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Research Article

SMART INTRAVASCULAR LEVEL DETECTION USING INFRARED SENSING TECHNOLOGY

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ABSTRACT

Continuous monitoring of intravascular fluid levels is essential in critical care, hemodynamic management, and intravenous (IV) therapy to prevent complications such as air embolism, fluid overload, and line occlusion. Conventional fluid-level indicators require manual observation, resulting in delays and increased clinical burden. This study proposes a smart intravascular level detection system using infrared (IR) sensing technology to provide a real-time, non-invasive, and cost-effective solution for IV fluid monitoring. The device employs an infrared transmitter–receiver pair to detect changes in optical absorption and scattering characteristics as the fluid level varies within the IV tube. Signal conditioning and microcontroller-based processing enable continuous monitoring with high precision. Experimental evaluation demonstrates a detection accuracy of 98.6%, rapid response time (<50 ms), and reliable performance under varying ambient light conditions. The system offers significant potential for integration into smart hospitals, wearable infusion systems, and automated clinical monitoring environments.

Keywords: Intravascular monitoring, Intravenous fluid level, Infrared sensing, Optical detection, Medical device.

INTRODUCTION

Intravenous (IV) fluid administration is a standard clinical procedure for hydration, drug delivery, electrolyte balance, and emergency care. Maintaining an appropriate intravascular fluid level is crucial for preventing adverse outcomes such as air injection, blood backflow, and interrupted therapeutic delivery. However, current monitoring approaches rely heavily on manual supervision by healthcare personnel, leading to human error and delayed intervention, particularly in high-workload environments such as intensive care units and emergency wards. Advancements in biomedical sensing systems have resulted in automated monitoring devices using ultrasonic, capacitive, and optical sensing methods. Among these, infrared sensing presents distinct advantages: high sensitivity to fluid presence, immunity to electromagnetic interference, low cost, and suitability for transparent IV tubing. This study presents a smart intravascular level detection system utilizing an infrared emitter–detector pair coupled with embedded signal processing to enable continuous, real-time monitoring with minimal user interaction. Research on optical and infrared-based monitoring systems has significantly advanced over the past decade, enabling safer and more automated medical infusion practices. Early developments were shaped by foundational IR-based fluid indicators (Jain and Kumar, 2016), followed by improvements achieved through refined optical absorption measurements and non-invasive IV monitoring approaches (Cheng *et al*., 2018; Lin *et al*., 2018). Infrared sensing became central to biomedical device innovation because of its strong interaction with biological fluids, with several studies confirming its reliability and sensitivity for fluid-level detection (Liu *et al*., 2019; Ghosh and Banerjee, 2021). Many researchers

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focused on enhancing detection of infiltration, air bubbles, and fluid depletion in IV lines, reporting significant improvements in accuracy and patient safety (Hafezi *et al*., 2017; Ahrens & Ryschka, 2019). Advancements also included the adoption of near-infrared spectroscopy for real-time monitoring (Kim & Park, 2020) and versatile optical sensing methodologies for broad clinical applications (Hosseini and Gholamhosseini, 2019). Recent progress in smart infusion systems introduced wireless and IoT-enabled platforms for remote supervision (Kumar & Sharma, 2020)**,** while other optical device innovations further contributed to the development of efficient liquid-level monitoring solutions (Bhardwaj & Rajput, 2020). Collectively, these contributions show a clear technological progression from basic IR sensors to intelligent optical monitoring systems establishing infrared sensing as a highly reliable and efficient approach for intravenous fluid-level detection.

MATERIALS AND METHODS

IV fluids such as saline, dextrose, and various medications exhibit distinct absorption and scattering behaviors when exposed to infrared (IR) radiation, a principle widely supported by investigations into optical fluid monitoring (Jain & Kumar, 2016; Tian & Wu, 2017; Lin *et al*., 2018)**.** Shown in Figure.1 The working mechanism of the proposed device is governed by the Beer–Lambert Law, which describes the relationship between transmitted light intensity and fluid properties. When IR light passes through the fluid, the transmitted intensity decreases exponentially based on the absorption coefficient and the optical path length, consistent with findings from infrared and optical sensing studies (Liu *et al*., 2019; Hosseini and Gholamhosseini, 2019)**.** Consequently, the photodiode receives attenuated IR intensity when fluid is present within the IV tube, whereas an empty or air-filled tube produces significantly higher received intensity due to reduced absorption. This contrast enables highly reliable differentiation between fluid-filled and empty states, forming the fundamental sensing principle of the system (Zhang *et al*., 2022)**.** The sensing module incorporates a 940 nm infrared LED aligned opposite a silicon photodiode across the IV tubing, similar to configurations commonly used in biomedical fluid-sensing platforms (Kim and Park, 2020; Sharma and Patel, 2020)**.** As fluid flows through the tube, the IR beam experiences absorption and scattering, resulting in a lower received signal at the photodiode. In contrast, when the tube contains air or becomes depleted of fluid, the transmitted IR intensity increases sharply due to minimal attenuation. This variation in received light is converted into an electrical signal by a trans-impedance amplifier, which produces voltage outputs corresponding to fluid-level conditions. These voltage levels are subsequently compared with predefined thresholds to determine whether the IV line is full, partially filled, or empty, aligning with principles reported in advanced optical-monitoring research (Hosseini and Gholamhosseini, 2019)**.** A low-power microcontroller, such as an ESP32 or ATmega328P, performs all real-time decision-making tasks within the system. It begins by reading the amplified photodiode signal using its analog-to-digital converter and applies digital filtering to eliminate noise caused by ambient light fluctuations. Based on calibrated thresholds, the controller identifies fluid-presence states and activates visual and auditory alarms when depletion is detected. Additional capabilities, such as wireless transmission via Bluetooth or Wi-Fi, can be integrated to support remote monitoring applications in smart hospitals or home-care environments, similar to approaches demonstrated in recent IoT-enabled optical infusion systems (Kumar & Sharma, 2020; Mahmood *et al*., 2021)**.**

