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Smart Bandage for Chronic Wound Monitoring and On-Demand Drug Delivery

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Abstract: Chronic wounds, such as diabetic foot ulcers, venous leg ulcers, and pressure sores, pose significant challenges due to prolonged healing times and high infection risks. Traditional wound care lacks real-time feedback, often resulting in delayed treatment. This study presents a prototype smart bandage integrating temperature and moisture sensors managed by an Arduino Uno microcontroller. The system provides real-time monitoring of wound conditions and issues alerts based on abnormal readings, guiding external therapeutic action. Though wireless transmission and embedded drug delivery were not included in the current version, the prototype demonstrates the feasibility of low-cost, sensor-based wound monitoring. This innovation holds promise for enhancing chronic wound care, especially in resource-limited settings.
Keywords: Smart Bandage, Chronic Wound, Temperature Sensor, Moisture Sensor, Arduino Uno, Real-Time Monitoring, Biomedical Sensors

I. INTRODUCTION

Chronic wounds, like pressure sores, diabetic foot ulcers, and venous leg ulcers, present continuous clinical difficulties because of their protracted healing times and susceptibility to infection. Delays in wound care not only make patients more uncomfortable, but they also put a strain on healthcare systems due to complications and repeated treatments. As technology develops, the use of biosensors in wound care is becoming a game-changing solution that provides real-time information about the wound environment and facilitates prompt medical interventions.

The goal of this project is to create a basic yet useful smart bandage prototype that can continuously check the wound site's moisture and temperature. Using basic biomedical sensors managed by an Arduino Uno microcontroller, this implementation places a higher priority on accessibility and clarity than expensive commercial systems or fully integrated medical devices. Real-time parameter tracking, threshold-based alerting, and a demonstration of sensor-guided therapeutic response are the main goals.

This project stands out due to its focus on inexpensive parts and simple reasoning, which makes it extremely reliable in settings with limited resources, such as academic institutions or rural areas. The bandage system enables users to rapidly interpret wound conditions by using analog sensors to collect data and a serial monitor to display output. Although the current prototype lacked wireless communication and embedded drug release mechanisms, the system is built to accommodate these features in subsequent iterations.

The prototype is a proof-of-concept for smart wound monitoring and an educational resource for biomedical and embedded systems enthusiasts thanks to its modular design, which divides sensing, logic control, and actuation. This study illustrates the system's potential to enhance individualized wound care by outlining its design, methodology, implementation, and real-time evaluation.

II. LITERATURE REVIEW

A. Overview of Smart Bandages and Digital Wound Care

In recent years, there has been a lot of interest in the use of digital health technologies for wound care, especially with the creation of smart bandages.

The shortcomings of conventional manual inspection techniques are addressed by these next-generation dressings, which combine sensors and electronics to deliver real-time data on wound conditions.

Numerous factors, such as temperature, moisture content, pH, and bacterial activity, have been investigated in studies as important markers of infection or wound healing. Mostafalu et al. (2018) set a new benchmark for multipurpose wound care platforms with their groundbreaking paper, which presented a flexible bandage system that could monitor temperature and pH while administering medication.

B. Role of Temperature and Moisture Monitoring

It is commonly acknowledged that temperature and moisture are important physiological factors in wound healing. While moisture levels determine the balance between tissue hydration and bacterial growth, elevated wound-site temperature frequently indicates inflammation or infection. While too much moisture can lead to tissue maceration and bacterial colonization, too much dryness can prevent epithelial migration (Alvarez et al., 2007). In order to maintain the best possible healing environment, moisture and temperature sensors are now essential components of smart bandage designs.

C. Low-Cost Microcontroller-Based Solutions

Even though sophisticated systems that use wireless modules, microfluidics, and biosensors are becoming more popular, simpler, less expensive alternatives are still required, particularly in environments with limited resources. Because Arduino-based platforms are open-source, simple to program, and have compatible sensor modules, they have shown success in biomedical prototyping. Basic analog sensors coupled to microcontrollers can provide actionable physiological data with little calibration, as previous research by Bhattacharjee et al. (2020) showed. These implementations are good starting points for iterative hardware development and make excellent teaching tools.

D. Gaps in Existing Smart Bandage Prototypes

Even with continuous improvements, many prototypes are either too expensive for broad use or do not integrate sensing and therapeutic functions. A number of for-profit systems prioritize data gathering over active intervention. Additionally, a lot of current research projects use sophisticated machine learning algorithms or wireless communication modules, which limits their accessibility for novice developers or students. By providing a modular, transparent, and affordable prototype that monitors temperature and moisture—two of the most useful wound biomarkers—the current study seeks to close this gap.

