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Smart Syringe Pump with Real-Time Vitals Monitoring and IPFS-Based Secure Drug Logging

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Abstract: Accurate medication delivery, ongoing patient health monitoring, and secure clinical data management are now more important than ever due to the quick uptake of electronic medical devices in healthcare. Due to their fixed flow rates and inability to adjust to real-time changes in the physiological conditions of the patient, conventional syringe infusion pumps may administer an excessive or insufficient dosage. This paper suggests a smart syringe pump system that integrates IPFS-based secure drug data logging and real-time vital sign monitoring in order to overcome these constraints. Using biomedical sensors, the system continuously measures body temperature, heart rate, and blood oxygen saturation (SpO2). These variables are processed by an ESP32 microcontroller, which then dynamically adjusts a stepper motor to control the infusion rate in accordance with preset safety thresholds. Real-time visualization and user interaction are provided by a mobile application that is Bluetooth enabled. The InterPlanetary File System (IPFS) stores patient vitals and drug delivery data as structured JSON files at the end of each infusion session, guaranteeing decentralized, impenetrable data storage. The suggested system provides a safe, scalable solution for managing healthcare data while enhancing patient safety and reducing manual intervention.

Keywords: *The Internet of Things (IoT), ESP32, Adaptive Medication Infusion, Smart Syringe Pump, Real-Time Vital Monitoring, InterPlanetary File System (IPFS), and Decentralized Healthcare Systems*

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I. INTRODUCTION

In order to ensure the continuous and regulated administration of medications, syringe infusion pumps are widely used in modern healthcare settings, particularly in operating rooms, emergency rooms, and intensive care units. Precise control of infusion rates is crucial because an incorrect dosage can result in serious health issues or adverse drug reactions. Most conventional syringe pumps operate at predetermined infusion rates and require continuous manual supervision by medical personnel, increasing the possibility of human error over long treatment periods [1], [2].Additionally, a major safety concern in clinical practice has been identified as the limited capacity of traditional systems to adjust to real-time changes in patient physiological conditions [3].

Smart medical devices that facilitate remote monitoring and real-time data collection have been made possible by recent advancements in the Internet of Things (IoT). Several Internet of Things (IoT)-based healthcare systems have been proposed to use embedded sensor technologies to continuously monitor vital parameters like body temperature, heart rate, and blood oxygen saturation (SpO_2) [4]– [6]. Despite offering precise and timely physiological data, these systems are frequently used as stand-alone monitoring platforms that are not directly integrated with drug infusion systems. As a result, the infusion procedure does not adapt to changes in the patient's physio- logical condition [5], [7].

By controlling infusion rates in response to real-time phys- iological feedback, adaptive and closed-loop drug delivery systems have been studied as a way to improve patient safety [7], [8]. Although these techniques provide better control accuracy, many of the suggested solutions rely on intricate hardware designs or are not appropriate for portable and low- cost healthcare settings. Furthermore, despite data security being a crucial necessity in healthcare applications, a number of smart infusion systems pay little

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attention to the safe management and storage of patient data and infusion records [9], [10].

Ensuring secure storage of medical data is still a signifi- cant challenge in healthcare systems, in addition to attaining accurate drug infusion. Traditional centralised data storage models are vulnerable to single-point system failures, data manipulation, and unauthorised access [10], [**?**]. Decentralised storage technologies like blockchain and the InterPlanetary File System (IPFS) have drawn interest in response to these worries because they offer better data availability, privacy, and integrity. I typically use these technologies to store cryptographic hashes on-chain and the actual medical records off-chain [11]– [13]. Despite recent research highlighting the potential of decentralised storage solutions in smart healthcare applications, there is still limited practical integration of these solutions with embedded medical devices, such as syringe infusion pumps [14], [15].

Inspired by these difficulties, this paper introduces a smart syringe pump system that uses an inexpensive IoT platform to combine IPFS-based secure drug logging, adaptive drug infusion control, and real-time vitals monitoring. In healthcare applications, the suggested system seeks to improve patient safety, decrease manual intervention, and offer safe, scalable, and impenetrable infusion data storage.

