Intelligence and Humanized Computing, 13(10), 4681-4703.