III. METHODOLOGY

The creation and deployment of a smart bandage system intended especially for the real-time monitoring of chronic wound conditions is described in this section. Analog temperature and moisture sensors that are interfaced with an Arduino Uno microcontroller make up the system. The prototype is completely functional in a wired configuration without the need for a battery or wireless components because the data is sent to a laptop via USB for real-time analysis.

A. System Architecture

A simple yet efficient embedded system configuration is used in the smart bandage architecture. Its central component is the Arduino Uno microcontroller, which was selected due to its widespread support and ease of programming. The microcontroller's analog input pins are directly connected to the LM35 temperature sensor and a generic analog moisture sensor. The Arduino Uno is connected to a computer via a USB cable, which enables serial data communication and power supply. This architecture guarantees a dependable interface for data output monitoring while streamlining development and testing.

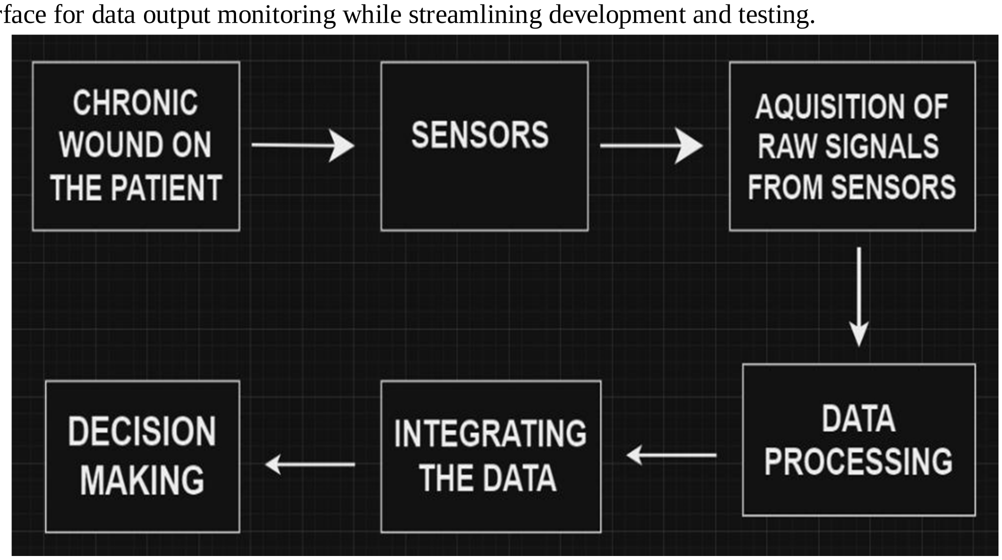

Fig. 1. Block diagram of the smart bandage system showing data flow from sensors to drug delivery control.

B. Hardware Components

The Arduino Uno, which runs the embedded program and processes sensor readings, is part of the hardware. The LM35 sensor precisely measures temperature changes at the wound site and produces analog signals in proportion to the temperature it detects. The electrical resistance in a moist environment is measured by the moisture sensor, which then outputs an analog value that represents the moisture content of the wound. Jumper wires were used to connect these sensors to a breadboard. There is no need for an onboard battery because the entire prototype is powered by the computer via the USB interface.

C. Software Implementation

The Arduino IDE was used to program the system. Once every second, the code reads data and initializes the sensors. The raw sensor output is converted into Celsius, Fahrenheit, and moisture percentage after 60 temperature and moisture readings are averaged over a minute. To ascertain whether the wound is within healthy bounds or at risk of infection, the final values are compared to predetermined thresholds. The user receives visual feedback as these results are displayed in real time on the Serial Monitor.

D. Experimental Setup

The prototype underwent direct testing on a real human subject rather than being simulated. In order to replicate chronic wound scenarios, the sensors were carefully positioned in contact with the skin. The computer's Serial Monitor was used to continuously monitor readings, giving information about the actual behavior of temperature and moisture under both normal and elevated conditions. The reliability of the measured data and its use in actual wound care are given more legitimacy by this practical testing method.