II. RELATED STUDY

Recent research has focused on using automation and em- bedded control techniques to improve the operational effective- ness and safety of syringe infusion pumps. An IoT-based smart infusion pump with automated drug delivery was presented by Kumar et al. [**?**]; however, the suggested system does not have real-time feedback from patient physiological parameters. Similar efforts were made by Rao et al. [2], who presented a microcontroller-based syringe pump that aimed to achieve high mechanical accuracy. However, the infusion process still relies on constant manual supervision and operates at a fixed rate. In their analysis of the safety issues surrounding smart infusion pumps, Das et al. [3] underlined the value of adaptive control systems and ongoing patient monitoring in lowering medication-related errors.

In IoT-based healthcare applications, the incorporation of real-time patient monitoring systems has been thoroughly investigated. Patel and Mehta [6] suggested an embedded health monitoring system for ongoing patient care, while Lee et al. [**?**] and Zhang et al. [5] created real-time heart rate and SpO_2 monitoring systems for healthcare settings. Despite offering precise physiological data, these systems don’t support automated infusion rate adjustments based on patient condition and operate independently of drug delivery mechanisms.

To overcome the drawbacks of fixed-rate infusion systems, adaptive and closed-loop drug delivery strategies have been put forth. In order to increase infusion safety, Park and Kim [7] presented a closed-loop drug delivery system that uses physiological feedback. Adaptive ontrol strategies for medical infusion devices were investigated by Zhao and Yang [8], who concentrated on ontrol algorithms rather than full end-to-end embedded implementations appropriate for low-cost healthcare systems.

In the current healthcare system, safe storage and efficient management of medical data have emerged as key research topics. IoT-based smart healthcare solutions were analyzed by Chen et al. [9] and Singh et al. [10], who also identified the main security and dependability issues with medical devices. Xu et al. [11] suggested blockchain-based frameworks for healthcare data management in order to guarantee data in- tegrity and immutability. Verma and Gupta [12] and Chatterjee et al. [13] used the InterPlanetary File System (IPFS) to introduce decentralized off-chain storage solutions in order to overcome scalability constraints. Despite providing safe and impenetrable data storage, these techniques are still not widely used in embedded medical devices like syringe infusion pumps [14], [15].

It is clear from the literature that the majority of earlier research concentrated on specific elements like secure medical data forage, patient vital monitoring, or infusion control. How- ever, there hasn’t been enough research done on a complete system that integrates decentralized off-chain data storage, daptive syringe infusion, and continuous real-time vital sign monitoring into a single inexpensive embedded platform. The study’s contribution can be summed up as follows:

- A decentralized storage approach is proposed in which infusion and patient data are stored in IPFS.
- An adaptive smart syringe pump system is developed that dynamically controls drug infusion rates based on real-time patient vital parameters.

III. PROPOSED MODEL

The suggested model presents a smart syringe pump system that integrates adaptive drug infusion control, decentralized data storage via the InterPlanetary File System (IPFS), and real-time patient vital sign monitoring. By automatically mod- ifying the drug infusion procedure in response to ongoing assessments of the patient’s physiological parameters, the stem enhances patient safety and reduces the need for manual intervention. Because all infusion-related data is kept in IPFS as structured JSON files, medical data can be stored securely, tamper-resistantly, and decentralizedly without relying on cen- tralized servers.

