Flood Monitoring and Early Warning System Enabled by High-Sensitivity MWCNTs-PDMS Flexible Strain Sensors

(Sistem Pemantauan Banjir dan Amaran Awal Didayakan oleh Sensor Tegangan Fleksibel MWCNT-PDMS Bersensitiviti Tinggi)

RAZA ULLAH[1], QIANG LI[1,*], FANGLONG SU[1], JINGCHAO GENG[1], SHENGBO SANG[1] & LIFENG DING[2]

[1]Shanxi Key Laboratory of Artificial Intelligence & Micro Nano Sensors, College of Integrated Circuits, Taiyuan University of Technology, Taiyuan, 030024, China
[2]Department of Chemistry and Chemical Engineering, Taiyuan Institute of Technology, Taiyuan, 030008, China

ABSTRACT

This study presents a novel flood monitoring and early warning system leveraging multi-walled carbon nanotube (MWCNT)-embedded polydimethylsiloxane (PDMS) flexible strain sensors for real-time water-level detection. Traditional systems, such as acoustic Doppler profilers, ultrasonic sensors, and IoT-based networks, face limitations related to cost, environmental adaptability, and accuracy. In contrast, the proposed system integrates stretchable MWCNT-PDMS sensors with an Arduino Nano microcontroller and Bluetooth-enabled data transmission to achieve high sensitivity (detecting deformations as small as 0.1 mm), low power consumption, and robust performance in harsh environments. The sensors detect the structural strain caused by rising water levels, translating mechanical deformation into resistance changes. A hardware-software framework processes these signals to trigger three-tier alerts: safe (blue LED), cautious (yellow LED), and dangerous (red LED), with real-time updates via an LCD and wireless Bluetooth communication (HC-05). Experimental results demonstrate a gauge factor exceeding 5 for optimized sensors, enabling precise threshold-based warnings. The system's non-intrusive design, durability, and adaptability to irregular surfaces such as riverbanks and infrastructure offer significant advancements in disaster resilience. By addressing critical gaps in cost, accuracy, and deployment flexibility, this work provides a scalable solution for mitigating flood risks in vulnerable regions.

Keywords: Early warning system; flexible strain sensors; flood monitoring; MWCNTs-PDMS composite; real-time detection

ABSTRAK

Penyelidikan ini melaporkan sistem pemantauan banjir dan amaran awal yang novel menggunakan sensor regangan fleksibel polidimetilsiloksana (PDMS) terbenam tiub karbon nano berbilang dinding (MWCNT) untuk pengesanan aras air masa nyata. Sistem tradisional seperti profiler Doppler akustik, sensor ultrasonik dan rangkaian berasaskan IoT menghadapi batasan berkaitan kos, kebolehsuaian persekitaran dan ketepatan. Sebaliknya, sistem yang dicadangkan mengintegrasi sensor MWCNT-PDMS boleh regang dengan mikropengawal Arduino Nano dan penghantaran data berkemampuan Bluetooth untuk mencapai kepekaan tinggi (mengesan ubah bentuk sekecil 0.1 mm), penggunaan kuasa rendah dan prestasi teguh dalam persekitaran keras. Sensor mengesan tegasan struktur yang disebabkan oleh kenaikan aras air, menterjemahkan ubah bentuk mekanikal kepada perubahan rintangan. Rangka kerja perkakasan-perisian memproses isyarat ini untuk mencetuskan amaran tiga peringkat: selamat (LED biru), berhati-hati (LED kuning) dan berbahaya (LED merah) dengan kemaskini masa nyata melalui LCD dan komunikasi Bluetooth tanpa wayar (HC-05). Keputusan uji kaji menunjukkan faktor tolok melebihi 5 untuk sensor yang dioptimumkan, membolehkan amaran berasaskan ambang yang tepat. Reka bentuk sistem yang tidak invasif, ketahanan dan kebolehsuaian kepada permukaan tidak sekata seperti tebing sungai dan infrastruktur menawarkan kemajuan signifikan dalam daya tahan bencana. Dengan menangani jurang kritikal dalam kos, ketepatan dan kefleksibelan penempatan, kertas ini menyediakan penyelesaian berskala untuk mengurangkan risiko banjir di kawasan terdedah.

Kata kunci: Komposit MWCNT-PDMS; pemantauan banjir; pengesanan masa nyata; sensor regangan fleksibel; sistem amaran awal

INTRODUCTION

Numerous catastrophes in recent decades have demonstrated that the risk from water-related events has been increasing significantly worldwide. Amongst those events are flash floods, river floods, tsunamis, and storm surges. The factors that lead to this risk are the concentration of people in high-risk zones such as flood plains and coasts, the increase in vulnerability of assets, the increase in population, infrastructure, and climate change. Floods are one of the most dangerous natural disasters, causing significant losses of land, lives, agricultural production, and infrastructure, and affecting local economic development worldwide. Scientists estimate that by 2030, an increase of just 4 inches in sea level could cause severe damage due to flooding in many parts of the world (Tariq & Van De Giesen 2012).