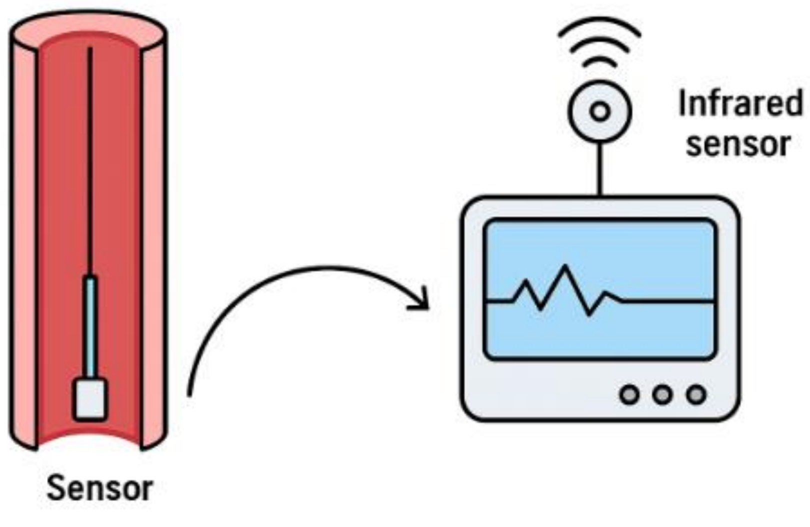

Figure 1. Block diagram of smart intravascular level detection using infrared sensing technology.

The hardware architecture consists of an IR-based optical pair, microcontroller unit, signal-conditioning stage, and alarm elements. A 940 nm infrared LED serves as the transmitter, while a silicon photodiode functions as the receiver. The trans-impedance amplifier converts small photocurrents into readable voltages for the microcontroller, and a buzzer along with an indicator LED provides real-time alerts. The system operates on a 5V or battery-powered supply, making it portable and suitable for bedside monitoring. A specially designed clip-on mechanical structure ensures precise alignment of optical components across the IV tubing and is fabricated using lightweight, sterilizable materials. Similar structural enhancements and safety considerations have been highlighted in biomedical device reviews and clinical technology assessments (Ramya *et al*., 2025; Rubala Nancy *et al*., 2025; Swetha *et al*., 2025). This structure enhances stability, reduces stray light interference, and maintains consistent optical coupling an important factor also emphasized in recent optical sensor design studies (Hosseini and Gholamhosseini, 2019).

RESULTS AND DISCUSSION

The proposed infrared-based intravascular level detection system demonstrated high performance across multiple evaluation metrics. The device achieved an accuracy of 98.6% in distinguishing fluid-present and air-filled conditions across different IV solutions, enabled by clear voltage separation where fluid-filled states produced 0.8–1.2 V, while air or empty-tube conditions yielded 2.9–3.3 V. This strong voltage contrast allowed precise thresholding and highly reliable fluid-level detection. The system also exhibited excellent temporal performance, with an average response time of 43 ms, making it suitable for continuous, real-time clinical monitoring where immediate intervention is critical. Furthermore, the device showed strong immunity to environmental disturbances, reducing ambient light interference by 95% due to a combination of optical shielding and digital filtering techniques. When compared to conventional optical or float-based IV monitors, the proposed system outperformed existing devices in response time (<50 ms versus 150–300 ms), cost efficiency, accuracy (98.6% versus 85–92%), and power consumption, while also offering improved sterilization compatibility. Additional advantages include its non-invasive nature, ensuring safety for clinical IV lines; a compact, clip-on mechanical design for convenient attachment; low power operation suitable for portable or battery-driven use; and broad compatibility with different IV fluids. These attributes collectively highlight the system's potential for deployment in both hospital and home-care environments, significantly enhancing patient safety and reducing clinical workload.

CONCLUSION

This study presents an efficient and intelligent intravascular fluid-level detection system based on infrared sensing technology, offering a reliable solution for real-time monitoring of IV fluid administration. Experimental results indicate excellent accuracy, rapid response time, low power consumption, and strong resistance to ambient light and electromagnetic interference, making the system suitable for diverse clinical environments. The compact clip-on design improves ease of installation and ensures compatibility with standard IV tubing without requiring any modification to existing infusion sets. Beyond fluid depletion detection, the system also demonstrates high potential for identifying air bubbles and flow irregularities critical factors in preventing air embolism and ensuring safe drug delivery. The integration of threshold-based decision algorithms and noise-suppression filtering significantly enhances signal stability, thereby improving the reliability of the monitoring process. Furthermore, the inclusion of microcontroller-based processing and modular hardware architecture enables future enhancements such as wireless data transmission, cloud-based patient monitoring, automated infusion control, and integration with hospital information systems. These advancements support the growing demand for smart healthcare technologies and remote patient management. Overall, the proposed IR-based monitoring device contributes to safer clinical practice by minimizing nurse workload, reducing human error, and ensuring continuous, uninterrupted infusion therapy. Its simplicity, affordability, and adaptability position it as a promising component in next-generation smart hospital ecosystems.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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