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A Novel and Low-Cost Cloud-Enabled IoT Integration for Sustainable Remote Intravenous Therapy Management

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Abstract: Intravenous therapy is the standard medical procedure that is used for administering medications directly into the vein. The automated drug infusion devices are designed in such a way that they provide exact medication doses with safety measures included. On the other hand, this is why they must be regularly watched by healthcare providers. This paper introduces a cloud-based IoT drug infusion system that was developed to address remote patient care needs. This system enables remote, accurate, and secure management of medication delivery. Its key contributions include allowing healthcare providers to control and monitor IV infusions remotely while maintaining safety features. The system consists of a microcontroller that is responsible for data processing, a control system that oversees infusion rate regulation, and an IoT-based framework that allows for remote monitoring and alerts via a user-friendly web interface. This new approach to care will therefore improve patient care by providing remote management of medications.

Keywords: automated; drug infusion; IoT-based

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1. Introduction

In the pursuit of meeting the growing need for cutting-edge healthcare solutions, this paper proposes a novel method of integrating cloud-based IoT technologies into automated drug infusion systems. By integrating microcontroller technologies with complex control systems and the robust IoT framework, the system is not only capable of remote, precise, and secure infusion operation but also raises the bar for the standard of patient care. The significance of this venture lies in the fact that it can bring a revolution in the field of modern healthcare for health professionals as they can have full control and surveillance over the drug administration, no matter where they are located, irrespective of geographical barriers. Furthermore, the use of real-time data exchange and monitoring enables not only safer patient care but also better medical procedures which, in turn, results in improved patient outcomes and healthcare efficiency [1]. In this paper, we have demonstrated that our approach has the potential to be a game-changer in the world of IoT-enabled medical devices and to pave the way for further advancements in the field.

This project seeks to create an affordable IoT-based automated drug infusion device capable of precisely managing and monitoring the infusion rate, the volume of the infusion fluid, and the timing of the infusion process through both local and remote communication methods. The initiative successfully demonstrates the feasibility of an infusion device, featuring an instant feedback mechanism to enhance power efficiency and the overall satisfaction of remote medication administration. It encompasses the development of a basic infusion pump integrated with a real-time feedback algorithm and a sensor system for monitoring and detecting potential issues during the infusion. Moreover, it advances communication protocols and the interface between the infusion mechanism device and the respective computers. Our proposed methodology is divided into four main blocks:

microcontroller/program algorithm, Internet of Things (IoT), uninterruptible power supply (UPS), and control system, all of which interact to ensure project success. The block diagram, shown in Figure 1, provides a system overview.

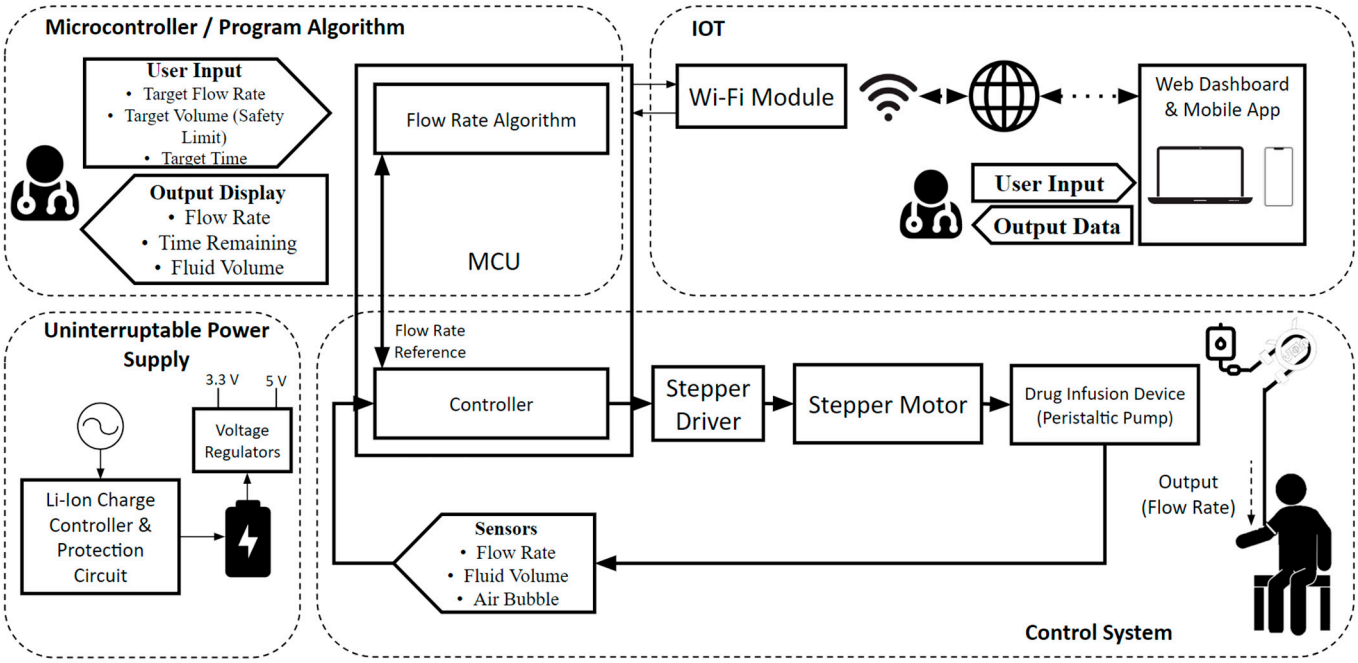


Figure 1. Block diagram of our proposed system.

Users interact with the system through a physical interface, inputting prescribed data (target volume, duration, and flow rate) into the microcontroller. An in-built algorithm then determines the optimal flow rate; based on this, data will assist in the overall control mechanism system of the infusion device. Sensor data, such as the immediate flow rate and amount delivered, are displayed for ongoing monitoring. The control system employs a closed-loop feedback mechanism, maintaining the flow rate at the user-defined level. A notable project feature is enabling remote drug administration by healthcare professionals through a web dashboard and mobile app, facilitating global device management via cellular or Wi-Fi connections. The system's front end, developed using HTML, CSS, and JavaScript, provides a graphical user interface for server interaction, while the back end leverages the Blynk Cloud Server for data management. An uninterruptible power supply ensures the device's continuous operation and charging without disruption.

2. Literature Review

2.1. Intravenous Therapy

Intravenous therapy (IV therapy) is the scientific term for delivering medical liquids, crucial medications, and important nutrients directly into a person's blood. This method is crucial for adjusting fluid volumes and electrolyte balances or for providing essential nutrition when oral ingestion is not viable [2]. It is also employed for the administration of various treatments such as chemotherapy and anesthetics and for carrying out procedures like blood transfusions [3].

The human body is made up mostly of water (approximately 60%), and we rely heavily on water for a variety of activities, including body temperature regulation and organ health. Even vital organs such as the brain and heart contain more than 70% water [4]. We constantly lose water through breathing, sweating, urination, and physical activity. High temperatures, alcohol consumption, and strenuous exercise increase the risk of dehydration. While oral hydration can take up to an hour to be fully absorbed, IV fluid delivery provides immediate replenishment directly into the vein.