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A. System Architecture

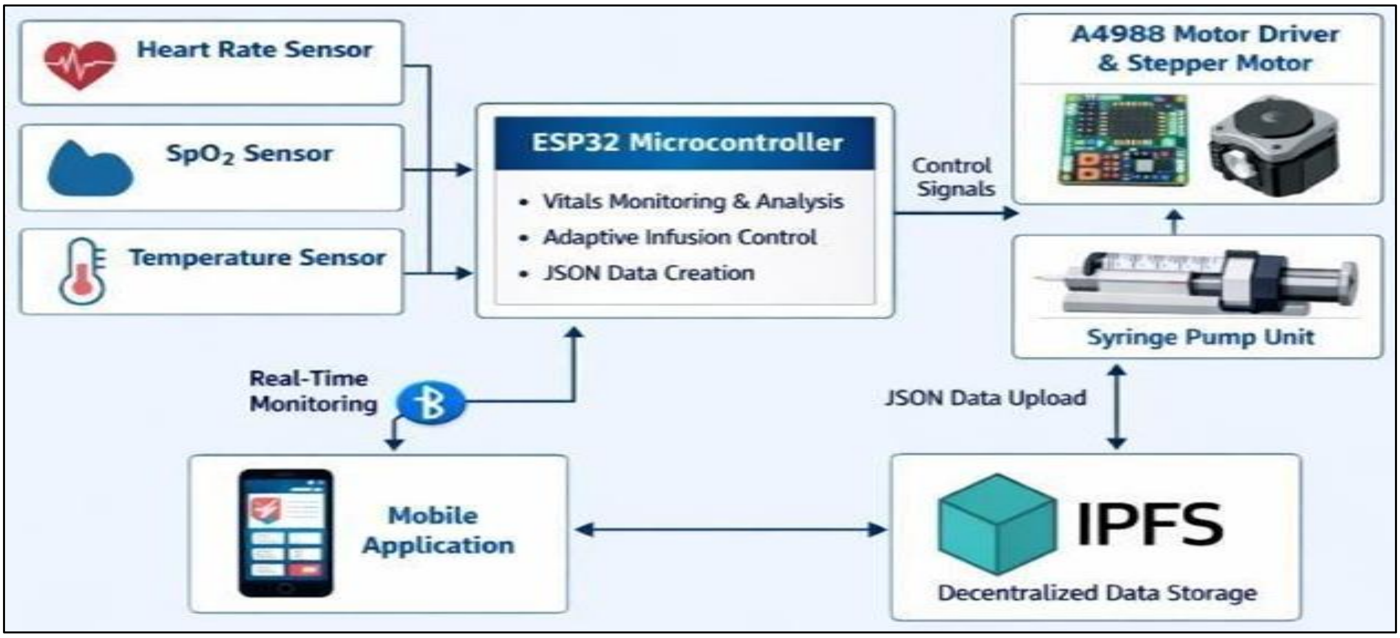

Fig 1 System Architecture of Proposed Model

Figure 1 shows the suggested system architecture. An ESP32 microcontroller for data processing and control logic, an A4988 motor driver with stepper motor for syringe actu- ation, biomedical sensors (heart rate, SpO_2, and temperature sensors), a Bluetooth module for wireless communication with a mobile application, and IPFS for decentralized data storage make up the system.

B. Working of the Proposed Model

The biomedical sensors monitor the patient's blood oxygen saturation (SpO_2), heart rate, and body temperature. These sensor readings are sent to the ESP32 microcontroller, which compares them to predetermined threshold values. If all pa- rameters remain within the normal range, the syringe pump maintains the drug infusion at the prescribed rate. When ab- normal vital conditions are detected, the system automatically lowers or stops the infusion to prevent potential health risks.