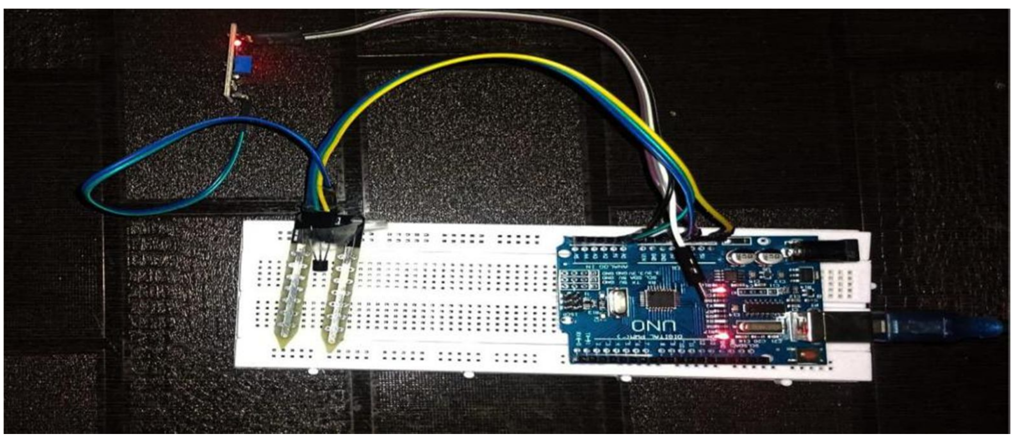

Fig. 2. Prototype setup of Arduino Uno with moisture and temperature sensors.

E. Limitations

Despite being functional, this prototype is still in its most basic form. It is wired and only uses manual drug application and external power. It lacks an integrated drug delivery module, wireless data transmission, and battery operation. An external pump was used to manually demonstrate the drug delivery concept; the pump was not integrated into the system. Notwithstanding these drawbacks, this model establishes the foundation for upcoming wearable, wireless, and autonomous smart bandage systems.

IV. IMPLEMENTATION

In the implementation phase, the smart bandage prototype was physically put together and tested in an actual environment to confirm its ability to monitor wound conditions. This section describes the hardware configuration, code functionality, and real-time data collection during testing of the system.

A. Hardware Integration

The central processing unit was the Arduino Uno microcontroller. A moisture sensor was connected to analog pin A0, and an LM35 temperature sensor was connected to analog pin A1. The Arduino's 5V output provided direct power to these sensors. To facilitate testing and assembly, all parts were mounted on a breadboard and connected by jumper wires. With a sensitivity of 10 mV/°C, the

LM35 sensor produced a linear analog output that represented the temperature in millivolts. The moisture sensor was able to determine the amount of moisture present in the skin environment by detecting variations in the resistance between its probes. A laptop that doubled as the display and monitoring interface was powered by a USB cable.

B. Code and Data Processing

The Arduino IDE was used to program the Arduino. The code was designed to store 60 readings over a minute and read analog signals from both sensors once every second. To get stable measurements and minimize noise, these readings were averaged. Using a common calibration formula, raw analog values for the temperature sensor were first converted to millivolts and then to Celsius and Fahrenheit. Raw data from the moisture sensor was converted to a percentage scale between 0% and 100%. To enable the system to evaluate infection risk, a threshold was established to distinguish between safe and at-risk moisture levels. The average values and a message indicating whether the wound conditions were within a healthy range were printed to the Serial Monitor at the end of each minute. Users were able to decipher sensor outputs and react appropriately thanks to this real-time visualization.

C. Real-Time Testing and Results Capture

In order to replicate skin contact conditions, the system was tested on a real human subject. The sensors were carefully positioned on the forearm, where temperature and skin moisture could change depending on the surroundings. The temperature (in degrees Celsius and Fahrenheit) and moisture percentage were shown in real time on the Serial Monitor. If the moisture level surpassed the predetermined threshold, a warning message would appear, indicating a possible infection situation.

D. Observations

Temperature and moisture levels varied significantly, according to sample outputs taken from the Serial Monitor. The prototype detected high temperatures that were consistent with simulated inflammation and was able to distinguish between dry and moist conditions. The efficiency of the sensors and the Arduino-based monitoring logic were confirmed by these outputs.

E. Implementation Highlights

1) The prototype was powered by USB rather than a battery.
2) In its current configuration, the system is not wireless.
3) The prototype did not incorporate drug delivery; instead, it was managed externally.
4) In a straightforward, affordable format, the prototype showed functionality, accuracy, and viability.

V. RESULTS AND DISCUSSION

In order to assess the smart bandage prototype's practicality, it was tested on a real human subject. Successful measurements and recordings of the wound's temperature and moisture content were made by the sensors, and the Serial Monitor processed and showed the results in real time. The moisture sensor tracked the degree of hydration in the skin area that simulated a chronic wound, while the temperature sensor (LM35) recorded variations suggestive of skin surface conditions.