Intravenous fluids are broadly categorized into crystalloids and colloids, with the former preferred for dehydration treatments. Crystalloids, aqueous solutions of mineral salts or water-soluble molecules, bolster circulatory volume while maintaining vascular chemical balance [5]. Sodium chloride solution at 0.9% concentration, known as normal saline, stands out as the predominant crystalloid choice. In the surgical care context, IV therapy is essential, aiming preoperatively to uphold or replenish fluid and electrolyte levels, thus averting conditions of hypovolemia or dehydration [6]. Hypovolemia, characterized by insufficient blood volume, jeopardizes organ oxygenation, potentially leading to organ failure or shock [7]. Conversely, fluid overloading can trigger complications such as edema, impaired tissue repair, and elevated risks of postoperative complications [7].

Parenteral nutrition (PN), another application of IV therapy, provides vital nutritional support through an intravenous line for individuals unable to meet dietary needs orally, often due to gastrointestinal complications [7]. The administration of IV therapy offers a swift conduit for distributing fluids and drugs body-wide, ensuring optimal therapeutic drug concentrations in the bloodstream. This method is especially critical for delivering treatments like chemotherapy, blood transfusions, antibiotics, and other medications unsuitable for oral administration [8].

To mitigate medication dosing inaccuracies during patient care transitions, standardized guidelines for the concentration and dosing schedules of certain medications have been instituted [9]. These protocols facilitate the identification of necessary dosing rates and timings for prevalent IV therapy drugs, as illustrated in Table 1, drawing on data from various medical centers and organizations [10–13].

Table 1. Guidelines for intravenous medications [10–13].

Drug Name	Std Concentration	Std Dilution	Dosing Rate
Abciximab	36 μg/mL	9 mg/250 mL	0.125 μg/kg/min × 12 h
Amiodarone	1.8 mg/mL	450 mg/250 mL	1 mg/min × 6 h
Bumetanide	0.04 mg/mL	10 mg/250 mL	0.25–0.5 mg/h
Cisatracurium	0.8 mg/mL	200 mg/250 mL	0.15–0.2 mg/kg/h
Dexmedetomidine (Precedex)	4 μg/mL	200 μg/50 mL	0.2–1.4 μg/kg/h
Diltiazem (Cardizem)	1 mg/mL	100 mg/100 mL	5–15 mg/h
Dobutamine (Dobutrex)	2 mg/mL	500 mg/250 mL	2.5–20 μg/kg/min
Dopamine	1.6 mg/mL	400 mg/250 mL	2–20 μg/kg/min
Fentanyl	10 μg/mL	1000 μg/100 mL	25–150 μg/h
Heparin	100 units/mL	2500 units/250 mL	13 units/kg/h
Insulin (Regular)	1 unit/mL	100 units/100 mL	Based on blood glucose level, follow protocol
Isoproterenol	16 μg/mL	4 mg/250 mL	0.5–20 μg/min
Lidocaine	4 mg/mL	1000 mg/250 mL	1–4 mg/min
Magnesium	20 mg/mL	1000 mg/50 mL	1000 mg/h
Morphine	1 mg/mL	50 mg/50 mL	1–10 mg/h
Potassium Chloride	0.1 mEq/mL	10 mEq/100 mL	≤10 mEq/h
Propofol (Diprivan)	10 mg/mL	1000 mg/100 mL	5–75 μg/kg/min
Vasopressin	0.4 unit/mL	20 units/50 mL	0.04 units/min

These standardized dosing concentrations and rates for medications give us valuable insight into the operational requirements of an infusion device. Considering "Amiodarone" as an instance, where the prescribed dosing period spans 6 h, we can ascertain the necessary dosing rate for a diluted solution by calculating

$$60\frac{\text{mg}}{\text{h}} \times 250\ \text{mL} \div 450\ \text{mg} = 33.33\ \text{mL/h} \quad (1)$$

The device should administer the solution at a rate of 33.33 mL per hour. Over the course of 6 h, the device is thus tasked with delivering a total of 200 mL of this diluted medication. This calculation underscores the importance of an infusion device's ability to operate over extended periods with precision in dosing.

2.2. Comparison of Infusion Device Products

In reviewing various infusion devices to enhance the IoT-based drug infusion device project, nine distinct products were selected, each showcasing unique features and designs that contribute valuable insights. These devices, ranging in functionality and technological integration, offer a broad perspective on potential improvements and innovations for the project. Table 2 presents a comparative analysis of the features across the nine products, offering a concise overview of their capabilities and distinctions.

Table 2. Comparison of products [14–24].

Products	Features					
	Flow Rate and Volume Monitoring	Alarm Warning	Air-In Line Detection	WLAN	Pressure Anomaly Detection	Automatic Infusion
[25,26]	No	No	No	No	No	No
[27]	Yes	Yes	No	No	No	No
[28]	No	No	No	No	No	Yes
[29]	Yes	Yes	No	No	Yes	Yes
[30]	Yes	Yes	No	Yes	Yes	Yes
[31]	Yes	Yes	Yes	No	Yes	Yes
[32]	Yes	Yes	No	Yes	Yes	Yes
[33]	Yes	Yes	Yes	No	Yes	Yes
[34]	Yes	Yes	Yes	No	Yes	Yes

The IV drip stand setup usually consists of a vertical frame with adjustable hooks used to hold IV fluid bags, which enables gravity-driven fluid administration to patients [25,26]. Shift Labs' DripAssist is a lightweight infusion monitoring system that regulates IV flow rates, thus ensuring accurate medication dispensing [27]. The B. Braun Easypump II ST/LT is a programmable infusion pump system that can give fluids, medicines, and nutrition to patients for either a short or long time [28]. The Alaris GH Plus Guardrails Syringe Pump, which is a syringe infusion pump, has the guardrails technology added to it so that drug errors can be avoided [29]. The Agilia SP MC WiFi is a smart infusion pump that has wireless connectivity and can be remotely monitored and controlled to adjust the infusion parameters [30]. The Alaris GP Plus Volumetric Pump with Guardrails is a volumetric infusion pump designed to deliver fluids and medications accurately, incorporating guardrails technology to enhance patient safety and prevent adverse events [31]. Additionally, the Agilia VP MC is another smart infusion pump model with WiFi capabilities that allow for more enhanced infusion management and safety [32]. The Moog CURLIN 6000 is a portable infusion pump system that is appropriate for delivering a wide range of medications and therapies in both clinical and home settings [33]. Lastly, the Moog CURLIN PainSmart IOD is an advanced infusion pump that was created to address pain management issues and provides precise dosing as well as customizable therapy options [34].

The variety of infusion devices selected for examination employs distinct infusion technologies, categorized by their operating mechanisms, including peristaltic pumps, syringe-driven systems, gravity-fed units, and elastomeric reservoirs. The method of drug delivery implemented by each device varies, encompassing continuous or intermittent infusion, bolus dosing, and specific therapeutic applications like patient-controlled analgesia (PCA). These differences highlight the versatility and adaptability of infusion technologies to meet diverse medical needs. Table 3 provides a side-by-side comparison of the specifications for six automated infusion devices, showcasing their unique attributes and functionalities. This comparison aids in understanding how each device aligns with the operational needs of an IoT-based drug infusion device project, considering the various technological approaches to achieve accurate and efficient drug delivery.