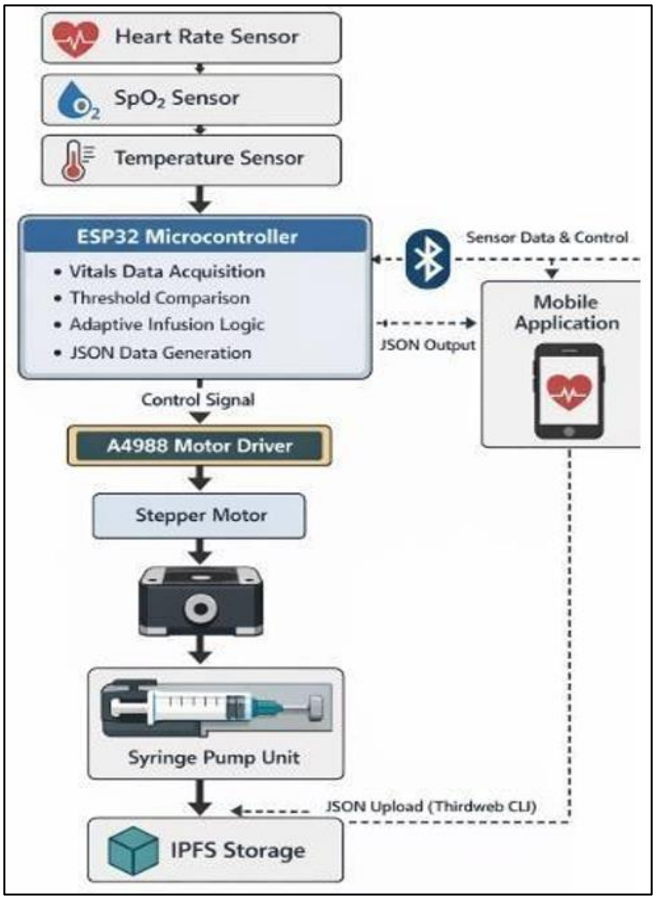

Fig 2 Block Diagram of the Proposed System

A stepper motor is used to control the infusion mecha- nism, guaranteeing accurate and precise syringe movement. Healthcare professionals can enter patient information, check infusion status, and monitor vitals in real time using a mobile application that is Bluetooth enabled. All of the

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information gathered during the infusion session, such as the patient's in- formation, the type of medication, the volume of the infusion, vital signs, and the timestamp, is saved as a JSON file and uploaded to IPFS for safe and decentralized record keeping.

Fig. 2 displays the block diagram of the suggested system. Sensor data collection is the first step in the system workflow. The ESP32 microcontroller then implements adaptive infusion logic and compares thresholds. The stepper motor speed is controlled by sending control signals to the A4988 motor driver. After the mobile application receives real-time data via Bluetooth, JSON-formatted data is uploaded to IPFS storage.

C. Drug and Vitals Threshold Data

- *Vital Threshold Values:*

The system's vital parameter monitoring thresholds are shown in Table 1. To guarantee patient safety during drug infusion, the system continuously measures body temperature, heart rate, and SpO_2.

Table 1 Vitals Threshold Values

Parameter	**Normal Range**	**System Action**
Heart Rate (BPM)	60-100	Adjust or stop function
SpO_2 (%)	≥95	Pause infusion
Body Temperature (°C)	36.5-37.5	Alert and regulate flow

- *Data on Sample Drug Infusion Control:*

Syringe diam- eter and infusion duration for frequently used drugs in critical care settings are among the sample drug infusion parameters displayed in Table 2.

Table 2 Sample Drug Infusion Control Data

Drug Name	**Diameter (mm)**	**Time (min)**
FENTANYL	4.7	10
MORPHINE	6.3	15
ATROPINE	5.0	8
EPINEPHRINE	4.0	12
MIDAZOLAM	6.0	20

IV. IMPLEMENTATION RESULTS AND ANALYSIS

The experimental findings from the deployment of the IPFS- Based Secure Drug Logging system and Smart Syringe Pump with Real-Time Vitals Monitoring are covered in this section. Sensor accuracy, adaptive infusion control, data structuring, and secure decentralized storage are used to assess the system's performance.

A. Sensor Accuracy and Calibration Analysis

Table 3 presents the comparison of sensor errors before and after calibration for heart rate, blood oxygen saturation (SpO_2), and body temperature sensors. Fig. 3 illustrates the sensor error comparison graphically.

The calibrated sensors provide reliable and precise physiological measurements, which form the foundation for the adaptive infusion control algorithm. The observed erro reduc- tion of more than 60% in all sensors ensures improved patient safety and system credibility.

