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Smart Bandage with Multi-Drug Deliver System

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Abstract
Chronic wounds and post-surgical infections remain significant challenges in modern healthcare, necessitating the development of intelligent and responsive treatment systems. This paper presents the design and implementation of a Smart Bandage with Multi-Drug Delivery System, integrating biomedical sensing, real-time monitoring, and automated drug administration into a compact wearable platform. The proposed system utilizes an ESP32 microcontroller as the central processing unit, interfaced with a suite of sensors including moisture, pH, temperature, and SpO_2 *sensors, to continuously monitor wound conditions. Sensor data is displayed via an onboard LCD and transmitted wirelessly using IoT technology for remote access and clinical supervision. The innovative feature of this system is its ability to deliver specific medications through a stepper motor-driven 3D drug injector, which is activated based on sensor feedback or remote-control commands. This closed-loop feedback mechanism ensures timely and personalized treatment, potentially reducing healing time and minimizing complications. The smart bandage framework offers a scalable and cost-effective solution for remote healthcare, with applications in chronic wound management, military medicine, and post-operative care. Experimental validation demonstrates the system's accuracy in parameter detection and its effectiveness in controlled drug delivery, marking a significant advancement in the field of smart biomedical devices.*

Keywords: *Internet of Things (IoT), Biomedical Sensors, Wearable Medical Devices, Smart Bandage, Multi-Drug Delivery.*

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I. INTRODUCTION

Wound healing is a complex and dynamic biological process involving the coordinated action of cells, signaling molecules, and the surrounding environment. In clinical scenarios such as chronic ulcers, burns, and post-surgical wounds, effective and timely treatment is crucial to minimize complications such as infection, delayed healing, or even amputation. Traditional wound care often relies on passive dressing and routine inspection, which may not provide sufficient real-time data or allow timely therapeutic intervention. With advancements in wearable electronics, biomedical sensing, and Internet of Things (IoT) technologies, there is a growing interest in developing *smart bandages*—intelligent wound dressings that monitor healing parameters and respond actively to the wound environment. A *smart bandage* is an advanced form of wound dressing that integrates sensors, microcontrollers, and actuators to provide real-time data collection and intelligent treatment delivery. By continuously monitoring key physiological indicators—such as moisture level, temperature, pH, and blood oxygen saturation (SpO_2)—smart bandages enable healthcare providers to assess the wound condition more precisely and intervene when necessary. The incorporation of microelectronic components, wireless communication modules, and cloud-based data storage transforms these devices into powerful tools for personalized and remote healthcare.

The rapid development of the *Internet of Things (IoT)* has significantly contributed to the evolution of smart healthcare systems. IoT facilitates seamless communication between medical devices and healthcare providers, enabling remote monitoring, real-time alerts, and data-driven decision-making. In the context of wound management, IoT integration allows the smart bandage to transmit sensor data to medical professionals in real time, ensuring continuous patient supervision even outside clinical settings. This capability is particularly beneficial for elderly patients, individuals with limited mobility, or those living in remote areas, where frequent hospital visits are impractical. In addition to monitoring, an equally important aspect of wound management is timely drug administration. Conventional bandages require manual application of medications, which may lead to under- or over-dosing, as well as increased risk of contamination. To address this challenge, our system incorporates a *multi-drug delivery mechanism* using a stepper motorcontrolled 3D injector. This automated delivery system allows for precise dispensing of different drugs in response to sensor feedback, ensuring optimal treatment based on real-time wound conditions. The mechanism can administer antibiotics, anti-inflammatory agents, or healing promoters directly into the wound site without manual intervention, improving therapeutic outcomes and patient compliance.

The core of the proposed system is built around the ESP32 microcontroller, chosen for its high processing power, low energy consumption, and built-in Wi-Fi and Bluetooth capabilities, making it ideal for IoT applications. The ESP32 interfaces with various sensors—moisture, pH, temperature, and SpO□—to collect data and control the actuator-based drug delivery system. The processed data is displayed locally on an LCD and transmitted remotely via an IoT platform, enabling real-time monitoring and remote actuation if needed. This paper presents the design, development, and validation of a *Smart Bandage with Multi-Drug Delivery System* that brings together the power of IoT, wearable biosensing, and automated therapeutic intervention. The system aims to provide a costeffective, intelligent, and scalable solution to modern wound care challenges, offering significant benefits in both clinical and homebased settings.