Regardless of the chosen pump, common failures identified in infusion therapy, as per the literature, encompass issues like occlusion, air-in-line, free flow, cross-flow in multi-infusion scenarios, and infiltration or extravasation. Alarm fatigue and medication errors associated with infusion pumps were also highlighted as significant health technology hazards in recent years. To mitigate medication errors, Dimech et al. developed a drug library for smart pumps, designed to ensure safe medication administration while being practical

enough for consistent system compatibility [14]. Larsen et al. reported a 73% decrease in medication infusion errors through the integration of standard strength concentrations with smart syringe pumps, alongside medication label re-engineering [15]. The study by Wetterneck et al. showcased failure mode and effects analysis (FMEA) as a vital tool for identifying smart pump implementation risks and for assessing IV pump technologies to enhance programming accuracy and reduce IV medication errors [16]. Furthermore, smart pump technology has not only shown promise in improving efficiency but also in cost-effectiveness [17].

Table 3. Comparison of product specifications.

Products	Key Specifications					
	Flow Rate (mL/h)	VTBI (mL)	Accuracy	Battery Life	Pump Mechanism	Therapies
Alaris GH Plus Guardrails Syringe Pump [29]	0.1–1200	0.1–1000	±2% ≥1 mL	6 h @5 mL/h	Syringe	Continuous TPN Intermittent Variable
Agilia SP MC WiFi [30]	0.1–1200	0.1–999	±2%	13 h @5 mL/h (*w/o* WiFi) 9 h @5 mL/h (w WiFi)	Syringe	Continuous TPN Intermittent Variable
Alaris GP Plus Volumetric Pump with Guardrails [31]	0.1–1200	0.1–9999	±2%	6 h @25 mL/h	Four Finger Displacement Peristaltic	Continuous TPN Intermittent Variable
Agilia VP MC WiFi [32]	0.1–1500	0.1–9999	±5%	8 h @25 mL/h (*w/o* WiFi) 5 h @25 mL/h (w WiFi)	Linear Peristaltic	Continuous TPN Intermittent Variable
Moog CURLIN 6000 [33]	0.1–400	1–9999	±5%	30 h @ 125 mL/h	Curvilinear Peristaltic	Continuous PCA TPN Intermittent Variable
Moog CURLIN PainSmart IOD [34]	0.1–50	1–9999	±5%	30 h @ 125 mL/h	Curvilinear Peristaltic	PCA

3. Embedded Solutions in Cloud for IoT Medical Devices

In today's interconnected world, the internet serves as a global conduit, facilitating immediate communication and information sharing across distances. The swift progression of Bluetooth and wireless technologies has significantly enhanced the efficiency of connecting a myriad of devices to the internet. This technological evolution, coupled with advances in sensors and computing technologies, has paved the way for the emergence of the Internet of Things (IoT). The advent of IoT has profoundly impacted the medical and healthcare sectors, addressing long-standing challenges in hospital management and patient monitoring [18]. An IoT-based healthcare monitoring system (HCMS) integrates IoT medical devices and medical data processing components [19] with internet and communication services, as depicted in Figure 2.

Employing IoT in healthcare systems offers numerous advantages, including enhancing patient safety and quality of life through continuous monitoring and remote evaluations. It empowers individuals to manage their health with increased independence and proactive engagement with their wellness and medical conditions. Additionally, the remote monitoring and automated control of medical supplies facilitate cost savings in patient care and reduce inventory shortages in hospitals. Cloud computing plays a pivotal role in this ecosystem by offering essential system resources—such as servers, storage, databases, and networking—over the internet, thereby eliminating the need for extensive hands-on management. The healthcare sector benefits from cloud computing through the acceleration of medical technology innovations and the provision of efficient, patient-centered care experiences [20]. Table 4 presents a comparison of the cloud software utilized in various medical monitoring systems previously proposed.

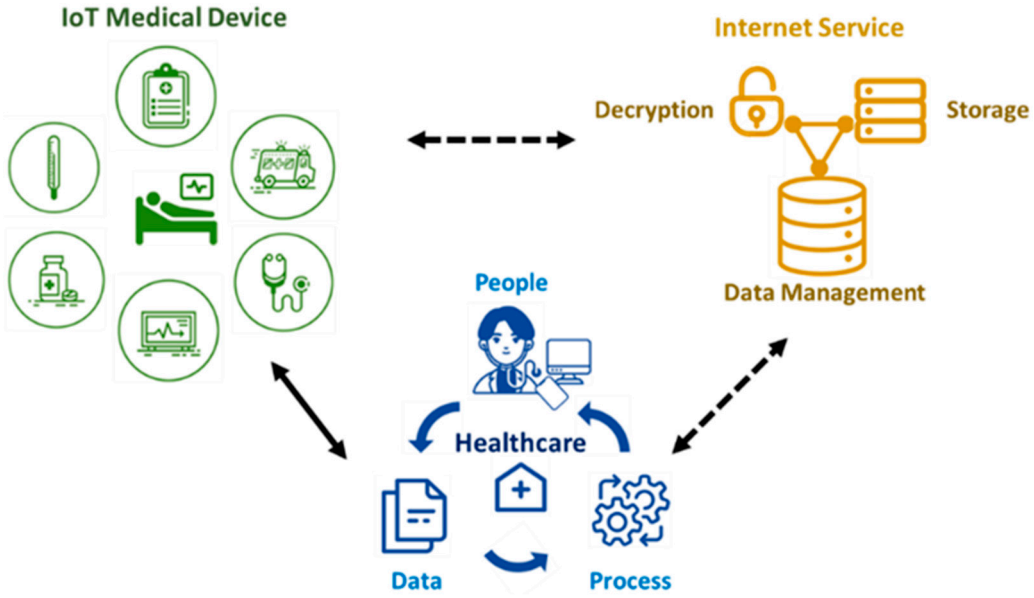


Figure 2. Monitoring system in a healthcare setting.

Table 4. Cloud software comparison [21–24].

Proposed System	Cloud Software	Application-Layer Protocols	Cryptographic Protocol
"Internet Connected Intravenous Drip Monitoring Device" [21]	Axelta Osmosis	HTTP	-
"IoT based wristband for Intravenous infusion level monitoring" [22]	Shiftr.io	Desktop App: HTTP Cloud: HTTPS/MQTT	Desktop App: - Cloud: TLS (unknown version)
"IoT based Healthcare Monitoring and Intravenous Flow Control" [23]	Firebase	REST	TLS (latest version, 1.3v)
"Mobile Healthcare Monitoring System" [24]	Blynk	HTTPS	TLS (latest version, 1.3v)