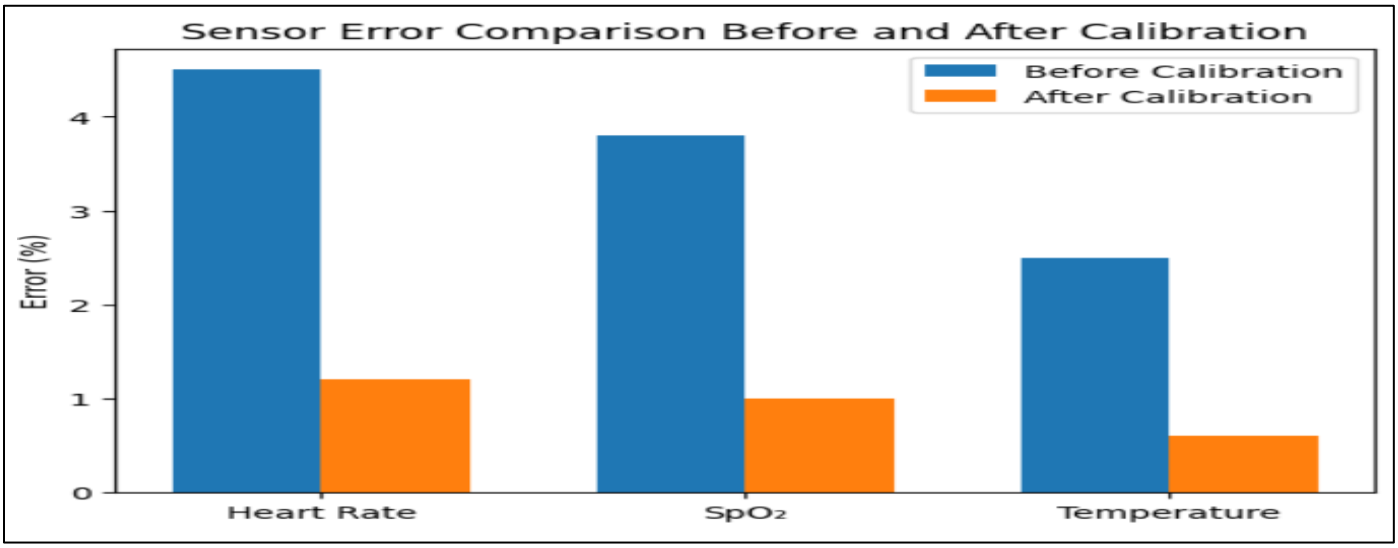

Fig 3 Sensor Accuracy and Calibration Analysis

Table 3 Sensor Error Comparison

Sensor Parameter	**Error Before Calibration (%)**	**Error After Calibration (%)**
Heart Rate	4.5	1.2
SpO_2	3.8	1.0
Temperature	2.5	0.6

B. Adaptive Infusion Control Response

Fig. 4 illustrates the adaptive control response flow imple- mented in the ESP32-based controller. The system continu- ously reads patient vitals, compares them against predefined safety thresholds, and dynamically adjusts the stepper motor speed controlling drug infusion.

