Sensors and Materials, Vol. 38, No. 2 (2026) 1103–1117
MYU Tokyo

S & M 4366

A Smart and Noncontact Infusion Monitoring and Alert System Based on ESP32-C3 with IoT Connectivity

Feng-Chia Chuang,[1,2] Tzu-Wei Chuang,[3,4] Jian-Chiun Liou,[5*]
Cheng-Fu Yang,[6,7**] Sheng-Xiong Huang,[3] and Yi-Hui Chen[8]

[1]School of Marine Mechatronics, Xiamen Ocean Vocational College, Xiamen 361102, China
[2]Xiamen Key Laboratory of Intelligent Fishery, Xiamen 361100, China
[3]Department of Nursing, Dayeh University, Changhua 515, Taiwan
[4]Changhua Christian Hospital, Changhua 500, Taiwan
[5]School of Biomedical Engineering, Taipei Medical University, Taipei 110, Taiwan
[6]Department of Chemical and Materials Engineering, National University of Kaohsiung, Kaohsiung 811, Taiwan
[7]Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan
[8]Chaoyang Experimental School, Shantou City 51500, Guangdong

(Received January 28, 2026; accepted February 18, 2026)

Keywords: noncontact sensing, capacitive sensor, ESP32-C3, wireless fidelity (Wi-Fi), Message Queuing Telemetry Transport (MQTT), IoT

Intravenous (IV) infusion remains one of the most widely performed clinical procedures; however, routine infusion monitoring still relies predominantly on manual inspection by nursing staff. Such reliance increases the risk of delayed bag replacement, undetected flow interruption, backflow, and air embolism, particularly under high workload conditions. In this study, we present a smart, inexpensive, and noncontact infusion monitoring and alert system based on an ESP32-C3 SuperMini microcontroller with IoT connectivity. The proposed system integrates a capacitive noncontact liquid-level sensor, enabling the detection of fluid presence and flow status through the infusion tubing without the direct contact or physical modification of the infusion set, thereby preserving sterility and simplifying clinical deployment. Real-time infusion status is transmitted wirelessly via wireless fidelity using the Message Queuing Telemetry Transport protocol to both a mobile application and a web-based dashboard, supporting centralized multibed monitoring. Local and remote alerts are provided through light-emitting diode indicators, an acoustic buzzer, and optional servo motor actuation for auxiliary mechanical responses. The system architecture, hardware integration, firmware logic, and enclosure design fabricated via fused deposition modeling using polyethylene terephthalate glycol are described in detail. A cost analysis demonstrates that the proposed solution occupies a favorable middle ground between simple standalone infusion alarms and high-cost commercial infusion pumps. Furthermore, an evaluation protocol, safety considerations, and deployment guidelines for pilot clinical use are discussed. Overall, this work provides a practical and minimally invasive approach to digitizing infusion monitoring, enhancing patient safety while reducing nursing workload and integration barriers in existing healthcare workflows.

*Corresponding author: e-mail: jcliou@tmu.edu.tw
**Corresponding author: e-mail: cfyang@nuk.edu.tw
https://doi.org/10.18494/SAM6230

ISSN 0914-4935
https://myukk.org/

1. Introduction

Intravenous (IV) infusion is one of the most frequently performed medical procedures in healthcare systems, and its safety is closely linked to the ability to reliably sense and monitor infusion states in real time. From a sensing perspective, the accurate detection of infusion flow conditions is essential to ensure that fluids and medications are delivered according to prescribed dosages, while enabling the early identification of an abnormal event such as flow interruption, excessive infusion, or infusion completion. Previous clinical studies have indicated that inadequate monitoring may lead to fluid overload or tissue damage caused by high local drug concentrations, which can subsequently induce inflammatory responses such as phlebitis.[1] These findings highlight the importance of infusion monitoring as a sensing problem, where measurement accuracy and response timeliness directly affect patient safety and therapeutic outcomes. Despite the therapeutic advantages of IV infusion, the process inherently involves multiple risk factors that are difficult to detect without continuous sensing.

Common complications, including infiltration, phlebitis, hematoma formation, and catheter occlusion, are often preceded by subtle changes in flow behavior or fluid presence, which are not readily observable through intermittent visual inspection. Such complications have been shown to prolong hospitalization and increase patient discomfort and clinical burden.[1–5] From a sensing and measurement standpoint, these risks underscore the need for monitoring approaches capable of detecting flow-state changes with sufficient sensitivity and robustness under routine clinical conditions. Early infusion monitoring approaches primarily relied on mechanical flow regulators and the visual assessment of drip chambers, representing indirect and discontinuous measurement methods.[6] While simple and widely adopted, these approaches depend heavily on frequent bedside inspection and are limited by human perception, environmental lighting, and workload-related delays. To address these limitations, dedicated infusion monitoring devices were introduced to enable automated sensing and alerting.

Prior studies have demonstrated that such devices effectively reduce dependence on repeated bedside checks and improve the timeliness of abnormal-state detection, thereby lowering the risk of infusion-related complications.[1,7] These developments confirm the clinical value of sensor-assisted infusion monitoring but also reveal practical challenges related to system complexity and deployment. Subsequent research has focused on sensing technologies capable of detecting abnormal infusion rates and flow dynamics. Excessively rapid infusion has been shown to induce endothelial damage through high shear stress or elevated drug concentration, triggering inflammatory responses that may result in fever, phlebitis, electrolyte imbalance, and increased circulatory load.[8] Severe cases may progress to pulmonary edema or cardiac failure.[1,9,10] To mitigate these risks, infusion pumps and alert-based systems incorporating flow sensing and rate control have been developed, enabling the stabilization of drip rates and the detection of abnormal flow conditions caused by patient movement or fluid properties.[6] While effective, these systems typically require direct interaction with the infusion line or the replacement of conventional gravity-based setups, increasing cost and limiting scalability.