BLOCK DIAGRAM

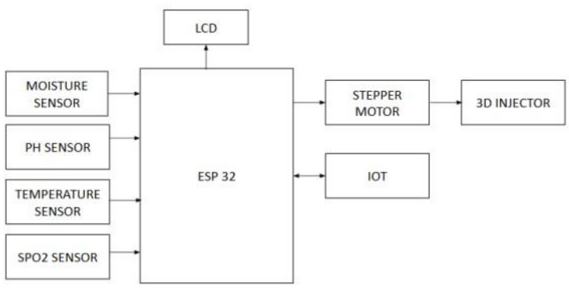

Figure 1: Block Diagram

II. SYSTEM METHODOLOGY

2.1 ESP32 Microcontroller

The ESP32 microcontroller serves as the central processing unit of the smart bandage system. It is a powerful, low-power system-on-chip (SoC) with integrated Wi-Fi and Bluetooth, making it highly suitable for IoT applications. In this project, the ESP32 collects data from various sensors—including moisture, pH, temperature, and SpO□ sensors—through its GPIO (General Purpose Input/Output) pins and ADCs (Analog-to-Digital Converters). The microcontroller processes this real-time physiological data, makes decisions based on pre-defined thresholds, and triggers appropriate responses such as activating the drug delivery mechanism or sending alerts through the IoT interface. Its compact size, energy efficiency, and rich set of features make it ideal for integration into wearable biomedical devices like smart bandages.

2.2 Moisture Sensor

The moisture sensor in the system plays a vital role in monitoring the hydration level of the wound environment. Maintaining optimal moisture is essential for wound healing, as too much moisture can cause maceration while too little can desiccate tissues and slow recovery. This sensor detects the presence and level of fluid within the bandage and sends analog signals to the ESP32. The data helps the system determine whether the wound is excessively wet or dry, prompting corresponding actions like alerting medical personnel or activating the 3D injector to deliver a drying or hydrating agent. By continuously tracking moisture levels, the sensor ensures a conducive environment for healing and minimizes the risk of infection.

2.3 pH Sensor

The pH sensor is crucial for detecting changes in the wound's chemical environment, which can be an early indicator of infection or tissue damage. Healthy wounds generally exhibit a slightly acidic pH; however, infected wounds tend to become more alkaline. This sensor provides continuous monitoring of the wound’s pH level and feeds the data to the ESP32 microcontroller. If the pH deviates from the normal range, the microcontroller can initiate specific drug delivery responses—such as releasing antibiotics—or send alerts to caregivers via the IoT interface. Monitoring pH levels in real time enables more responsive wound management and helps in preventing complications due to microbial growth.

2.4 Temperature Sensor

Temperature is a key physiological parameter that indicates the presence of inflammation or infection. The temperature sensor integrated into the smart bandage continuously measures the surface temperature of the wound area. Elevated temperatures may signify infection or localized inflammation, whereas lower-than-normal readings could indicate impaired blood flow. These temperature readings are sent to the ESP32, which interprets the data and responds accordingly—such as by triggering antiinflammatory drug delivery or alerting medical professionals. The inclusion of this sensor enhances the system's diagnostic capabilities and supports proactive treatment strategies.

2.5 SpO$_2$ Sensor

The SpO$_2$ (peripheral capillary oxygen saturation) sensor measures the level of oxygen in the blood near the wound area, which is a critical indicator of tissue viability and healing potential. Reduced oxygen levels can severely delay wound healing and are often observed in chronic wounds. By incorporating a SpO$_2$ sensor into the smart bandage, the system can assess how well oxygen is being delivered to the tissue. The ESP32 processes this data to determine whether oxygen delivery is sufficient, and in the case of hypoxia, it can trigger medical alerts or modulate drug delivery. This functionality is particularly beneficial for patients with diabetes or circulatory issues, where oxygen monitoring is essential.

2.6 LCD Display

The LCD (Liquid Crystal Display) provides a user-friendly interface for local data visualization. It displays real-time readings of moisture, pH, temperature, and SpO$_2$ values, allowing patients or caregivers to view the wound's status at a glance without needing to access a remote server. This local display enhances usability, especially in home-care settings where caregivers may lack access to advanced data monitoring tools. The integration of an LCD also serves as a feedback mechanism to confirm that the system is operating correctly and that the sensors are active.

2.7 IoT Module

The IoT module enables wireless data transmission between the smart bandage and external devices such as smartphones, tablets, or cloud-based healthcare platforms. By leveraging the Wi-Fi or Bluetooth capabilities of the ESP32, the IoT module allows real-time data sharing with healthcare providers, enabling continuous remote monitoring and reducing the need for frequent inperson checkups. This is particularly advantageous for patients in remote areas or those requiring long-term wound care. The system can also be configured to send alerts if any sensor parameter crosses a critical threshold, thereby facilitating timely medical intervention and reducing the risk of complications.