Various sensors and techniques have been used to monitor river water levels (Nihei & Kimizu 2008), proposed a system based on the horizontal acoustic Doppler current profiler (H-ADCP). This system is primarily designed to measure the flow of water, not the water level at different water bodies such as rivers, oceans, and streams. This system is more accurate at measuring the water flow than the water level, so this system is not suitable to be used as a flood monitoring system. Other limitations include cost, maintenance, environmental factors such as biofouling, water turbidity, and sediment concentration, complex data processing as it requires sophisticated data processing algorithms, range limitation, complexity as it needs additional calibration setup for the use of water level detection, and more power consumption. Sunkpho and Ootamakorn (2011) developed a real-time flood monitoring and warning system based on a wireless sensor network (WSN). They employed a STARFLOW sensor to calculate the flow of water and a Fischer to measure the precipitation level, which consists of a tipping bucket rain gauge system. The measured data were then sent to the server by the data transmitting and processing module, which employs a GPRS network, which makes their proposed method complicated and costly. Satria et al. (2018) developed a prototype of a flood monitoring information system based on the Internet of Things (IoT). They have used the (SDLC) software development life cycle methodology. Software development cycles consist of cycles from analysis, design, implementation, testing, and maintenance. The proposed system consists of Arduino UNO ATMEGA 328, with 8-bit processing power, an Ethernet component that performs as a web server using TCP/IP-based communication media, a rain sensor as a rainfall detector, an ultrasonic sensor HC-SR04 for water level detection, and a Wireless N Router TL-MR3020. As the ultrasonic sensor in this system is the main part whose performance can be affected by various factors, including temperature, humidity, and air turbulence, which can lead to inaccuracies in measuring water level. Other factors include maintenance to ensure reliable performance, so the transducer should be cleaned regularly of debris, dirt, and biological growth. Khan et al. (2020) proposed a forecasting Het-Sens model, which consists of different sensors to detect the increase or decrease in water level. They used a level sensor, a vane-meter to check the intensity of water flow, and a rainfall sensor for precipitation level. To alert the people, the collected data from all these sensors is then sent to the base station, which is responsible for communication and processing. The alert signal will be sent through the RF transmitter, and the people can get information through the FM channel. As this system uses different types of sensors, there is complexity as each sensor has its own data format, calibration requirements, and communication protocol. Other factors include compatibility and cost due to the use of different sensors, challenging data fusion, and deployment flexibility as compared to a single sensor.

NOVELTY AND DISTINCTION FROM EXISTING FLOOD MONITORING SYSTEMS

Conventional flood monitoring systems commonly rely on rigid sensors, such as pressure, ultrasonic, or float-based devices, which are prone to debris interference, mechanical wear, high cost, and increased power consumption in harsh flood conditions. While some IoT-based solutions focus mainly on improving data transmission, they offer limited sensing innovation. In contrast, the proposed system employs a flexible strain sensor as the primary water-level sensing element, where water-induced deformation produces resistance changes directly correlated with water height. This approach enables conformal installation, improved mechanical durability, and enhanced sensitivity to gradual water-level variations. Moreover, unlike existing flexible strain sensors primarily developed for wearable or biomedical applications, this work demonstrates their effective adaptation for low-cost, real-time, and scalable environmental flood monitoring using a simple Arduino Nano-based readout and wireless communication.

The flexible strain sensors have received great attention due to their significant potential in different electronic applications such as human-machine interfaces (Han et al. 2021; Hang et al. 2020; Heng, Solomon & Gao 2022; Yin et al. 2021), human motion detection (Chang et al. 2023; Duan et al. 2025; Fu et al. 2024; Lan et al. 2024; Li et al. 2021; Yang et al. 2020; Yuan et al. 2022), heart beat monitoring (Dual et al. 2020), artificial muscle design (Roach et al. 2019), gesture interaction (Ji et al. 2024), blood pressure monitoring (Yuan et al. 2024), temperature and pressure monitoring (Geng et al. 2025), pressure and safety warning purpose (Ji et al. 2021) and some other fields as well. Current research on flexible sensor-based water level monitoring has investigated various sensing principles and material platforms. Ren et al. (2024) worked on a flexible capacitive, non-contact

liquid level sensor based on interdigitated electrodes, in which water level variations are detected through capacitance changes; however, such a capacitive system requires careful electrode design and is susceptible to parasitic capacitance and environmental interference. Xiang et al. (2023) proposed a paper-based flexible sensor capable of stable underwater operation with long-term durability, but the fabrication process relies on material-specific treatments that may limit the scalability. Sebicho, Lou and Anito (2024) presented a multiparameter flexible smart water gauge for urban water monitoring, integrating multiple sensing functions at the expense of a higher circuit complexity and power consumption. In contrast, the present study employs a single flexible strain sensor to directly convert water-level-induced mechanical deformation into an electrical signal, enabling a simpler, low-power, and easily applicable flood monitoring system.

Due to their reliability and high performance, in this paper, we also proposed a flexible strain sensor-based flood monitoring and early warning system because of their high level of processability, biocompatibility, and flexibility over the conventional sensors (Shin, Hong & Hwang 2020). Additional advantages include low energy consumption, low cost, ease of integration, adaptability to harsh environments, compactness, and durability (Shen et al. 2022). The more durable the conductive network, the more stretchable the sensor will be, as it will provide a conductive path if more strain is applied (Duan, D'hooge & Cardon 2020). It is assumed that the stretchability can be increased either by designing the material structure or by integrating stretchable materials. The most commonly used stretchable materials usually serve as substrates, including elastomers (rubbers), such as PDMS (Peng et al. 2022), natural rubber (NR) (Xu et al. 2021), TPU (Li et al. 2020), and elastic band (EB) (Li et al. 2022). We have selected PDMS for our project to achieve higher results, because we are using it for water level detection, as it is hydrophobic. Their pliable nature allows them to conform to various surfaces and structures, enabling seamless integration into diverse environments, including riverbanks, levees, and infrastructure prone to flooding. This flexibility not only enhances the sensor's coverage area but also ensures robustness against structural deformation and environmental fluctuations, thereby improving the longevity and reliability of flood monitoring systems.

The proposed flood monitoring and early warning system design consists of three components: MWCNTs-based flexible strain sensor, hardware circuit, and software. In hardware, we used an Arduino Nano as the main control chip. To communicate with the hardware circuit of the lower computer, we have used the C language. The upper computer platform is developed through Python to realize the control of the hardware platform, complete the processing and real-time data transmission of the collected data, and display it on the host computer. In contrast to the existing systems, our proposed method is versatile as it can conform to irregular surfaces, which makes it adapted to different water level monitoring and can be mounted on various surfaces like walls, and tanks. Other advantages include non-intrusive installation, reducing installation cost and time, and durability, as they are made up of robust materials resistant to moisture, temperature, and corrosion. Our proposed system can be operated on a 5V battery and is highly sensitive, detecting deformation as small as 0.1 mm, and enables real-time monitoring and early detection of water level change. To facilitate the users in timely decision-making and response, we have integrated the system with a Bluetooth module (HC-05), which sends alerts accordingly.