4. Firmware and Algorithm Designs

The successful operation of the cloud-enabled IoT-based automated drug infusion system hinges upon robust theoretical foundations that govern its firmware and algorithm designs. Time is of the essence in such a multi-faceted device. The microcontroller must manage network connectivity, operate the stepper motor, communicate with peripheral devices such as the OLED display via I2C and monitor sensor inputs at the same time. The very nature of these jobs, which require accuracy and precision in a short period of time, emphasizes the importance of the timely completion of the task. The slightest delay in the processes, whether it is sensing drip rates, controlling peristaltic pumps or transmitting data to the cloud server, can lead to significant challenges to operation and patient safety. The optimization of network communication protocols is the most crucial factor that determines the effectiveness of data exchange through the cloud server. Thus, the deployment of effective communication protocols and strategies will be one of the main issues to be solved in order to minimize the latency and maintain the continuous connection. The stepper motor and its precise control is another major pillar of the system, through which infusion rates can be easily regulated. This degree of accuracy requires complex control algorithms and systems that can respond to changing parameters of medication and the environment. Sensor input monitoring and interpretation in real time play the role of an early warning system against abnormalities or deviations from the set medication parameters. The system will be able to analyze the sensor data in real time and take the necessary corrective measures if any deviation is detected to keep therapeutic efficacy as well as patient safety intact. The multi-threaded programs that can run concurrently without compromising on performance and reliability are the core pillars for the handling of concurrent tasks. This allows for the appropriate resource allocation and scheduling strategies that will prevent contention and bottlenecks and maximize the use of computational resources. The problem

of the differences between the desired and real flow rates arises, and therefore the PID controller has to be included in the microcontroller framework. The PID controller provides a systematic feedback control algorithm that automatically adjusts the infusion rate based on the real-time feedback from the sensors which, in turn, ensures medication delivery precision and accuracy.

Based on the theoretical foundations that have been laid out so far, the following hypotheses serve as the basis for the design of the firmware and algorithms of the proposed infusion system.

- Immediate processing capabilities integrated with the firmware framework of the infusion device facilitate the execution of concurrent tasks without any interruption while meeting the strict time demands.
- A well-designed network communication protocol with the cloud server makes it possible to receive data in a timely manner and to maintain steady remote monitoring and management of the medication delivery processes.
- One of the critical features that make the stepper motor a suitable choice for an infusion device is its precise control mechanisms that allow the device to regulate infusion rates with high accuracy and consistency, which in turn improves medication delivery precision.
- In-time monitoring and translation of sensor data into understandable information enable the system to timely alert about any variations from the desired medication parameters and secure patient safety and treatment success.
- The ability of multi-threaded programs to be integrated seamlessly within the firmware architecture facilitates the management of tasks efficiently and resource utilization optimization, which results in improved system performance and reliability under different operating environments.
- The PID controller incorporated into the microcontroller architecture serves the purpose of delivering accurate doses of drugs by adjusting the infusion rate accordingly, thus reducing the difference between the desired and actual flow rate.

Affirming these hypotheses by conducting experiments and checking them rigorously is expected to prove the effectiveness and reliability of the proposed firmware and algorithm designs which will, in turn, improve the state-of-the-art in cloud-enabled IoT-based automated drug infusion systems.

4.1. Real-Time Operating System

Utilizing the ESP32 microcontroller, known for its dual-core processors and compatibility with a real-time operating system (RTOS), enables the creation of multi-threaded programs essential for real-time computing demands. Implementing an RTOS offers a solution by allowing for the scheduling of tasks to meet these strict deadlines. Unlike traditional programming paradigms that employ a super-loop architecture, where tasks are executed sequentially in a loop, an RTOS enables the concurrent running of multiple tasks. This shift enhances the system's ability to handle various operations simultaneously without compromising on the execution timing. Figure 3 provides a visual comparison of the program flow between the super-loop and RTOS architectures.

The ESP32's ability to manage user interactions, control hardware, perform complex computations, and efficiently handle wireless communications protocols is further optimized through the use of an RTOS. This approach divides system functions into separate tasks, leveraging the modified FreeRTOS kernel tailored for the ESP32's Symmetric Multiprocessing (SMP) architecture. With SMP, a multithreaded application can execute across multiple cores under a single operating system, each with its scheduler. This architecture facilitates shared resources among the cores while maintaining task coherence and cache integrity.

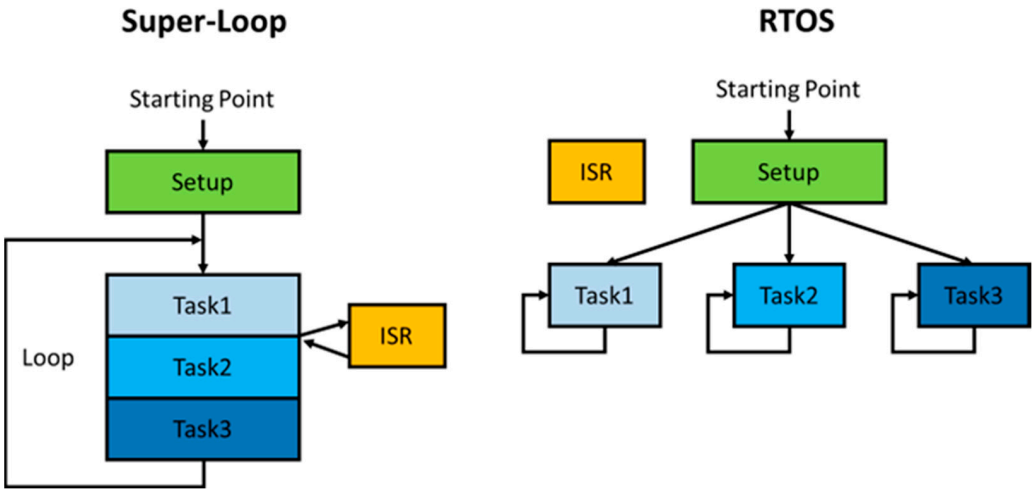


Figure 3. Super-loop and RTOS architectures.

In the SMP setup of the ESP32, one core is designated for handling communication protocols like Bluetooth and Wi-Fi, whereas the second core, the application core, is tasked with executing user-defined operations. This delineation allows for efficient core usage by scheduling tasks to run on an available core when not explicitly assigned to one. However, for operations requiring hardware interrupts, such as an air bubble sensor triggering an interrupt service routine (ISR), tasks must be explicitly assigned to cores due to each core's unique interrupt setup.

The ESP32 is engineered to concurrently execute four primary tasks. The strategic core assignment for these tasks ensures optimal performance and reliability of the infusion device, as demonstrated in Figure 4. This intricate design underscores the importance of RTOS in facilitating real-time computing for complex IoT-based medical devices.

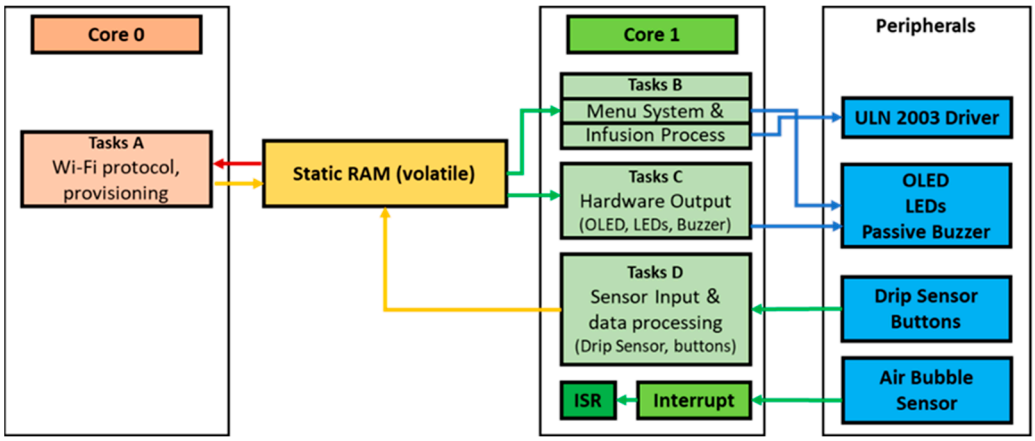


Figure 4. Core assignment design.