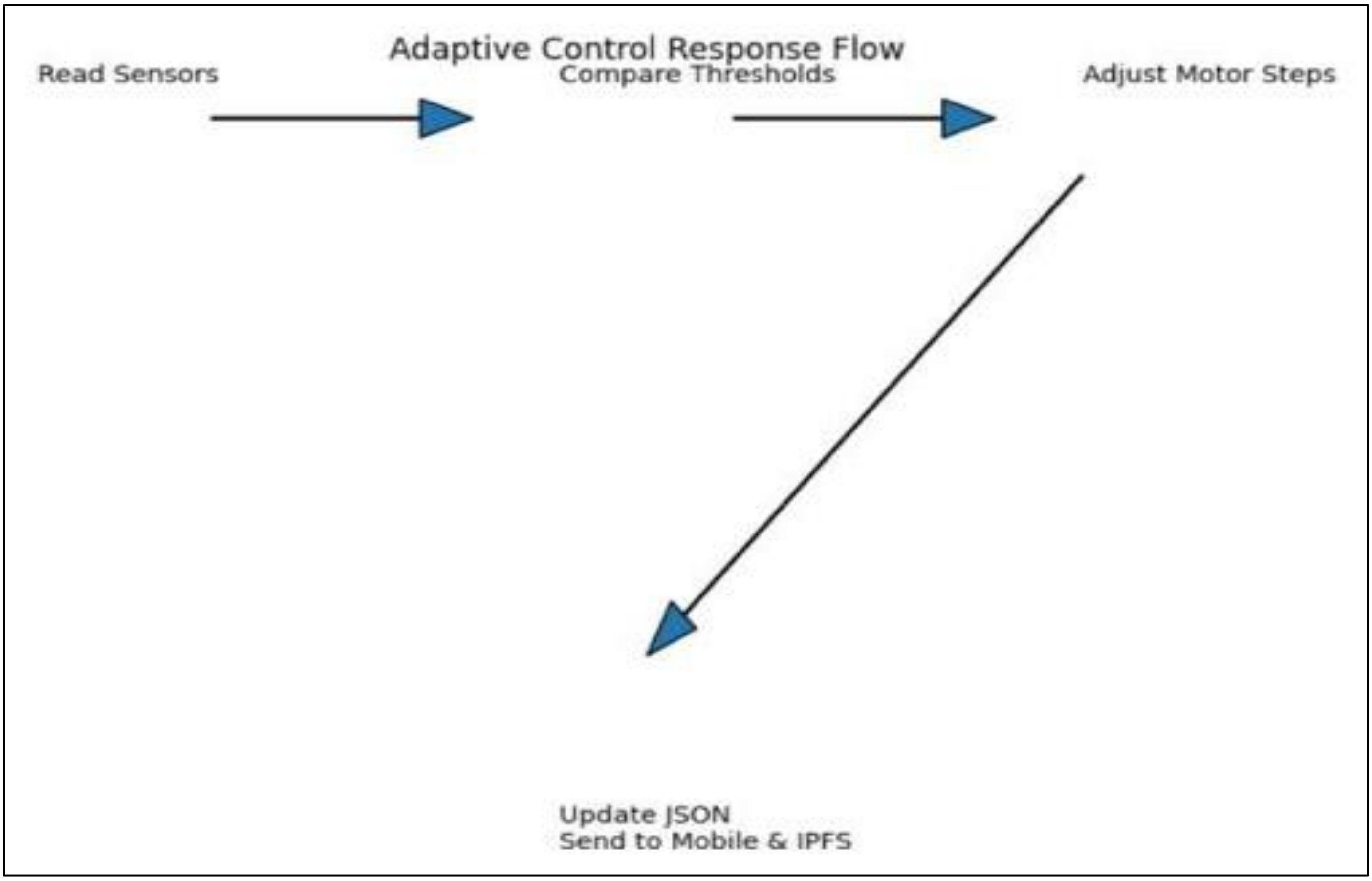

Fig 4 Adaptive Control Response Flow

➢ *The Adaptive Logic Evaluates:*

- Heart Rate (<50 bpm or >120 bpm)
- SpO_2 (<90%)
- Body Temperature (>38.5 °C)

The motor step delay is recalculated to adjust the infusion rate in real time when anomalous conditions are identified. Updated infusion parameters are ready for data logging at the same time.

The system can make decisions in real time without human assistance thanks to the closed-loop feedback mechanism. The suggested system dynamically modifies drug delivery, lowering the possibility of over-dosing or under-dosing during critical patient conditions, in contrast to traditional syringe pumps that run at fixed infusion rates. According to exper- imental findings, the system reacts in less than a second, proving that it is appropriate for real-time clinical applications.

C. Patient Data Structuring and JSON-Based Logging

The structured patient data stored in JSON format within Visual Studio Code is shown in the implementation. The JSON file includes patient demographics, real-time vitals, drug information, syringe specifications, infusion timing, and timestamps.

➢ *The Structured Format Enables:*

- Easy parsing by software applications
- Seamless transmission between embedded system and cloud
- Compatibility with IPFS and blockchain-based storage systems