The description 'vulnerability to damage – very low', for our proposed system, means low risk of sensor damage under flood-related environmental conditions, which includes debris interactions, prolonged exposure to water, as it is hydrophobic, and mechanical deformation. This improvement is attributed to the flexible and conformal characteristics of the strain sensor compared to the conventional rigid systems.

MATERIALS AND METHODS

Polydimethylsiloxane (PDMS), along with the curing agent, was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd., and MWCNT having a diameter of 3-15 nm and a length of 15-30 μm, purity/% >98% was purchased from Shenzhen Suiheng Technology Co., Ltd.

FABRICATION

To fabricate the flexible strain sensor, firstly, we mixed polydimethylsiloxane (PDMS) A and B (14 g and 1.4 g) in a ratio of 10:1, mixed it well, and put it for 24 h in the refrigerator to avoid bubbles in it. Then, we took a glass slide of size (7.5 cm * 2.5 cm *1 mm), cleaned it, put it on a plane surface, and poured some of the PDMS mixture onto it. Specifically, we poured 1.50 g of PDMS mixture (parts A and B) onto a glass slide to form the substrate. We left the poured mixture for about (5-7) min at room temperature to self-level simultaneously on the glass and let the bubbles degas if there are some. The mixture was then put in an oven for about 20 min at a temperature of 80 °C. After cooling it at room temperature, we made another mixture of Multi-Walled Carbon Nano Tubes (MWCNTs) 0.145 g, PDMS A 5 g, and PDMS B 0.5 g, respectively. We applied two electrodes at both ends under the conductive layer of MWCNT. Then we used 9.17%, which is 0.0133 g of the MWCNT mixture as a conductive layer, and leveled it using a capillary tube. We put it again in the oven for 20 min to dry the layer of MWCNTs at a temperature of 110 °C to cure it. Our desired flexible strain sensor is ready, and we carefully removed the fabricated sensor from the slide after it had cooled. The actual weight and the thickness of the sensor are about 1.5257 g (including the weight of electrodes) and 0.45 mm in total.

TABLE 1. Comparison between existing work and our proposed system

| Feature	WSN-based system	Ultrasound-based system	IoT-based system	Het-Sens-based system	Proposed flexible strain sensor-based system
Sensing element	Multiple sensors	Ultrasonic sensor	Ultrasonic / pressure sensors	Multi-sensor array	Flexible strain sensor
Sensing mechanism	Flow/level estimation	Distance measurement	Distance/pressure	Multi-parameter sensing	Mechanical deformation due to the water level
Sensor structure	Rigid	Rigid	Rigid / semi-rigid	Rigid	Flexible and conformal
Deployment	On the ground	Stationary	On the ground	On the ground	Almost any surface
Coverage	Local/regional	Local	Local/regional	Local/regional	Specific critical areas
Sensitivity	Moderate	Moderate	Moderate	Moderate	High
Response time	Near real-time	Moderate – high	Near real-time	Near real-time	Real-time
Accuracy	Moderate – high	Moderate – high	Moderate – high	Moderate – high	High
Environmental robustness	Moderate	Debris-sensitive	Moderate	Moderate	Hydrophobic & robust
Vulnerability to damage	Moderate – high	Low	Low	Low	Very low
Installation adaptability	Fixed	Fixed	Fixed	Fixed	Highly adaptable
Power & complexity	Moderate – high	Moderate	Moderate – high	High	Low (ADC-based readout)
Infrastructure requirement	Moderate – high	Moderate	Moderate	Moderate	Low
Cost	Moderate – high	Moderate – high	Moderate – high	Moderate – high	Low
Data accessibility	Local / cloud	Local / cloud	Local / cloud	Local / cloud	Local / cloud
Main contribution	Networking maturity	Established sensing	Remote monitoring	Sensor fusion	Simple deformation-based sensing
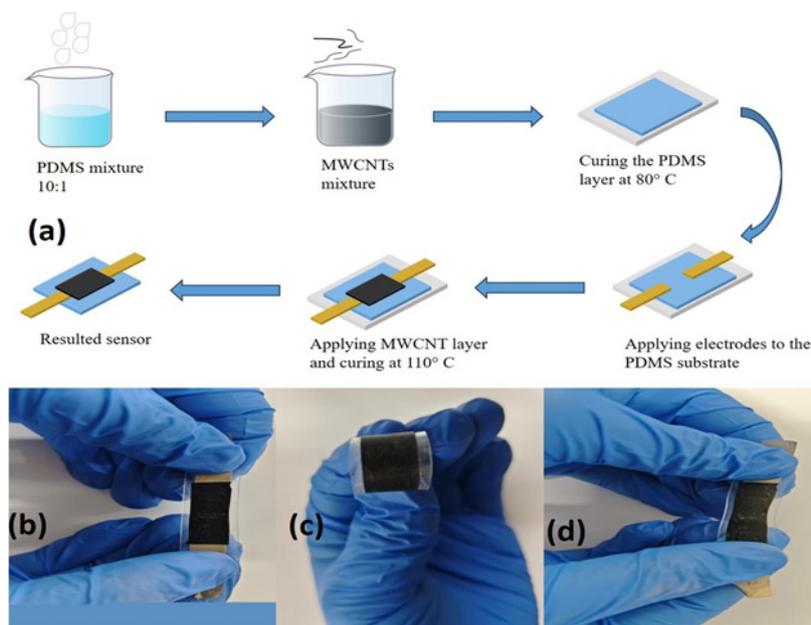
FIGURE 1. (a) Fabrication method (b) original position of the sensor (c) bent position, and (d) stretched position

SENSOR'S CHARACTERIZATION AND MORPHOLOGY

Figure 2 shows the morphology and structure of MWCNTs observed using scanning electron microscopy (SEM) images obtained using JSM-7900F SEM (Hitachi Corporation) operated at 10 kv. Energy dispersive X-ray (EDX) analysis was also performed with the same instrument.