In current clinical practice, high-precision infusion pumps are widely regarded as the most reliable sensing and control solution for infusion monitoring. However, their high acquisition and

maintenance costs restrict universal deployment, particularly in long-term care facilities, outpatient clinics, and small hospitals.[6,11,12] As a result, a large proportion of infusion procedures continue to rely on low-level monitoring with limited sensing capability. This gap highlights a critical need for alternative sensing approaches that can provide essential flow-state information without the complexity, cost, or sterility concerns associated with pump-based systems. Recent studies have therefore emphasized the development of simplified, sensor-driven infusion alert systems that prioritize ease of deployment, noninvasiveness, and remote monitoring capability. Such systems have been shown to reduce nursing workload while maintaining clinically meaningful sensing performance, allowing healthcare personnel to focus on high-level assessment and care activities.[13,14]

From an engineering perspective, cost-effective sensing solutions also enable more efficient resource allocation and improved operational efficiency in healthcare organizations.[15] Against this backdrop, a clear sensing gap remains between rudimentary standalone alarms and fully integrated smart infusion pumps. The infusion monitoring architecture presented herein addresses this gap through a noncontact sensing strategy that overlays existing infusion sets without physical modification. A capacitive sensing mechanism is employed to detect flow-state changes via variations in effective capacitance around the infusion tubing, thereby avoiding direct interaction with the sterile fluid path. The system integrates sensing, edge processing, communication, and alerting functions, with hardware implementation centered on an ESP32-C3 SuperMini microcontroller and firmware logic optimized for real-time state classification and measurement stability. Wireless data transmission is achieved via wireless fidelity (Wi-Fi) using the Message Queuing Telemetry Transport (MQTT) protocol, enabling synchronized visualization on browser-based dashboards and mobile interfaces. In addition, enclosure engineering based on fused deposition modeling (FDM) using polyethylene terephthalate glycol (PETG) supports stable sensor placement and practical deployment. By emphasizing noncontact sensing reliability, system integration, and deployment-oriented design, in this work, we directly respond to the sensing challenges identified in prior infusion monitoring research.

2. Working Principle and System Architecture

2.1 Working principle

The proposed smart infusion alert system is designed to provide simple and remotely accessible monitoring and warning functions. As shown in Fig. 1, the system adopts a modular layered architecture comprising a sensing and detection layer, a wireless communication layer, and a front-end control layer, enabling the real-time monitoring and early warning of infusion status. The sensing and detection layer employs a noncontact liquid-level sensor based on capacitive variation to determine infusion flow conditions. This relationship can be expressed as $C_{total} = C_{base} + C_{touch}$, where C_{base} is the baseline capacitance and C_{touch} is the capacitance induced by the liquid. When liquid approaches the sensing electrode, an additional capacitance C_{touch} is formed between the liquid and the electrode, resulting in an increase in total system capacitance (C_{total}). A detection chip converts these capacitance changes into digital signals,

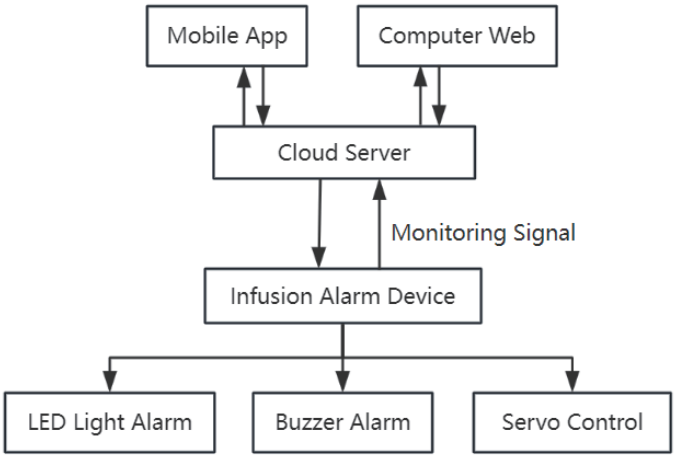

Fig. 1. System architecture diagram of the smart infusion control and alert system.

allowing the system to identify whether the infusion is flowing normally or has stopped. Wireless communication is implemented using the MQTT protocol over Wi-Fi to establish bidirectional data exchange between the device and a cloud server. Through this layer, sensing data and alert messages are transmitted in real time with low latency and high reliability. The front-end control layer provides remote access via both mobile applications and a web-based dashboard hosted on the built-in ESP32 web server, which supports real-time status updates without page reloading. When infusion completion or abnormal conditions are detected, alert notifications are issued, and optional auxiliary actions such as tube clamping via a servo motor can be triggered if required. The complete operational workflow of the smart infusion monitoring and alert system is illustrated in Fig. 2.

2.2 Overall architecture and system operation

Figure 3 is intended to provide a system-level overview of the overall architecture and wireless communication framework, whereas the detailed capacitive sensing mechanism and signal detection principle are described and illustrated separately in the corresponding sensing-related figures and sections of the manuscript. The overall architecture of the proposed system, as illustrated in Fig. 3, consists of a power supply module, which provides stable electrical power to all system components; a control switch, used to initiate or terminate system operation; the investigated system, responsible for capacitive-based noncontact infusion status detection, local signal processing, and decision logic; a cloud server (C-server), which performs data aggregation, storage, and remote service management; and multiple user-side interfaces and alert components. The sensing and monitoring module is connected to indicator and LED lights to convey real-time infusion status through visual cues, as well as to a buzzer that provides immediate acoustic alerts under abnormal conditions such as infusion completion or flow interruption. The system acquires infusion status data through the sensors and infusion monitoring and alert system, and transmits the data wirelessly to the cloud server for processing and storage. The processed