In a dedicated effort to ensure the infusion device's network communication tasks are efficiently managed, Core 0 is exclusively reserved for Wi-Fi network provisioning. This approach is critical due to the significant processing requirements associated with maintaining network connectivity, initializing backend communications, handling HTTP protocols, and managing TLS encryption/decryption processes. By isolating these tasks on Core 0, the system safeguards against the potential for task starvation and consequential data losses, which are critical risks in the operation of IoT-based medical devices.

To bolster the determinism and reliability of the infusion device, all additional tasks are assigned to Core 1. This strategic distribution allows the system to effectively manage interrupts, such as those from an air bubble sensor, pausing other tasks to address urgent

issues promptly. This ensures uninterrupted operation of Core 0 tasks, enabling continuous data exchange with the server backend and facilitating timely notifications to medical practitioners via web and mobile platforms.

Task scheduling in FreeRTOS is adeptly designed to simulate concurrent task execution, even on single-core processors, by slicing tasks into manageable intervals or "ticks", typically set at 1 ms. The system's scheduler is tasked with selecting the most pertinent task for execution at each tick, based on priority and state, ensuring an equitable and efficient distribution of processing resources.

Figure 5 provides a visual representation of the task states within FreeRTOS, illustrating the transitions between ready, running, blocked, and suspended states. A task in the ready state is queued for execution, transitioning to running when selected by the scheduler. Tasks may enter a blocked state when awaiting events or the release of resources, such as during a delay or when waiting for a mutex. Alternatively, tasks can be explicitly placed into a suspended state via vTaskSuspend(), with vTaskResume() reactivating them to a ready state. This dynamic interplay of task states ensures a responsive and adaptable system capable of meeting the real-time demands of the infusion device.

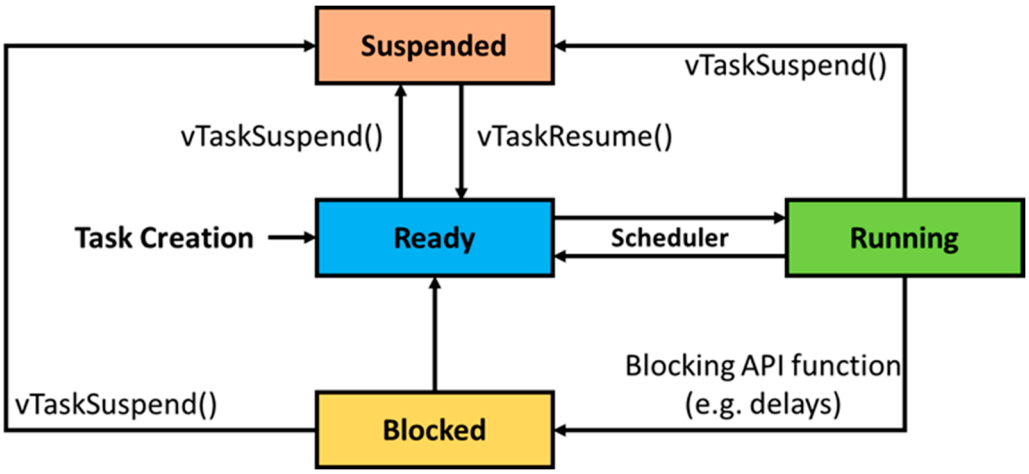


Figure 5. Task states.

The infusion device leverages this sophisticated task management framework to maintain a high level of operational efficiency. By carefully orchestrating the sequence of tasks, particularly those pinned to Core 1 as detailed in Table 5 and visualized in the task scheduling flowchart, shown in Figure 6, the device achieves a balance between real-time data processing and physical device control. This ensures not only the device's functional reliability but also its capacity to provide critical care through timely and accurate medical interventions.

In the firmware design for Core 1, initially, the system operates akin to a super-loop architecture where only Task B is active, monopolizing the CPU resources. This design choice is deliberate for the initial phase of menu selection, which is not considered time-critical. Utilizing a super-loop structure simplifies the design and minimizes the risk of multi-threaded programming issues such as race conditions, deadlocks, and task starvation. It is only after the input parameters are set via the menu that Tasks C and D are reactivated from their suspended state. This transition is crucial for the infusion process, where the timely execution of multiple tasks becomes paramount, necessitating the switch to a multi-threaded operational mode. The overall task scheduling and the transition between super-loop and multi-threaded designs are depicted in Figure 7.

Figure 7 showcases the overall task scheduling process, illustrating the strategic activation and suspension of tasks based on the system's operational phase. This diagram emphasizes the firmware's adaptability, transitioning between different operational modes to optimize performance and reliability.

In this system, all tasks are assigned equal priority, ensuring that the scheduler employs a round-robin method to cycle through tasks in a ready state, thus preventing any single task from causing system-wide latency or starvation. This equitable approach to task management underlines the RTOS's capability to evenly distribute processor time across tasks, ensuring a balanced system performance.

Table 5. Instruction sequences for tasks in Core 1.

Tasks	Sequence	Instruction
Setup	S1	Create Task A, B, C, D
	S2	Suspend Task C, D
Task B	B1	Displaying Menu GUI to the OLED
	B2	Polling for input parameters
	B3	Verifying input parameters
	B4	Calibrate stepper motor according to the input parameters
	B5	Resume Task C, D
	B6	Start infusion process (driving stepper motor)
	B7	Suspend Task C, D
Task C	C1	Update OLED display with real-time data (infusion GUI/error GUIs/alert GUIs)
	C2	Delay Task C for 1000 ms
Task D	D1	Poll reading of drip sensor pin state
	D2-1	If drip state is high, calculate the time interval between the previous drip and current drip
	D2-2	Turn on Drip LED pin
	D2-3	Increment drip count
	D2-4	Calculate real-time flow rate -> PID Control
	D2-5	Delay Task D for 25 ms
	D3	Turn off Drip LED pin
	D4	Calculate remaining infusion time
ISR	I1	Update OLED display with the air bubble error GUI
	I2	Poll for 'Start' and 'Cancel' button response