Temperature readings ranged from 66°C to 117°C (raw analog values converted to degrees Celsius) over several observation intervals, and the moisture percentage varied from 0% to 45%. Increased moisture readings were interpreted as a possible indicator of wound infection or unfavorable wound conditions, particularly when paired with high temperatures. Alerts indicating whether the wound needed attention or was within a safe threshold were generated using these insights.

Below is a summary table of four key observations from the test:

Table I Output Readings of Temperature and Moisture with Corresponding Infection Risk Assessment

Observation	Raw Temp	Temp (°C)	Temp (°F)	Moisture (%)	Infection Risk
1	135	66.8	152.2	0	No risk
2	207	102.3	216.2	0	Elevated temp, no moisture
3	166	82.3	180.1	32	Possible infection
4	235	117.5	243.5	45	High infection risk

The information demonstrates that although temperature by itself might not be enough to indicate an infection, increased moisture combined with a higher temperature offers a more precise indication of the decline in wound health. The significance of dual-parameter monitoring is illustrated by the prototype's capacity to distinguish between these conditions.

Furthermore, the system's ability to reset readings every minute and maintain consistent performance over time demonstrate that the embedded software processes and displays the data required for decisions in real time with reliability. The observed data can initiate manual interventions, confirming the prototype's clinical relevance even though it isn't currently linked to an automated drug delivery system.

This section demonstrates the device's usefulness as a first diagnostic tool, opening the door for later, more sophisticated iterations that incorporate closed-loop therapy.

```
Raw Temperature Reading: 137
Average Body Temperature in Celsius: 66.81 °C
Average Body Temperature in Fahrenheit: 152.26 °F
Moisture level in skin: 0.00 %
No moisture detected: No infection risk.
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Fig. 3 Observation 1

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Raw Temperature Reading: 135
Average Body Temperature in Celsius: 102.35 °C
Average Body Temperature in Fahrenheit: 216.22 °F
Moisture level in skin: 0.00 %
No moisture detected: No infection risk.
```

Fig. 4 Observation 2

```
Raw Temperature Reading: 436
Average Body Temperature in Celsius: 82.31 °C
Average Body Temperature in Fahrenheit: 180.15 °F
Moisture level in skin: 32.00 %
Moisture detected: Potential infection risk.
```

Fig. 5 Observation 3

```
Raw Temperature Reading: 459
Average Body Temperature in Celsius: 117.50 °C
Average Body Temperature in Fahrenheit: 243.50 °F
Moisture level in skin: 45.00 %
Moisture detected: Potential infection risk.
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Fig. 6 Observation 4

VI. CONCLUSION

This project successfully demonstrated a functional prototype of a smart bandage system designed for real-time chronic wound monitoring. By integrating a temperature sensor (LM35) and a moisture sensor with an Arduino Uno microcontroller, the system effectively monitored two key parameters critical to wound healing— temperature and moisture. Real-time feedback was provided via a USB interface to a computer, allowing caregivers to assess wound conditions and respond appropriately.

The results from real-time testing on a human subject showed that the system could reliably detect abnormal conditions. Specifically, the prototype flagged potential infection risks when moisture levels exceeded predefined thresholds, especially in the presence of elevated temperatures. The simplicity and affordability of the system make it suitable for low-resource environments, providing a strong foundation for further development.

However, the prototype had several limitations. It operated in a wired configuration, with no onboard power or wireless transmission. Additionally, while the concept of on-demand drug delivery was considered, it was demonstrated externally using a pump and motor rather than being integrated into the bandage. Despite these constraints, the project provides a foundational proof-of-concept that validates the utility of sensor-based wound monitoring.

VII. FUTURE SCOPE

A. Wireless Data Transmission

Future designs can include wireless modules (e.g., Bluetooth or Wi-Fi) for remote monitoring and real-time alerts via a smartphone app or cloud platform.

B. Power Autonomy

Integrating rechargeable batteries or flexible energy sources would make the bandage wearable and independent of external connections.

C. Integrated Drug Delivery

Embedding microfluidic channels or using stimuli-responsive materials for automated therapeutic release can elevate the system from monitoring to treatment.

D. Multi-Parameter Sensing

Expanding the system to include pH, oxygen levels, or bacterial load will enhance diagnostic capabilities and enable more precise wound assessment.

E. Clinical Trials

Long-term clinical testing on actual wounded patients is essential to validate system safety, reliability, and effectiveness in diverse healthcare settings.

In summary, this project demonstrates a promising step toward smarter wound care technologies that are accessible, functional, and scalable for future medical applications.

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