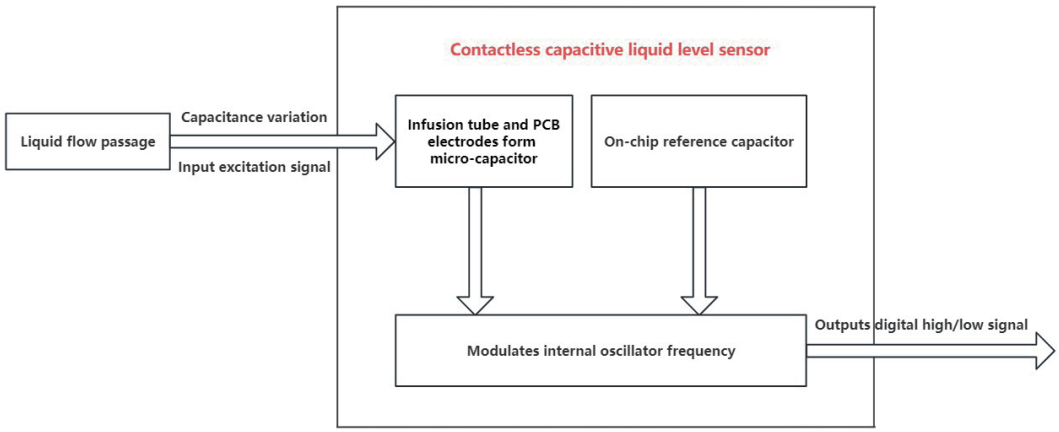

Fig. 2. (Color online) Flowchart of the smart control infusion alert system working principle.

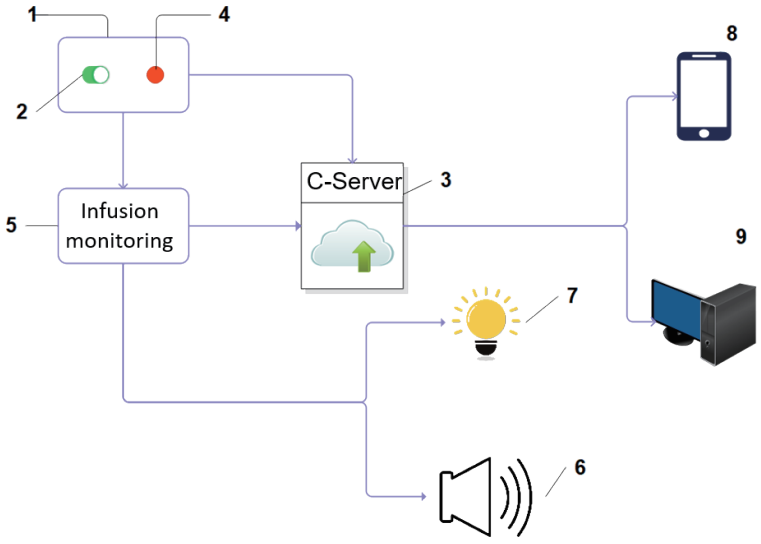

Fig. 3. (Color online) Overall architecture of the proposed system: 1. power supply, 2. switch, 3. cloud server (C-server), 4. indicator light, 5. sensors and infusion monitoring and alert system, 6. buzzer. 7. light-emitting diode (LED) light, 8. mobile device, and 9. computer terminal.

information is then fed back in real time to user terminals, including mobile devices, which support bedside or on-the-move monitoring via a mobile application, and computer terminals, which provide a web-based interface for centralized supervision and multibed management. This architecture supports both local alerts and cloud-based supervision while maintaining a compact and modular hardware design, facilitating practical deployment in clinical environments.

The system modules described above, including the power supply module, control switch module, sensing and infusion monitoring and alert system, control unit, and alert devices, were all implemented using custom-designed electronic circuits developed in this study. Rather than

employing commercially available modular units, we designed the circuit schematics, fabricated the printed circuit boards, and assembled and soldered the electronic components in-house to meet the specific functional and size requirements of the proposed system. For example, Fig. 4(a) shows the wireless communication circuitry designed for the system, which integrates the Wi-Fi module with the main control unit to support IoT connectivity. Figure 4(b) illustrates the circuit used for the indicator function, which drives visual alert components based on the infusion status detected by the sensing module. These representative circuits demonstrate the custom hardware implementation approach adopted throughout the system.

The detailed operational flow is shown in Fig. 5. When the system is powered on, the device initializes and performs a power status check, including battery level verification. The proposed system adopts a fully rechargeable, battery-operated power design. As a self-developed prototype, the device does not employ a commercially integrated power module; instead, it is powered by a standard rechargeable lithium battery with a nominal specification of 103040/1200 mAh/3.7 V, selected for its compact form factor and suitability for portable operation. Under normal working conditions, the battery provides an operational duration of approximately 4–6 h, which is sufficient for typical infusion monitoring scenarios in clinical wards. As the hardware is custom-designed and assembled, the battery used is a commonly available rechargeable lithium cell rather than a proprietary module from a specific manufacturer. To ensure reliable operation under power interruption or voltage fluctuation scenarios, multiple protective and mitigation mechanisms are incorporated into the system design. These include support for wired power supply operation to maintain continuous functionality, wireless notifications via Wi-Fi to inform users of abnormal power conditions, and local acoustic alerts generated by an onboard buzzer. When unstable or insufficient power is detected, visual warnings are displayed via LED indicators, and the system can enter a low-power sleep mode to prevent malfunction or data corruption. Once stable power is restored, the system supports automatic or manual restart, allowing normal operation to resume without complex reconfiguration.