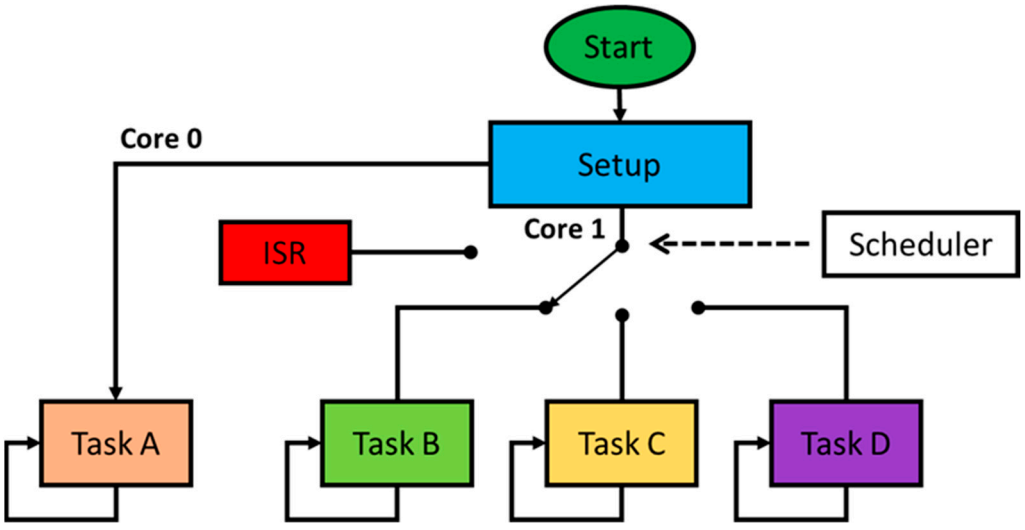


Figure 6. Task scheduling design flowchart.

The RTOS architecture notably excels in handling task delays efficiently. Unlike traditional programming models where a delay operation might halt task execution wastefully, an RTOS reallocates the CPU to other ready tasks during these delay periods. This efficiency is particularly evident in implementing software-based debouncing for button inputs, as illustrated in Figure 8. The RTOS method of debouncing leverages vTaskDelay() to ignore spurious signals generated by the mechanical bounce of button contacts, ensuring that

button presses are accurately and reliably registered. This method not only circumvents the need for additional hardware for debouncing but also showcases the RTOS's ability to enhance system responsiveness and reliability through smart task scheduling.

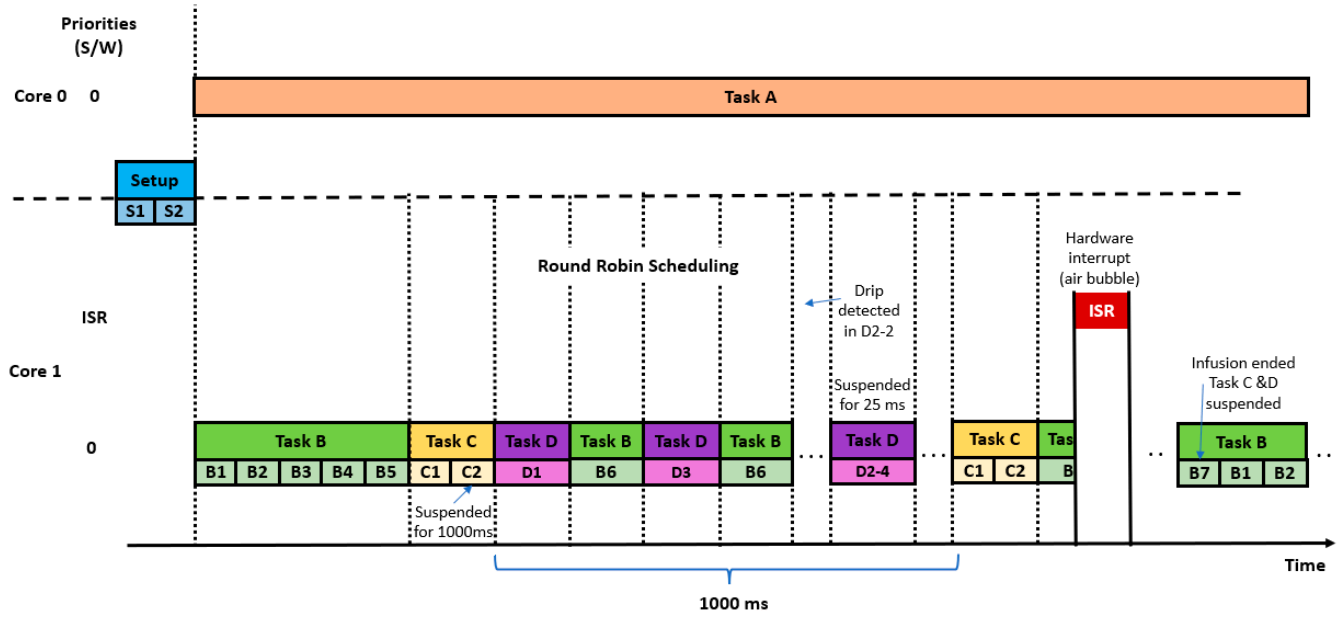


Figure 7. Overall task scheduling process.

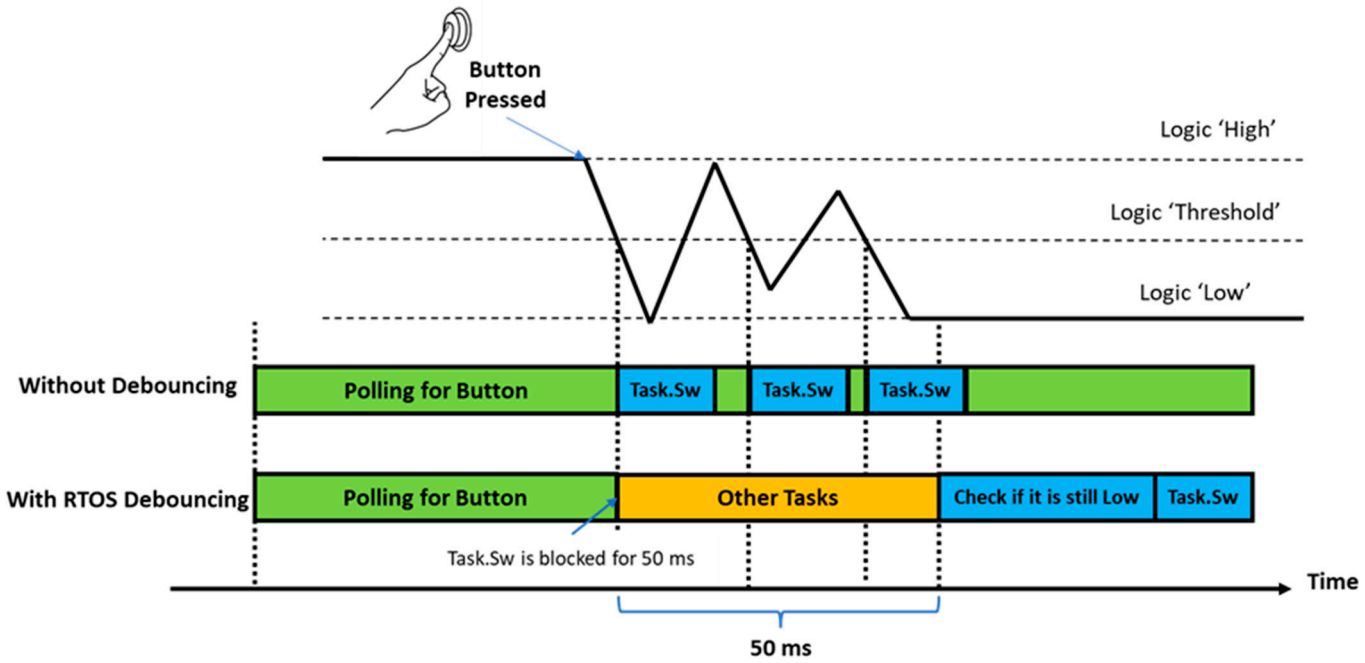


Figure 8. RTOS button debouncing.