SENSOR'S TESTING PLATFORM

The experimental platform was built for the MWCNTs-PDMS sensor tensile test, as shown in Figure 5(i) and 5(j). The mount was adjusted to the same plane, and the sensor was placed on it, and the apparatus was tightly clamped to align with the spiral rod and facilitate sensor stretching. The ends of the fabricated sensor were connected to a measuring instrument (Keithley 2400), which showed us the sensor's piezo resistivity and electrical conductivity. The screw rod of the mount was rotated in half a circle repeatedly (elongation 0.25 mm) to measure the sensor's resistance until the resistance of the sensor became infinite. The collected data were then analyzed using Origin software.

PROJECT DESCRIPTION

The main aim of the project was to develop a prototype of water level detection that can serve as a flood monitoring and early warning system. As mentioned earlier, our proposed system's hardware mainly consists of three main components: an Arduino Nano, flexible strain sensors, and a Bluetooth module (HC-05). After the deformation in the sensor's shape due to strain, its resistance will be changed, and if it crosses the threshold value, indications of safe, cautious, or dangerous conditions are displayed on the LCD, while the corresponding LED is activated.

WORKING OF OUR PROPOSED SYSTEM

The proposed system describes an Arduino-based alerting system that uses three flexible strain sensors to monitor and display the water level. The system employs three LEDs (Blue, Yellow, and Red) to indicate different alert statuses and a 16×2 LCD for displaying the water level and corresponding alert messages. Additionally, the data is printed to the Serial Monitor for debugging and real-time monitoring. Components required include: a) Arduino Nano: This is the main controller that processes the input from the flexible strain sensors and controls the LEDs and LCD, b) Three flexible strain sensors: Analog sensors (H1, H2, H3) have been used to provide varying resistance values based on their deformation statuses, c) Three LEDs (Blue, Yellow, and Red): Indicators for different alert statuses, and d) 16×2 LCD: Used to display resistance values and alert messages.

HARDWARE CONNECTION

The connection of the different components is described as:

Flexible stain sensor connections The three flexible strain sensors are connected to the Arduino's analog input pins A1, A2, and A3, with their anodes connected to 5 V on the Arduino Nano. The cathodes of the sensors are each connected to a 1 kΩ resistor and then to the GND pin on the Arduino.

LED connection The blue LED's anode (longer leg) is connected to digital pin 10, with its cathode connected to GND through a 1 kΩ series resistor. The yellow LED anode is connected to digital pin 11, and its cathode is connected to GND. Similarly, the red LED anode is connected to digital pin 12, and its cathode is also connected to GND.
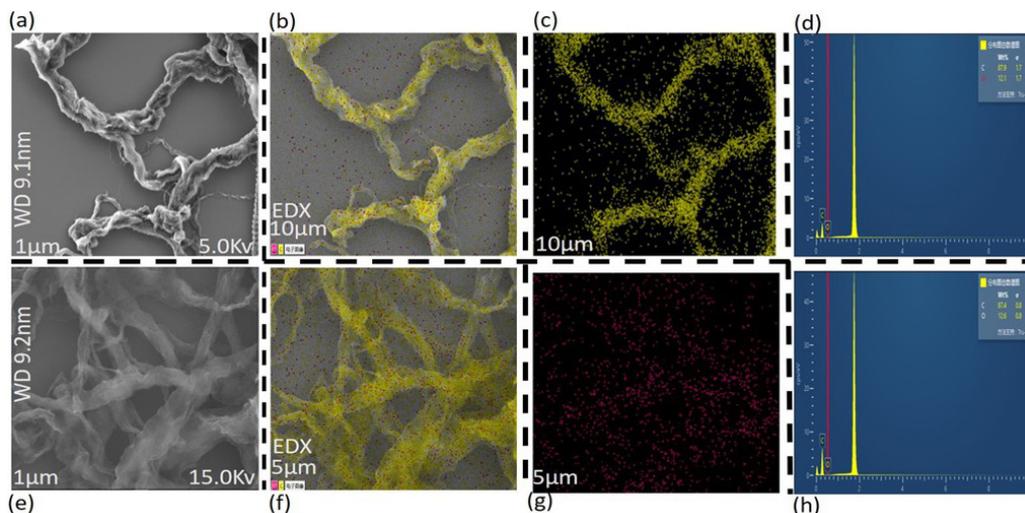

FIGURE 2. The SEM images of the MWCNTs

LCD connections The LCD's GND pin is connected to the Arduino Nano's GND (pin 4), and its VCC is connected to 5 V (pin 27). The SDA and SCL lines are connected to pins 24 and 23, respectively.

Bluetooth module (HC-05) connections The HC-05 module's RX pin is connected to the Arduino Nano's TX pin (pin 1), and its TX pin is connected to the Nano's RX pin (pin 2). The HC-05's GND is connected to the Arduino's GND, and its VCC is connected to the Arduino's VCC.