Upon the confirmation of adequate power, the noncontact sensing module is activated and begins the continuous monitoring of the infusion tubing. During operation, detected infusion states are transmitted to the cloud server and synchronized with mobile and desktop platforms,

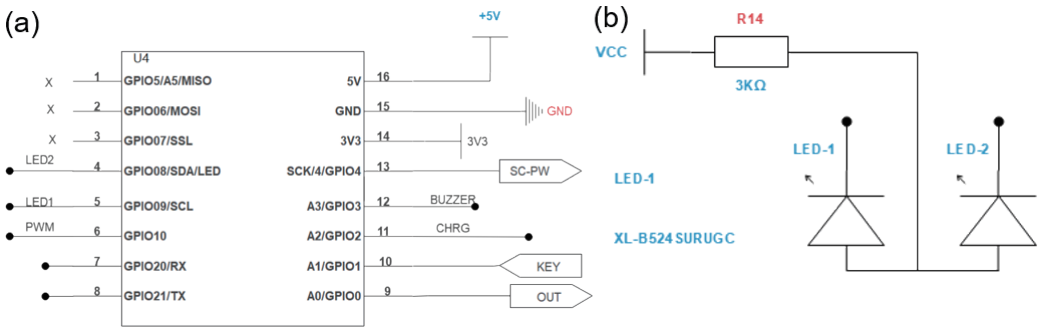

Fig. 4. (Color online) Circuits for (a) Wi-Fi module and (b) indicator function.

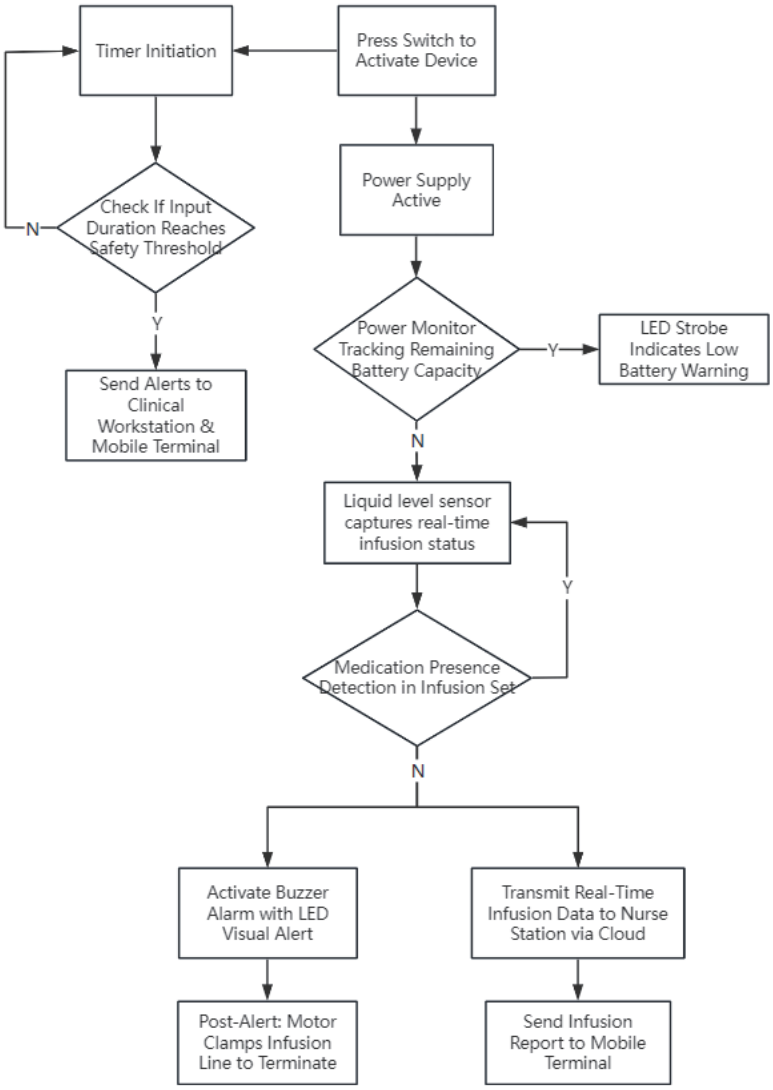

Fig. 5. Flow design of the investigated infusion alert system.

enabling healthcare personnel to remotely monitor infusion conditions. When the sensed infusion state reaches a predefined warning threshold indicating imminent infusion completion, early warning notifications are automatically delivered to both desktop and mobile interfaces. If the sensor detects the absence of liquid in the infusion tube, indicating infusion completion or abnormal interruption, the system classifies the condition as abnormal. In response, audible alarms are activated through the buzzer and visual warnings are displayed via LED indicators, while alert messages are simultaneously transmitted to user terminals. To enhance operational reliability, the system incorporates an internal timing and feedback mechanism that continuously cycles through sensing, evaluation, and notification processes. This closed-loop monitoring strategy ensures the stable and continuous observation of infusion status, reduces the likelihood of missed events due to transient disturbances, and improves the overall safety and efficiency of clinical infusion care.

3. Results and Discussion

The noncontact infusion monitoring and alert system developed in this study is primarily fabricated using three-dimensional printing technology, which necessitates the creation of a detailed digital model prior to physical manufacturing. Accordingly, computer-aided design software was employed to construct the system enclosure and internal structural components, as illustrated in Fig. 6. This approach enables precise control over geometric features, facilitates rapid design iteration, and supports customization to accommodate sensor placement, electronic components, and clinical usage constraints. For material selection, PETG was chosen as the primary enclosure material. Compared with commonly used polylactic acid, PETG exhibits superior mechanical durability and impact resistance, allowing the enclosure to withstand minor collisions and handling stress and routine wear encountered in daily clinical operation. From a materials perspective, this enhanced toughness reduces the likelihood of enclosure cracking or deformation, which could otherwise compromise sensor alignment and measurement reliability.