2.8 Stepper Motor

The stepper motor in the system functions as a precision actuator that drives the 3D drug injector. It converts electrical signals from the ESP32 into mechanical motion with high accuracy and repeatability. This precision is crucial for administering the correct dosage of medication directly to the wound site. The motor can be programmed to rotate in specific increments, allowing for controlled delivery of one or more drugs stored in separate reservoirs. Its compact size and reliability make it ideal for use in a wearable application where space and power efficiency are critical.

2.9 3D Injector

The 3D injector is the final component in the drug delivery chain, responsible for administering medication based on the wound's real-time condition. It works in conjunction with the stepper motor to deliver small volumes of drugs—such as antibiotics, anti-inflammatory agents, or wound healing accelerators—directly to the wound site. The 3D design allows for multiple drugs to be stored and dispensed independently or in combination, making the system adaptable to different treatment regimens. Controlled drug release enhances the effectiveness of therapy, minimizes manual intervention, and ensures patient compliance.

III. RESULTS AND DISCUSSION

The hardware prototype of the smart bandage system was successfully developed and tested under controlled laboratory conditions. The entire system was built around the ESP32 microcontroller, which served as the core unit for interfacing with all sensors, controlling actuators, and managing IoT connectivity. The sensors were embedded in a simulated wound environment to replicate real-time changes in physiological parameters such as moisture, pH, temperature, and oxygen saturation (SpO$_2$). The **moisture sensor** reliably detected varying fluid levels, showing an increase in analog values in response to higher hydration. The **pH sensor** demonstrated sensitivity across a range of 4 to 10 pH, enabling early detection of wound alkalinity, which indicates infection. The **temperature sensor** tracked temperature changes accurately within ±0.5°C, which is sufficient for identifying inflammation or infection risks. The **SpO$_2$ sensor** measured oxygen saturation levels and provided consistent results when placed near tissuemimicking materials. The stepper motor-controlled 3D injector was evaluated for precision in drug dispensing. The system was configured to deliver predefined doses in response to threshold breaches from sensor inputs. Upon high pH or temperature detection, the ESP32 activated the stepper motor, which rotated in defined steps to dispense small volumes of simulated drugs. The injector mechanism was able to differentiate between multiple drug chambers, allowing selective delivery based on specific sensor triggers. The motor's step count and speed were precisely controlled using PWM signals, ensuring accurate volume delivery (±0.1 ml variation). The IoT functionality was implemented using the ESP32's built-in Wi-Fi module. Sensor readings were sent to a cloudbased dashboard, where the data could be visualized in real time. Alerts and notifications were triggered whenever parameters exceeded safe thresholds. Remote users could monitor the bandage condition and manually initiate drug delivery through a mobile application interface. Data logs were used to analyze wound conditions over time, showing trends in moisture and temperature levels under various conditions. The entire hardware system was tested for responsiveness and integration efficiency. From sensor input to actuation and IoT data transmission, the system exhibited low latency (under 2 seconds total delay) and reliable operation. All components worked harmoniously without signal conflict or noise interference. Power consumption was within acceptable limits for wearable medical devices, with the ESP32 operating efficiently in a low-power mode when idle.

IV. CONCLUSION

The Smart Bandage with Multi-Drug Delivery System represents a significant advancement in the field of wearable healthcare technology and wound management. By integrating a suite of biomedical sensors—moisture, pH, temperature, and SpO□—along with an ESP32-based IoT-enabled control unit, the system provides real-time monitoring of critical wound parameters. The inclusion of a stepper motor-controlled 3D injector enables targeted and automated drug delivery, ensuring timely treatment based on the dynamic needs of the wound environment. This closed-loop system not only reduces the need for constant clinical supervision but also empowers remote healthcare, thereby improving patient outcomes and reducing healthcare costs. Furthermore, the IoT connectivity enhances the system's accessibility and responsiveness, allowing medical professionals to track wound healing progress and intervene, when necessary, even from distant locations. The real-time display through an LCD interface also offers immediate feedback for users and caregivers, improving the overall usability of the system. As demonstrated, this smart bandage platform is scalable, cost-effective, and adaptable to various clinical scenarios, making it a promising solution for managing chronic wounds, post-operative care, and emergency trauma situations. Future enhancements may include machine learning algorithms for predictive healing analytics and miniaturization for better wearability, thus further expanding its potential in smart healthcare systems.

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