SYSTEM FUNCTIONALITIES

The system operation begins with the Arduino Nano continuously reading analog signals from the three flexible strain sensors connected to pins A1, A2, and A3. These analog values (0-1023) are converted into resistance values (in ohms), assuming a maximum resistance of 1 kΩ for each sensor. The calculated resistance values are then compared with predefined threshold levels to determine the alert status. When any resistance value is ≤ 490 Ω, the system enters Safe mode, activating the blue LED and displaying the message 'Safe'. If a resistance value exceeds 520 Ω, the system switches to Ready mode, indicated by the yellow LED and the message 'Ready'. When the resistance exceeds 500 Ω, Danger mode is triggered, the red LED is illuminated, and a 'Danger' alert is displayed. If all resistance values remain below 550 Ω, all LEDs are turned off and the message 'Below Threshold' is shown; these threshold values can be adjusted as required. The resistance data and corresponding alert messages are displayed on a 16×2 I²C LCD, which is updated twice per second, and are also printed to the Serial Monitor for real-time monitoring and debugging.
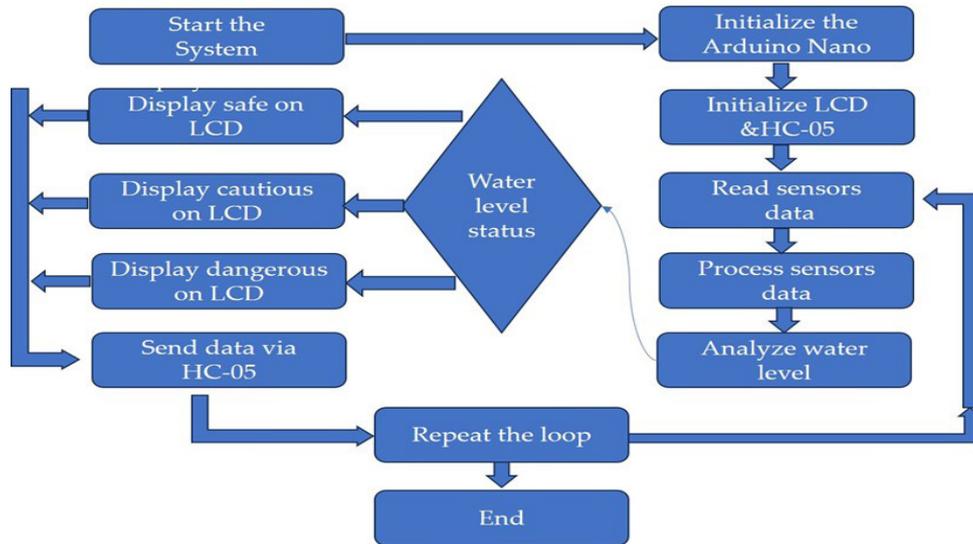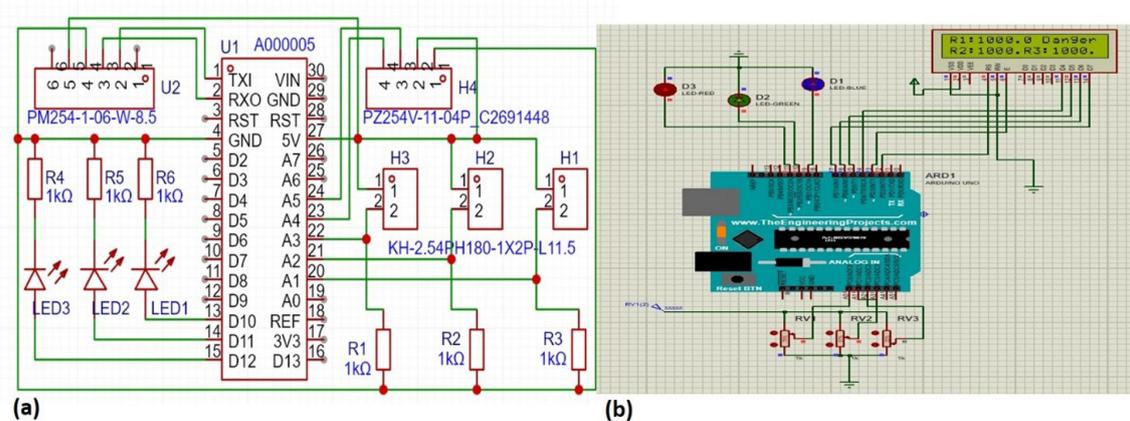

FIGURE 3. Flow chart of our proposed system

FIGURE 4. a) circuit diagram and b) simulation

HARDWARE CIRCUIT OPERATION AND DATA ACQUISITION PARAMETERS

The flood monitoring system is controlled by an Arduino Nano that acquires analog signals from three flexible strain sensors installed at different vertical levels. Each sensor is interfaced with the microcontroller's analog inputs (A1-A3) through a voltage divider, converting deformation-induced resistance changes into voltage signals. Data are digitized using the Arduino Nano's 10-bit ADC (0-5 V) and sampled at 2 Hz, which is adequate for capturing gradual water-level changes with stable, low-noise performance.

The acquired sensor values are displayed in real-time on a 16 × 2 I²C LCD module indicated as (H4) and simultaneously transmitted wirelessly through a Bluetooth module (HC-05) indicated as (U2). Operating at a baud rate of 9600 bps. A predefined threshold is applied to each sensor with its specific message to be printed on the LCD. Similarly, (H3) also has a particular threshold; when this value is reached, it activates a warning condition, indicated by an LED and a 'Danger mode' message on the LCD and Bluetooth interface.

RESULTS AND DISCUSSION

Firstly, the flexible strain sensors were made with different concentrations of MWCNTs (145 mg, 130 mg, and 120 mg). Their electrical conductivities are expressed by electrical resistance, which differs from each other. The sensor fabricated from 145 mg of MWCNTs has an initial resistance of 558-561Ω without deformation. The second has a resistance of 655-659Ω, and the third has a resistance of 734-737Ω without applying any strain. When we use some strain, the adjacent CNTs start getting apart from each other, which will affect the increase in total resistance due to tunneling resistance between these particles (Abot et al. 2015; Ferreira et al. 2013). Among the fabricated flexible strain sensors, the sensor with 130 mg of MWCTs has the highest gauge factor (GF), which is more than 5. The gauge factor is defined as $GF = \Delta R/\varepsilon R_0$, where ΔR is the change in resistance, R_0 is the initial resistance, and ε is the change in length of the sensor ($\Delta L/L$) due to strain. However, the relationship of relative change in resistance and the strain is not linear and experiences a sweeping wavelike rise after 15% strain. This is because a large number of the connected paths of CNTs begin to get apart, but few of them recombine simultaneously, and the effect of breaking is more significant. The sensor with the fewest MWCNTs in our situation has the most linear curve of the relative change in resistance against the applied strain, with a gauge factor of 2.25-2.62. The denser network made by MWCNTs generates more conductive paths, evading the drastic increase of resistance under stretching. When stretched, the electrical conductivity will not significantly decrease as long as the effective conductive paths are maintained by a sufficient quantity of MWCNTs (Georgousis et al. 2015). The details are shown in Figure 5(a)-5(f).