In addition to its mechanical advantages, PETG demonstrates favorable chemical resistance to commonly used hospital disinfectants, including alcohol-based solutions and sodium hypochlorite. This property is particularly important for medical and healthcare applications, where regular surface cleaning and disinfection are required to maintain hygiene and prevent cross-contamination. The ability of PETG to retain structural integrity and surface stability under repeated exposure to disinfectants makes it well suited for prolonged use in clinical environments. From a manufacturing standpoint, PETG also offers good printability and dimensional stability during FDM processes. Its relatively low thermal shrinkage helps ensure consistent dimensional accuracy, which is critical for maintaining the stable positioning of the noncontact sensor relative to the infusion tubing. Accurate sensor alignment directly affects sensing sensitivity and repeatability, especially in capacitive detection schemes where small geometric deviations can affect measurement performance. 3D printing with PETG provides a flexible and cost-effective fabrication strategy for the proposed noncontact infusion monitoring

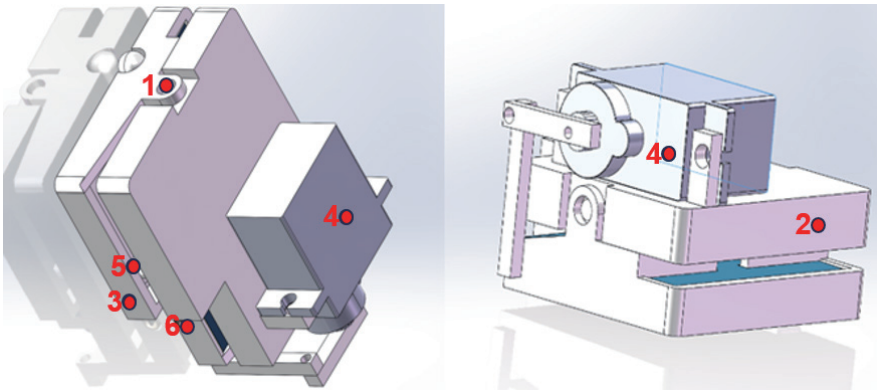

Fig. 6. (Color online) Designed infusion alert system: 1. spring, 2. top cover, 3. upper cover, 4. servo motor: controls the linkage to compress the infusion tubing, thereby regulating opening and closing of the fluid path, 5. clamp: uses the restoring force of the spring to securely grip the tubing, and 6. capacitive liquid-level sensor: detects the liquid level status within the infusion tubing.

system. This approach supports rapid prototyping, scalable production, and potential future customization for different clinical scenarios or infusion setups. From a broader perspective, integrating additive manufacturing with sensor-based medical devices offers a practical pathway for accelerating design iteration while maintaining material properties compatible with clinical safety, durability, and hygiene requirements.

The system enclosure is fabricated from PETG using FDM 3D printing technology. The material selection is based on the following considerations: from a mechanical performance perspective, PETG provides a tensile strength of approximately 50 MPa and exhibits a higher impact resistance than conventional PLA, allowing the enclosure to withstand minor collisions and handling stresses encountered during routine clinical use. In terms of chemical resistance and biocompatibility, PETG demonstrates good tolerance to commonly used disinfectants, such as alcohol and sodium hypochlorite solutions, making it suitable for repeated cleaning and disinfection in medical environments. Regarding printability and dimensional stability, PETG has a low thermal shrinkage rate, resulting in a high dimensional accuracy and structural stability after printing. When used with a 0.4 mm nozzle, the material supports the fabrication of fine structural features, including precision slots for sensor mounting. The enclosure is designed with a lightweight structure, featuring an optimized wall thickness of 2.2 mm and a honeycomb internal infill pattern with a density of 15%, which limits the total enclosure weight to less than 120 g. The outer surface is postprocessed by polishing to reduce visible layer lines, thereby minimizing dust accumulation and simplifying disinfection procedures. The sensor mounting bracket is integrated with the enclosure through a single-piece print and incorporates a U-shaped groove that precisely conforms to the infusion tubing. This integrated design ensures the stable positioning of the sensor relative to the tubing and enhances the reliability of noncontact capacitive detection.

Figure 7 presents the simplified smart remote-controlled infusion alert system, where Fig. 7(a) shows the side view and Fig. 7(b) the front view of the device. These photographs are intended to illustrate the actual implementation and operational configuration of the proposed

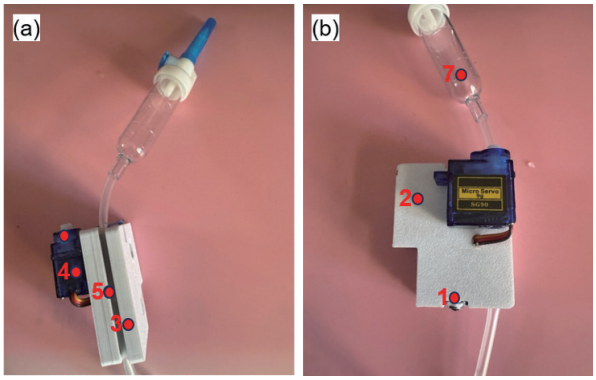

Fig. 7. (Color online) Fabricated infusion alert system: (a) side and (b) front views. 1. Spring, 2. top cover, 3. upper cover, 4. servo motor: controls the linkage to compress the infusion tubing, thereby regulating the opening and closing of the fluid path, 5. clamp: uses the restoring force of the spring to securely grip the tubing, 6. capacitive liquid-level sensor: detects the liquid level status within the infusion tubing, and 7. infusion tubing.

system in a clinical setting. As illustrated in Fig. 7, the designed infusion alert system is configured to wrap around and conform to the infusion tubing, allowing sensing operations to be performed without direct contact with the fluid path. This configuration visually clarifies how the device is installed and positioned during use, which is critical for practical deployment by nursing staff. The wrap-around mechanical structure enables the stable positioning of the noncontact sensing module relative to the infusion tube, which is essential for maintaining consistent sensing performance in real-world environments. By enclosing the tubing within the device structure, the sensor can continuously monitor infusion status while minimizing sensitivity to an external disturbance such as accidental displacement, vibration, or patient movement. Importantly, this design eliminates the need to modify or replace standard infusion sets, thereby preserving sterility and ensuring full compatibility with existing clinical workflows.