4.2. Task B Algorithm Design Flowchart

Task B's algorithm serves as the core interface for user interaction with the infusion device, acting through a menu system enabled by push buttons. This interface allows users to select the device's operational mode, choosing between manual input or predefined drug libraries. The calibration of the stepper motor in relation to the selected input variables is a critical function of Task B, ensuring precise control over the infusion process based on user inputs. The flow of operations within Task B, from initial user interaction to the calibration

and setting of operational modes, is systematically outlined in Figure 9, providing a visual guide to the algorithm's design and functionality.

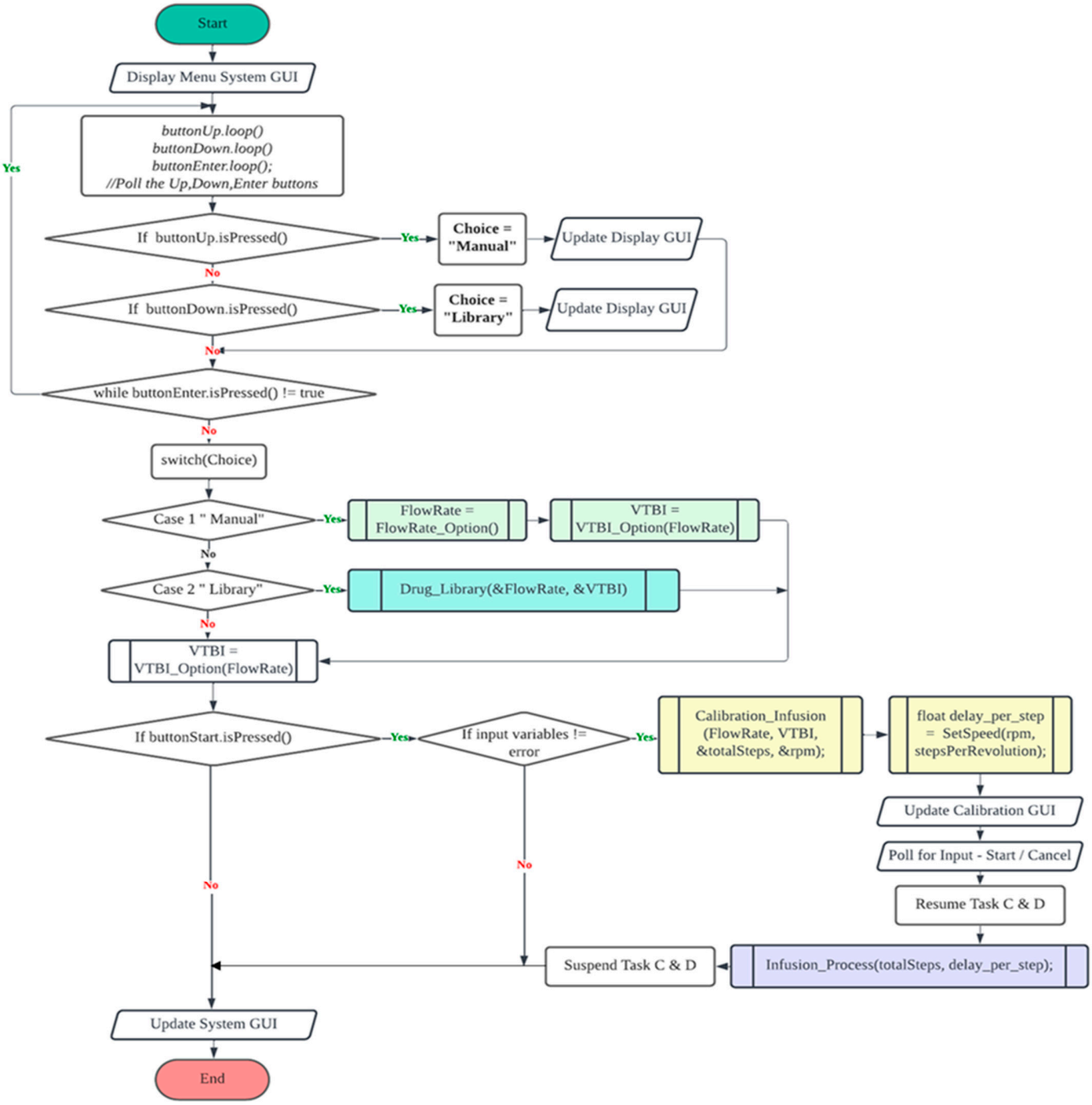


Figure 9. Task B algorithm flowchart.

4.3. Task C Algorithm Design Flowchart

Task C, activated during the infusion process as part of the multi-threaded operational phase, is responsible for managing the output to hardware peripherals. This includes tasks such as displaying the current infusion status on the OLED screen, activating specific LED signals, and generating notifications through a passive buzzer. The algorithmic flowchart for Task C, illustrated in Figure 10, delineates the steps involved in updating and controlling these hardware peripherals, highlighting the task's role in providing real-time feedback and notifications to the user.