Figure 5 shows the electromechanical characterization of the fabricated flexible strain sensors utilized in our proposed system (a-c) plots of relative resistance change (ΔR/R) versus applied strain for sensor 1, sensor 2, and sensor 3, respectively, together with linear fitting, which shows stable and nearly linear strain-response behavior. (d-f) show the corresponding gauge factor (GF) distribution of sensor 1, sensor 2, and sensor 3, across the applied strain range, highlighting the sensitivity consistency and reliability of all three fabricated sensors.

DURABILITY TEST

The flexible strain sensor exhibited a stable resistance response with negligible signal drift during cyclic loading-unloading at 20% strain and 100 mm/min, indicating strong mechanical resilience and electrical stability under repeated deformation relevant to flood monitoring, as shown in Figure 5(k). Environmental robustness is essential for reliable flood monitoring under harsh and variable outdoor conditions. The proposed flexible strain sensor demonstrates strong resistance to humidity, prolonged water exposure, and temperature variations, while maintaining structural integrity and stable electrical performance without delamination or signal degradation. Its encapsulated design further protects against water ingress and contaminants, supporting consistent long-term, real-time flood monitoring.

BENCHMARK COMPARISON

Compared to conventional flood monitoring devices such as pressure-based, floating, and ultrasonic sensors, as well as existing water-level early warning systems, the proposed MWCNTs–PDMS flexible strain sensor offers clear advantages. These include high sensitivity to minute water-level variations (as small as 0.1 mm), rapid real-time response, and flexible deployment across diverse environments. This comparison highlights the proposed system's improved performance and supports its potential for enhanced flood monitoring and early warning applications.

We tested our proposed system, and it performed as expected. Figure 6(a) shows the display of data on both the serial monitor and the LCD. Figure 6(b) shows no deformation in the sensor's structure, so all three LEDs are off. When the water level reaches the first sensor, as we have mentioned, a certain threshold value for that sensor is reached, so when the deformation increases and crosses the mentioned threshold value, the blue LED will turn on, and the same case will be for the rest of the two sensors (Figure 6(c) and 6(d)). It is clear from the images that we can receive the actual data on our phone twice a second, which is transmitted by HC-05. In the given Figures, S1, S2, and S3 are used to indicate the value of sensor 1, sensor 2, and sensor 3.
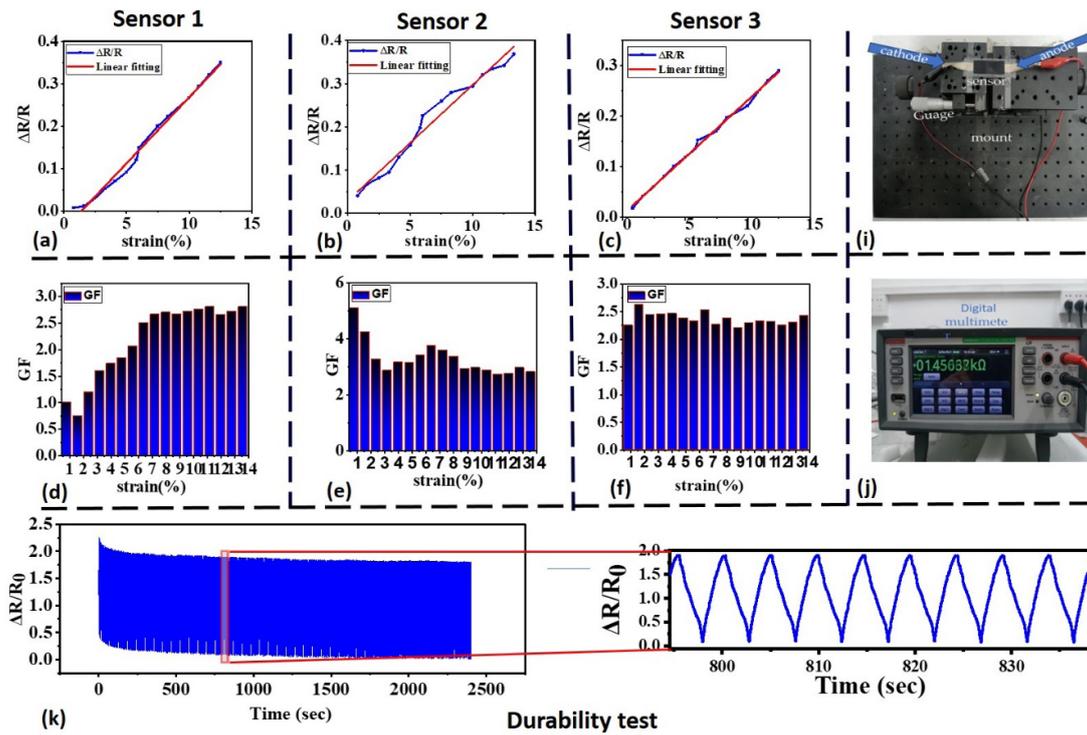
FIGURE 5. (a), (b), (c) relative change of resistance versus strain after applying strain, (d), (e), (f) gauge factor under variable strain, (i, j) testing platform, and (k) durability test

FIGURE 6. (a) data display (b) when the water level is low (c) when the water level reaches the first sensor (blue LED on), and (d) when the water level touches the second sensor (yellow LED on)

CONCLUSIONS

By designing a system that uses forefront flexible strain sensors for real-time water level monitoring, the project successfully fulfilled its primary objectives. The deformation of these sensors is essential to the system's novel technique, which makes precise water level detection and measurement possible. Three basic parts comprise the suggested system: An Arduino Nano module, flexible strain sensors, and C-language software for handling the data collection. The system's ability to achieve efficient flood control and monitoring has been shown by its hardware and software integration, giving users an effective solution for real-time data collection and analysis in a range of applications. Because of this project's success, flexible strain sensors can be used in environmental monitoring systems that have excellent feasibility and reliability.