From a sensing perspective, the enclosure geometry shown in Fig. 7 is deliberately designed to maintain a fixed and repeatable distance between the sensor electrode and the infusion tube. Such geometric consistency is a key requirement for capacitive-based noncontact detection, as variations in sensor-to-tube spacing can directly affect capacitance variation, measurement sensitivity, and signal stability. The illustrated wrap-around configuration therefore supports the reliable translation of the theoretical sensing mechanism into a robust physical implementation. In practical clinical settings, the compact and lightweight structure of the device facilitates rapid installation and removal without interrupting ongoing infusion procedures. The photographs in Fig. 7 further demonstrate that the system can be easily deployed across multiple beds, supporting scalable monitoring while maintaining ease of use. Overall, the physical implementation demonstrated in Fig. 7 confirms that the proposed simplified infusion alert system achieves an effective balance between noninvasive sensing, mechanical stability, and clinical practicality, thereby reinforcing its suitability for real-world infusion monitoring applications.

The proposed simplified smart remote-controlled infusion alert system is equipped with comprehensive remote monitoring and control capabilities, as illustrated in Fig. 8. Through the Internet Protocol (IP)-based configuration, healthcare personnel can access the system via a computer-based web interface to remotely track whether the infusion process is operating normally. This architecture supports the continuous supervision of infusion status without requiring constant bedside presence, thereby improving monitoring efficiency in busy ward environments. The system was functionally evaluated through large-scale deployment and operational testing in a hospital setting, during which the device was used repeatedly under routine infusion workflows. The evaluation focused on verifying system stability, wireless communication reliability, and the correctness of infusion status detection and alert triggering. When the infusion process is completed, the system can automatically initiate actions to stop fluid delivery, thereby reducing the risk of unnecessary infusion continuation and potential air entry. Experimental testing confirmed that the computer-based web interface supports real-time monitoring and remote control functions, and that infusion completion events can be reliably detected and reported to medical staff through remote notifications. The system was operated by trained healthcare personnel following standard usage procedures, and its performance was

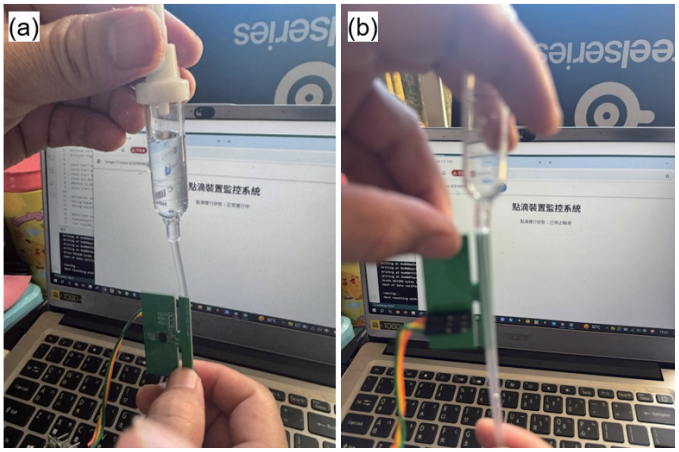

Fig. 8. (Color online) Practical testing images.

observed over extended operational periods across multiple infusion instances. This functionality is particularly beneficial in multibed wards, where the simultaneous supervision of multiple infusion setups is required and the nursing workload is high.

The computer-side web interface was developed using the Arduino Integrated Development Environment and implemented on the ESP32 platform, which hosts a lightweight embedded web server. The web-based monitoring system adopts a three-layer interaction architecture. First, a Hypertext Transfer Protocol (HTTP) server is created using the WiFi Server library to handle client requests. Second, infusion status data are dynamically generated and transmitted to the front-end interface. Third, Asynchronous JavaScript and XML technology is employed to enable real-time status updates without requiring page reloading. At the front end, the webpage sends asynchronous requests to the infusion status interface at a frequency of once per second. The back end parses the HTTP headers to identify specific application programming interface commands and directly returns the current infusion state, such as “normal operation” or “infusion stopped”. Using the Document Object Model, the interface content is updated dynamically, ensuring smooth and responsive user interaction.

From a sensing perspective, the capacitive noncontact liquid-level sensor continuously acquires infusion signals via digital input (digitalRead). When the sensor detects that infusion has stopped, the system simultaneously triggers local hardware feedback, including LED indicators and a buzzer alarm, and publishes abnormal status messages through MQTT. This synchronized sensing, local alerting, and remote notification mechanism demonstrates how sensor-derived information can be effectively translated into timely control actions and user feedback. Overall, the integration of sensor-driven detection, embedded web services, and remote notification enables a practical and scalable solution for intelligent infusion monitoring. The results shown in Fig. 8 highlight the feasibility of combining noncontact sensing with web-based supervision to improve infusion safety, enhance clinical efficiency, and support real-world deployment in healthcare environments.