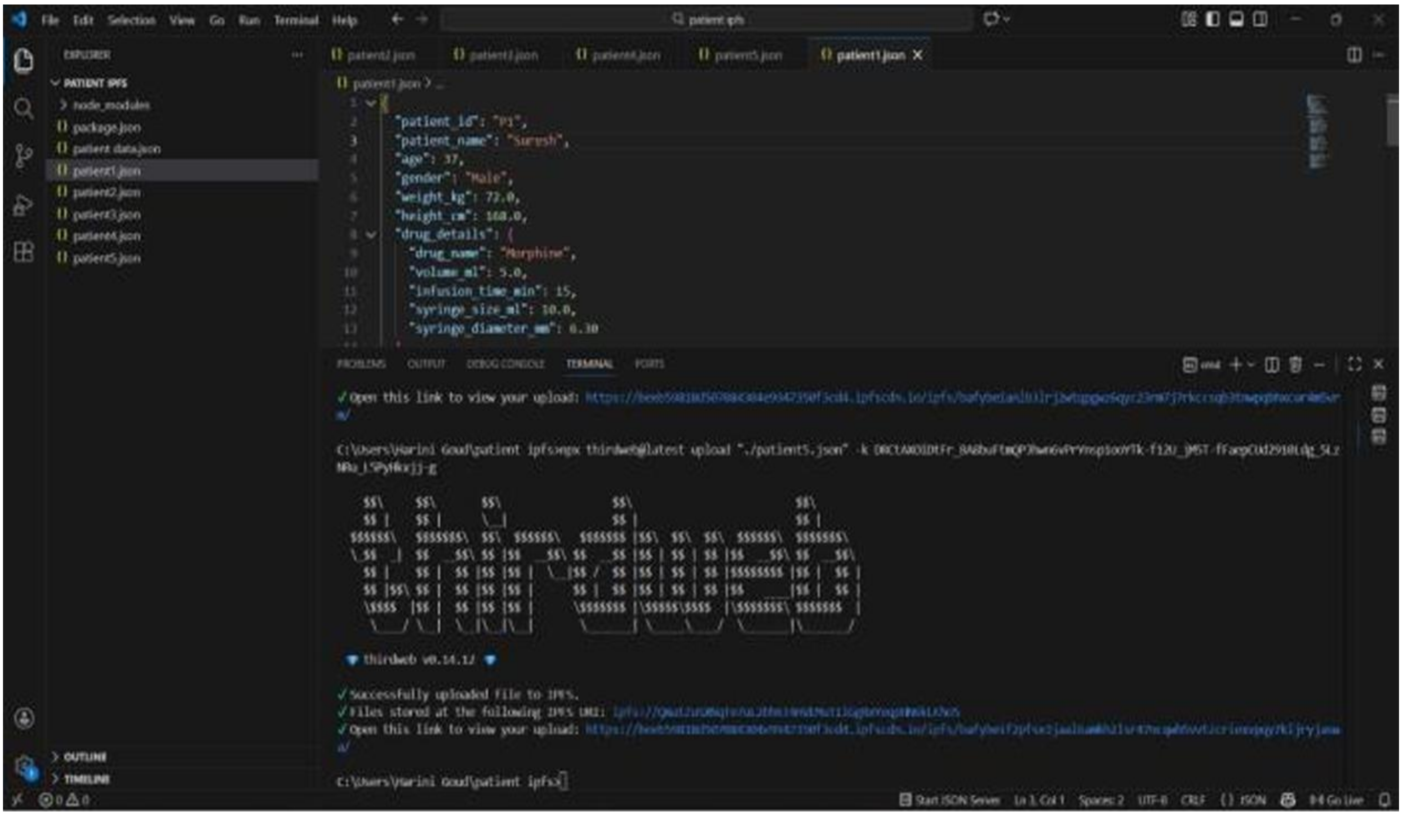

Fig 5 IPFS-Based Secure Data Storage

Scalability and interoperability are improved when JSON is used as the data format. It makes it possible to integrate AI- based analytics systems, hospital databases, and mobile applications. Timestamps and infusion metadata are included to guarantee traceability and facilitate upcoming medical audits.

D. IPFS-Based Secure Data Storage Results

Fig. 6 demonstrates the successful upload of patient infusion data to IPFS using Thirdweb CLI, along with the generated Content Identifier (CID) and retrieval through an IPFS gate- way.

Fig 6 Secure Data Storage Using IPFS

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The CID makes the data globally accessible and unchangeable after it has been uploaded. Data integrity would be assured because any modifications to the file would result in a different CID.

IPFS eliminates the need for centralized servers and safe- guards medical data from unauthorized access or manipulation. In healthcare settings, where data integrity, authenticity, and long-term availability are crucial requirements, this capability is especially crucial. The feasibility and efficacy of decentralized medical data storage are confirmed by experimental re- sults showing dependable patient data uploading and retrieval.

V. CONCLUSION

This project successfully demonstrated the creation and im- plementation of a smart syringe pump that integrates real-time vital sign monitoring and IPFS-based secure drug data logging. Decentralized data storage, Bluetooth-enabled communication, adaptive infusion control, and sensor-based monitoring were all successfully incorporated into the developed prototype. Ex- perimental evaluation validated unchangeable infusion record storage, rapid infusion adjustments, and accurate physiolog- ical sensing. Compared to conventional syringe pumps, the proposed system significantly improves patient safety while reducing the need for ongoing manual supervision.

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