REFERENCES

Abot, J.L., Kiyono, C.Y., Thomas, G.P. & Silva, E.C. 2015. Strain gauge sensors comprised of carbon nanotube yarn: Parametric numerical analysis of their piezoresistive response. *Smart Materials and Structures* 24(7): 075018. https://doi.org/10.1088/0964-1726/24/7/075018

Chang, Z., Li, Q., Ding, L., Chen, Y., Li, X., Li, L., Ullan, R., Jian, A., Zhang, Q. & Sang, S. 2023. Tailoring fractal structure via 3D printing to achieve flexible stretchable electrodes based on Ecoflex/CNT/CF. *Materials Today Communications* 38: 107721. https://doi.org/10.1016/j.mtcomm.2023.107721

Duan, A., Lin, X., Ding, T., Sun, Y., Wang, L., Huang, C., Li, B. & Wang, Y. 2025. Flexible strain sensors based on carbon nanotubes and silver nanowires and polydimethylsiloxane. *Journal of Materials Science: Materials in Electronics* 36(7): 445. https://doi.org/10.1007/s10854-025-14498-4

Duan, L., D'hooge, D.R. & Cardon, L. 2020. Recent progress on flexible and stretchable piezoresistive strain sensors: From design to application. *Progress in Materials Science* 114: 100617. https://doi.org/10.1016/j.pmatsci.2019.100617

Dual, S.A., Llerena, Z.B., Sündermann, S., Cesarovic, N., Kron, M., Magkoutas, K., Hengsteler, J., Falk, V., Starck, C., Meboldt, M., Vörös, J. & Schmid, D.M. 2020. Continuous heart volume monitoring by fully implantable soft strain sensor. *Advanced Healthcare Materials* 9(19): 2000855. https://doi.org/10.1002/adhm.202000855

Ferreira, A., Martínez, M.T., Ansón-Casaos, A., Gómez-Pineda, L.E., Vaz, F. & Lanceros-Méndez, S. 2013. Relationship between electromechanical response and percolation threshold in carbon nanotube/poly (vinylidene fluoride) composites. *Carbon* 61: 568-576. https://doi.org/10.1016/j.carbon.2013.05.038

Fu, Z., Zhu, J., Zhang, Q., Tang, W., Pei, Z., Zeng, Y., Zhang, C. & Li, Q. 2024. Graphene-based flexible high-resolution pressure sensors. *Physica Status Solidi A* 240: 01007. https://doi.org/10.1002/pssa.202400107

Geng, J., Li, Q., Liu, Z., Ding, L., Su, F., Ullan, R., Minami, T. & Sang, S. 2025. Multifunctional electronic glove via 3D printing for dual-mode pressure-temperature sensing and interactive applications. *Chemical Engineering Journal* 522: 167129. https://doi.org/10.1016/j.cej.2025.167129

Georgousis, G., Pandis, C., Kalamiotis, A., Georgiopoulos, P., Kyritsis, A., Kontou, E., Pissis, P., Micusik, M., Czanikova, M., Kulicek, J. & Omastova, M. 2015. Strain sensing in polymer/carbon nanotube composites by electrical resistance measurement. *Composites Part B: Engineering* 68: 162-169. https://doi.org/10.1016/j.compositesb.2014.08.027

Han, F., Li, M., Ye, H. & Zhang, G. 2021. Materials, electrical performance, mechanisms, applications, and manufacturing approaches for flexible strain sensors. *Nanomaterials* 11(5): 1220. https://doi.org/10.3390/nano11051220

Hang, C.Z., Zhao, X.F., Xi, S.Y., Shang, Y.H., Yuan, K.P., Yang, F., Wang, Q.G., Wang, J.C., Zhang, D.W. & Lu, H.L. 2020. Highly stretchable and self-healing strain sensors for motion detection in wireless human-machine interface. *Nano Energy* 76: 105064. https://doi.org/10.1016/j.nanoen.2020.105064

Heng, W., Solomon, S. & Gao, W. 2022. Flexible electronics and devices as human-machine interfaces for medical robotics. *Advanced Materials* 34(16): 2107902. https://doi.org/10.1002/adma.202107902

Ji, B., Wang, X., Liang, Z., Zhang, H., Xia, Q., Xie, L., Yan, H., Sun, F., Feng, H., Tao, K. & Yin, E. 2024. Flexible strain sensor-based data glove for gesture interaction in the metaverse: A review. *International Journal of Human–Computer Interaction* 40(21): 6793-6812. https://doi.org/10.1080/10447318.2023.2212232

Ji, C., Zhang, Q., Li, Q., Pei, Z., Zhao, D., Yuan, Z., Wang, J., Zhang, W. & Sang, S. 2021. A graphical pressure sensor array with multilayered structure written through graphene ink on cellulose paper substrate. *Macromolecular Materials and Engineering* 307(2): 2270009. https://doi.org/10.1002/mame.202100643

Khan, A., Gupta, S.K., Assiri, E.I., Rashid, M., Mohammed, Y.T., Najim, M. & Alharbi, Y.R. 2020. Flood monitoring and warning system: Het-Sens a proposed model. *Proceedings of the 2nd International Conference on Computer and Information Sciences (ICCIS)*. 10.1109/ICCIS49240.2020.9257693

Lan, W., Wu, X., Ding, Q., Zhou, T., Liao, Y., Gao, S., Liu, Y. & Wei, B. 2024. Highly sensitive flexible strain sensors with novel tubular fiber design for human motion monitoring. *Journal of Materials Science: Materials in Electronics* 35(14): 962. https://doi.org/10.1007/s10854-024-12641-1