In addition to monitoring infusion status during normal operation, the proposed system is designed to detect abnormal conditions at the start of infusion, such as the improper insertion of the infusion needle, the absence of liquid flow, or other initialization failures. During system startup, the sensing module performs a preliminary evaluation of the infusion state to confirm the presence of normal fluid flow within the tubing. If an abnormal condition is detected, the system automatically activates visual warnings via LED indicators and audible alarms through an onboard buzzer to provide immediate on-site feedback. At the same time, remote notifications are transmitted via Wi-Fi to user terminals, enabling healthcare personnel to respond promptly even when not physically present at the bedside. To enhance system stability and safety, the device can enter a protective sleep mode under persistent abnormal conditions, preventing continuous false triggering or unnecessary power consumption. After corrective action is taken, the system can be restarted automatically or manually, restoring normal monitoring operation. This integrated warning and recovery mechanism improves the reliability of infusion initiation and enhances patient safety in clinical environments.

Figure 9 illustrates the mobile interface architecture, the physical structure of the system device, and the application user interface design. Specifically, Fig. 9(a) presents the architecture of the mobile interface and the system appearance, whereas Fig. 9(b) shows the actual operation of the mobile application during system use. The mobile application includes a dedicated server connection status display to indicate the communication state between the infusion monitoring device and the cloud server. A specific “connect to server” button is implemented within the application interface. When the user presses this button, a connection event is triggered, and a Hypertext Transfer Protocol command is transmitted to the ESP32 through an embedded web component. Upon receiving this command, the ESP32 activates its built-in Wi-Fi module and initiates a connection to the MQTT server. If the connection is successfully established, the interface displays a message indicating that the server connection is successful; otherwise, a “not connected” status is shown to alert the user.

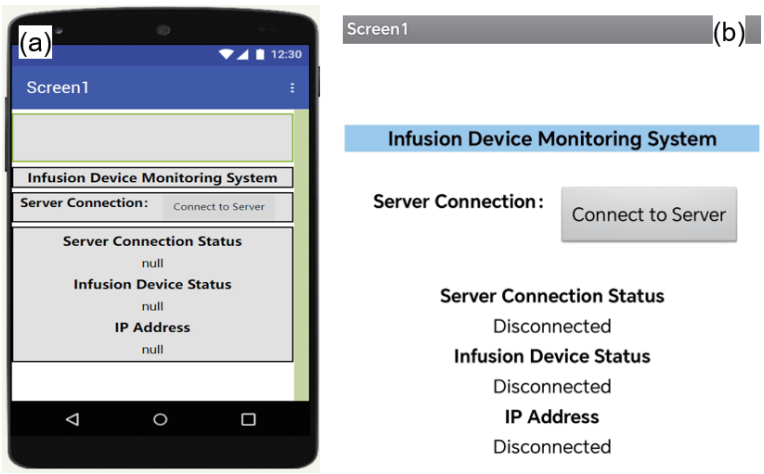

Fig. 9. (Color online) (a) Mobile interface architecture diagram and (b) app actual operation view.

Once the connection is established, the system continuously parses sensor data uploaded by the ESP32 to visualize the infusion status on the mobile interface. When the sensing module detects that liquid is flowing through the infusion tubing, the application displays a "normal operation" status. Conversely, when no liquid flow is detected, the application indicates that the infusion has stopped. This visualization allows healthcare personnel to intuitively assess infusion conditions on the basis of real-time sensor feedback, without the need for direct bedside observation. In addition to infusion status display, the mobile application provides a device IP address display function. After the ESP32 connects to the Wi-Fi network, it retrieves its local network address via the WiFi.localIP function and encapsulates the address in the format "IP: xxx.xxx.x.x", which is then published to a designated MQTT topic. Upon receiving the IP data packet, the mobile application extracts the relevant fields using a text-formatting function and displays the device network address within the interface.

This feature enables users to directly access the infusion monitoring device via a computer-based web interface using the displayed IP address, facilitating cross-platform monitoring and control. Experimental testing demonstrated that the mobile application supports both remote control and notification functions. Infusion completion events and abnormal conditions detected by the noncontact sensing module are automatically reported to the mobile device, enabling the timely notification of healthcare personnel. From a practical standpoint, this capability is particularly beneficial in multibed clinical environments, where the simultaneous monitoring of multiple infusion setups is required. By integrating sensor-based data acquisition, real-time visualization, and network-based notification, the mobile application serves as an effective bridge between sensing hardware and clinical workflow, enhancing infusion safety, reducing nursing workload, and improving overall operational efficiency.

To improve user-friendliness when multiple infusion-alert systems are deployed, the proposed platform adopts an intelligent and human-centered data transmission architecture, as illustrated in Fig. 10. Instead of requiring clinical staff to manage or interpret individual device IP

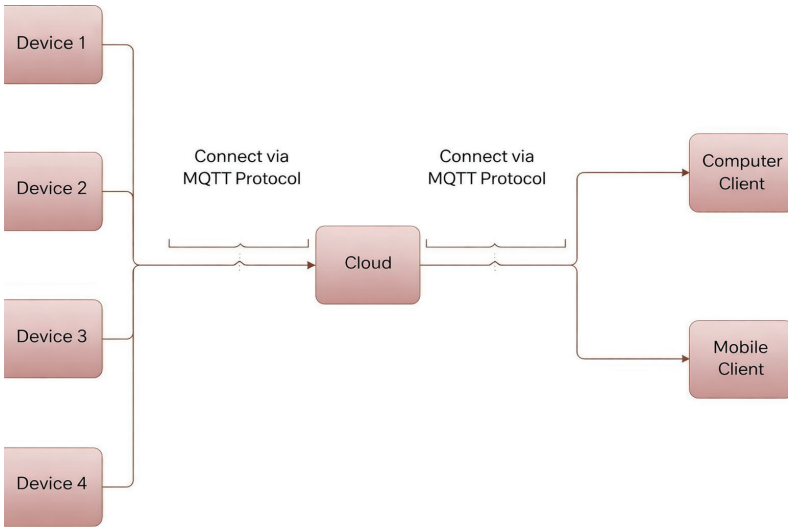

Fig. 10. (Color online) Scheme of multiple infusion-alert systems.