Li, B., Luo, J., Huang, X.W., Lin, L.W., Wang, L., Hu, M.J., Tang, L.C., Xue, H.G., Gao, J.F. & Mai, Y.W. 2020. A highly stretchable, super-hydrophobic strain sensor based on polydopamine and graphene reinforced nanofiber composite for human motion monitoring. *Composites Part B: Engineering* 181: 107580. https://doi.org/10.1016/j.compositesb.2019.107580

Li, Q., Sang, S., Zhang, Q. & Pei, Z. 2021. 3D printed stretchable sensor based on silver nanowires-polydimethylsiloxane. *Modern Physics Letters B* 35(30): 2150466. https://doi.org/10.1142/S0217984921504662

Li, S., Xu, R., Wang, J., Yang, Y., Fu, Q. & Pan, C. 2022. Ultra-stretchable, super-hydrophobic and high-conductive composite for wearable strain sensors with high sensitivity. *Journal of Colloid and Interface Science* 617: 372-382. https://doi.org/10.1016/j.jcis.2022.03.020

Nihei, Y. & Kimizu, A. 2008. A new monitoring system for river discharge with horizontal acoustic doppler current profiler measurements and river flow simulation. *Water Resources Research* 44(4): W00D20. https://doi.org/10.1029/2008WR006970

Peng, J., Wang, B., Cheng, H., Yang, R., Yin, Y., Xu, S. & Wang, C. 2022. Highly sensitive and superhydrophobic fabric sensor based on AgNPs/polypyrrole composite conductive networks for body movement monitoring. *Composites Science and Technology* 227: 109561. https://doi.org/10.1016/j.compscitech.2022.109561

Ren, Y., Zhang, X., Liu, J., Wang, Q. & Li, M. 2024. Capacitive and non-contact liquid level detection sensor based on interdigitated electrodes with flexible substrate. *Electronics* 13(11): 2228. https://doi.org/10.3390/electronics13112228

Roach, D.J., Yuan, C., Kuang, X., Li, V.C.F., Blake, P., Romero, M.L., Blake, P., Hammel, I., Yu, K. & Qi, H.J. 2019. Long liquid crystal elastomer fibers with large reversible actuation strains for smart textiles and artificial muscles. *ACS Applied Materials & Interfaces* 11(21): 19514-19521. https://doi.org/10.1021/acsami.9b04401

Satria, D., Yana, S., Munadi, R. & Syahreza, S. 2018. Design of information monitoring system flood based Internet of Things (IoT). *Proceedings of MICoMS* 201: pp. 337-342. https://doi.org/10.1108/S2516-2853201801

Sebicho, S.W., Lou, B. & Anito, B.S. 2024. A multi-parameter flexible smart water gauge for monitoring urban water levels. *Eng.* 5(1): 198-216. https://doi.org/10.3390/eng5010011

Shen, Z., Liu, F., Huang, S., Wang, H., Yang, C., Hang, T., Hang, T., Tao, J., Xia, W.H. & Xie, X. 2022. Progress of flexible strain sensors for physiological signal monitoring. *Biosensors and Bioelectronics* 211: 114298. https://doi.org/10.1016/j.bios.2022.114298

Shin, D.M., Hong, S.W. & Hwang, Y.H. 2020. Recent advances in organic piezoelectric biomaterials for energy and biomedical applications. *Nanomaterials* 10(1): 123. https://doi.org/10.3390/nano10010123

Sunkpho, J. & Ootamakorn, C. 2011. Real-time flood monitoring and warning system. *Songklanakarin Journal of Science & Technology* 33(2): 227-235.

Tariq, M.A.U.R. & Van De Giesen, N. 2012. Floods and flood management in Pakistan. *Physics and Chemistry of the Earth, Parts A/B/C* 47: 11-20. https://doi.org/10.1016/j.pce.2011.08.014

Xiang, H., Zhang, Y., Li, S., Chen, W. & Wang, L. 2023. Enabling a paper-based flexible sensor to work under water with exceptional long-term durability. *ACS Sustainable Chemistry & Engineering* 11(23): 8667-8674. https://doi.org/10.1021/acssuschemeng.3c01870

Xu, X., Wu, S., Cui, J., Yang, L., Wu, K., Chen, X. & Sun, D. 2021. Highly stretchable and sensitive strain sensor based on polypyrrole coated bacterial cellulose fibrous network for human motion detection. *Composites Part B: Engineering* 211: 108665. https://doi.org/10.1016/j.compositesb.2021.108665

Yang, H., Gong, L.H., Zheng, Z. & Yao, X.F. 2020. Highly stretchable and sensitive conductive rubber composites with tunable piezoresistivity for motion detection and flexible electrodes. *Carbon* 158: 893-903. https://doi.org/10.1016/j.carbon.2019.11.079

Yin, R., Wang, D., Zhao, S., Lou, Z. & Shen, G. 2021. Wearable sensors-enabled human-machine interaction systems: From design to application. *Advanced Functional Materials* 31(11): 2008936. https://doi.org/10.1002/adfm.202008936

Yuan, J., Li, Q., Ding, L., Shi, C., Wang, Q., Niu, Y. & Xu, C. 2022. Carbon black/multi-walled carbon nanotube-based, highly sensitive, flexible pressure sensor. *ACS Omega* 7(48): 44428-44437. https://doi.org/10.1021/acsomega.2c06548

Yuan, L., Gao, X., Kang, R., Zhang, X., Meng, X., Li, X. & Li, X. 2024. Flexible strain sensors based on an interlayer synergistic effect of nanomaterials for continuous and noninvasive blood pressure monitoring. *ACS Applied Materials & Interfaces* 16(20): 26943-26953. https://doi.org/10.1021/acsami.4c04134

*Corresponding author; email: liqiang02@tyut.edu.cn