addresses, the system utilizes the MQTT protocol as the primary communication mechanism to ensure real-time, stable, and scalable data exchange. At the front end, multiple infusion monitoring devices operate concurrently. Each device connects via Wi-Fi and transmits sensing data to a cloud server using the MQTT protocol. The cloud server acts as a centralized data hub, responsible for receiving infusion status data from all connected devices, performing real-time data processing, and storing the information. Through the MQTT-based publish–subscribe architecture, the processed monitoring results are automatically synchronized to both computer-based dashboards and mobile applications, where device status and infusion conditions are presented in a consolidated and intuitive format. This design abstracts low-level network information, such as IP addresses, from end users and allows nursing staff to identify and manage multiple infusion systems through a unified interface. The proposed architecture supports simultaneous multidevice connectivity and monitoring, reduces network transmission latency, and enhances overall system stability and clinical workflow efficiency. By leveraging the lightweight and efficient characteristics of MQTT, the system enables multipoint infusion monitoring, real-time status updates, and synchronized abnormal-event alerts, thereby significantly improving usability and supporting intelligent clinical care.

4. Conclusions

In this work, we presented a simplified, noncontact, and remotely accessible infusion monitoring and alert system that integrates sensing, embedded hardware, wireless communication, and user interfaces into a compact and practical solution for clinical infusion care. By employing a capacitive noncontact liquid-level sensing mechanism, the system is able to reliably detect infusion flow states without direct interaction with the sterile fluid path, thereby preserving clinical compatibility and reducing installation complexity. The sensing approach enables the stable and repeatable detection of infusion status while minimizing sensitivity to patient movement and environmental disturbances. From a hardware perspective, the system is built around an ESP32 SuperMini microcontroller, selected for its compact size, low power consumption, and integrated wireless communication capability. The device integrates essential functional modules, including the noncontact sensor, power management circuitry, LED indicators, a buzzer alarm, optional servo motor control, and a rechargeable power design, resulting in a cost-effective and energy-efficient platform suitable for long-term deployment. In addition, the enclosure fabricated via 3D printing using PETG material offers sufficient mechanical robustness, chemical resistance to common disinfectants, and stable sensor positioning, further enhancing sensing reliability in clinical environments. The system architecture combines MQTT-based wireless communication with browser-based and mobile interfaces, enabling real-time visualization, remote monitoring, and timely alert notification across multiple terminals. Experimental validation demonstrates that the proposed system can effectively support remote supervision, automatic infusion completion alerts, and scalable multibed monitoring. Overall, this study provides a practical sensor-driven solution that bridges the gap between manual infusion observation and high-cost infusion pumps, offering a promising pathway for improving infusion safety, reducing nursing workload, and facilitating intelligent clinical care.

Acknowledgments

This work is supported by projects under Nos. NSTC-114-2314-B-038-083, MOST-111-2221-E-038-007-MY2, MOST-111-2221-E-038-004-MY3, 109-TMU-NTUST-109-10, NSTC 113-2221-E-390-011, and NSTC 114-2622-E-390-001. The authors also like to thank the School of Marine Mechatronics, Xiamen Ocean Vocational College, for the support in the high-level talents research projects under No. KYG202552.

References

1 F. Borgonovo, M. Quici, A. Gidaro, D. Giustivi, D. Cattaneo, C. Gervasoni, M. Calloni, E. Martini, L. La Cava, S. Antinori, C. Cogliati, A. Gori, and A. Foschi: Antibiotics **12** (2023) 1338.
2 N. Marsh, J. Webster, A. J. Ullman, G. Mihala, M. Cooke, V. Chopra, and C. M. Rickard: J. Adv. Nurs. **76** (2020) 3346.
3 J. Garcia-Expósito, J. Sánchez-Meca, J. A. Almenta-Saavedra, L. Llubes-Arrià, A. Torné-Ruiz, and J. Roca: Nurs. Open **10** (2023) 1270.
4 R. Li, M. Zhou, L. Sun, L. Sha, B. Xu, T. Li, T. Tao, and L. Yuan: Trials **25** (2024) 380.
5 L. C. Hadaway: Nursing **35** (2005) 54.
6 J. C. Rooker and D. A. Gorard: Clin. Med. (London) **7** (2007) 482.
7 A. Puolitaival, M. Savola, P. Tuomainen, C. Asseburg, T. Lundström, and E. Soini: Adv. Ther. **39** (2022) 2096.
8 G. D. LaRue and M. Peterson: J. Infus. Nurs. **34** (2011) 117.
9 J. Pouska, V. Tegl, D. Astapenko, V. Cerny, C. Lehmann, and J. Benes: BioMed Res. Int. **2018** (2018) 8925345.
10 J. L. Vincent: Kidney Int. **96** (2019) 52.
11 C. S. Kruse, C. Kristof, B. Jones, E. Mitchell, and A. Martinez: J. Med. Syst. **40** (2016) 252.
12 N. Hedlund, S. Sarangpur, S. Kayler, K. O'Brien, and I. Beer: J. Infus. Nurs. **40** (2017) 206.
13 A. Puolitaival, M. Savola, P. Tuomainen, C. Asseburg, T. Lundström, and E. Soini: Adv. Ther. **39** (2022) 2096.
14 C. C. Chen, F. H. Chen, C. L. Hsu, W. C. Chuang, C. Y. Lee, C. H. Lee, C. T. Ho, Y. Ma, and T. L. Wu: Sens. Mater. **32** (2020) 2709.
15 A. Bertolazzi, V. Quaglia, and R. Bongelli: BMC Public Health **24** (2024) 506.