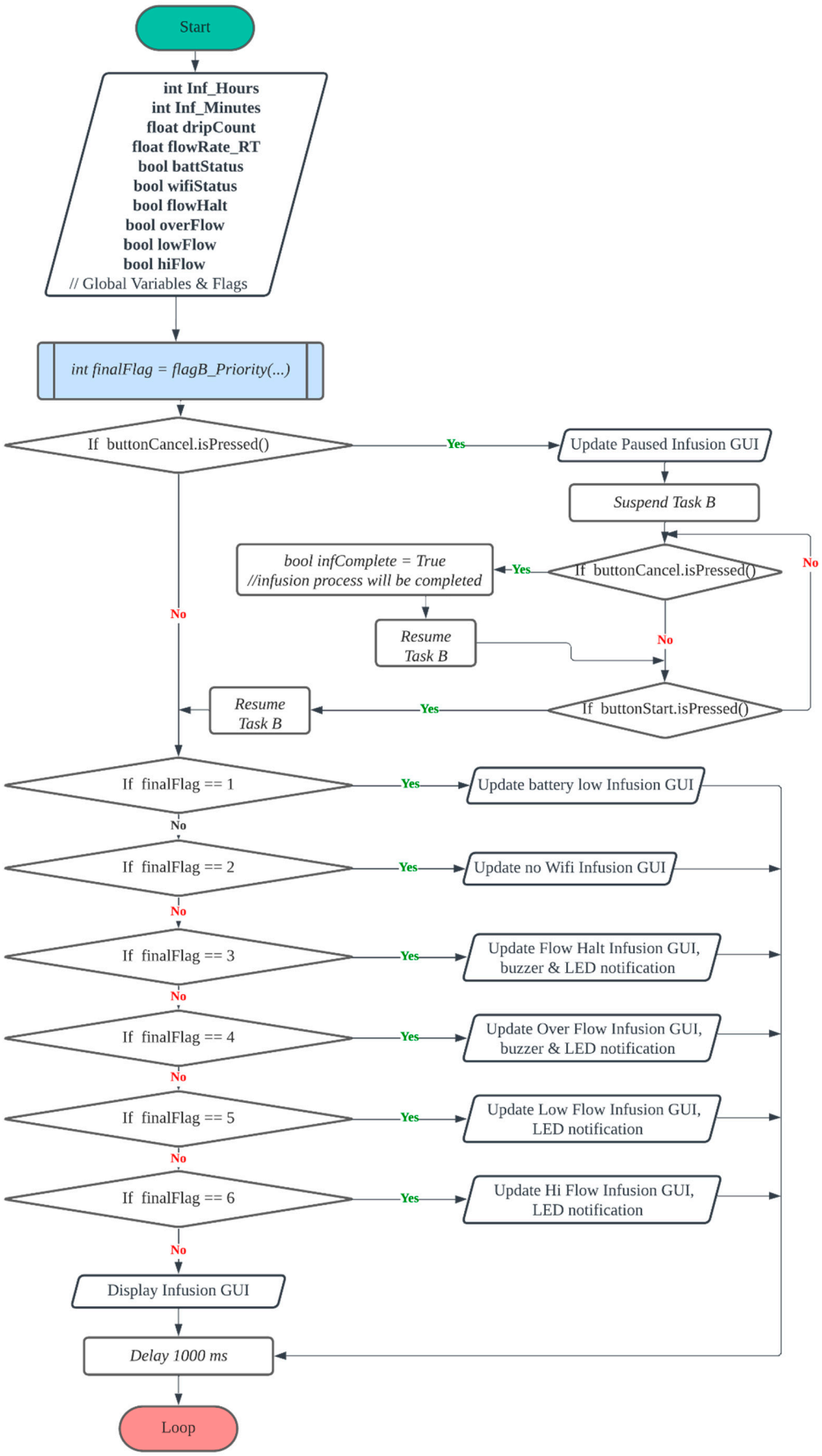


Figure 10. Task C algorithm flowchart.

4.4. Task D Algorithm Design Flowchart

Task D's algorithm is tasked with handling input from hardware peripherals and processing data crucial to the infusion process. This includes reading inputs from the drip sensor, calculating the real-time flow rate and remaining infusion time, managing PID control for precise flow regulation, and monitoring for any errors or alerts that may arise. The design and execution flow of Task D are encapsulated in Figure 11, offering insight into the complex data processing and control mechanisms operational during infusion.

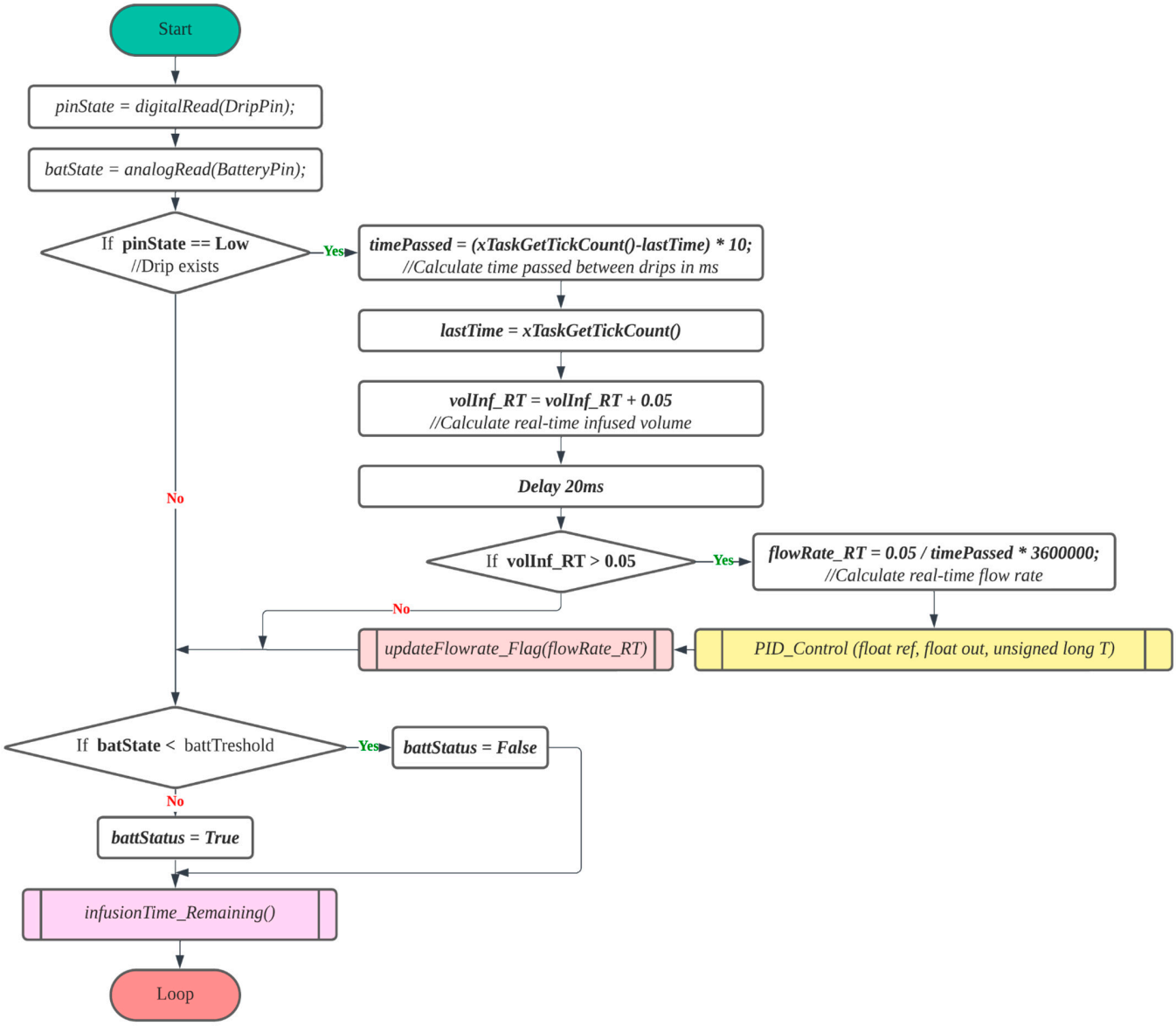


Figure 11. Task D algorithm flowchart.

4.5. Interrupt (Critical Scenario)

The system's response to critical scenarios, such as the detection of air bubbles within the IV tube, is managed through hardware interrupts. These interrupts prompt the processor to pause current tasks and execute a predefined interrupt service routine (ISR). Specifically, the detection of an air bubble triggers an interrupt signal sent to the ESP32's GPIO 27 pin, prompting immediate attention to the potential infusion disruption. The ISR's operational flow, including the suspension of tasks and the notification process through the mobile application, is depicted in Figure 12, highlighting the protocol for addressing such critical events.

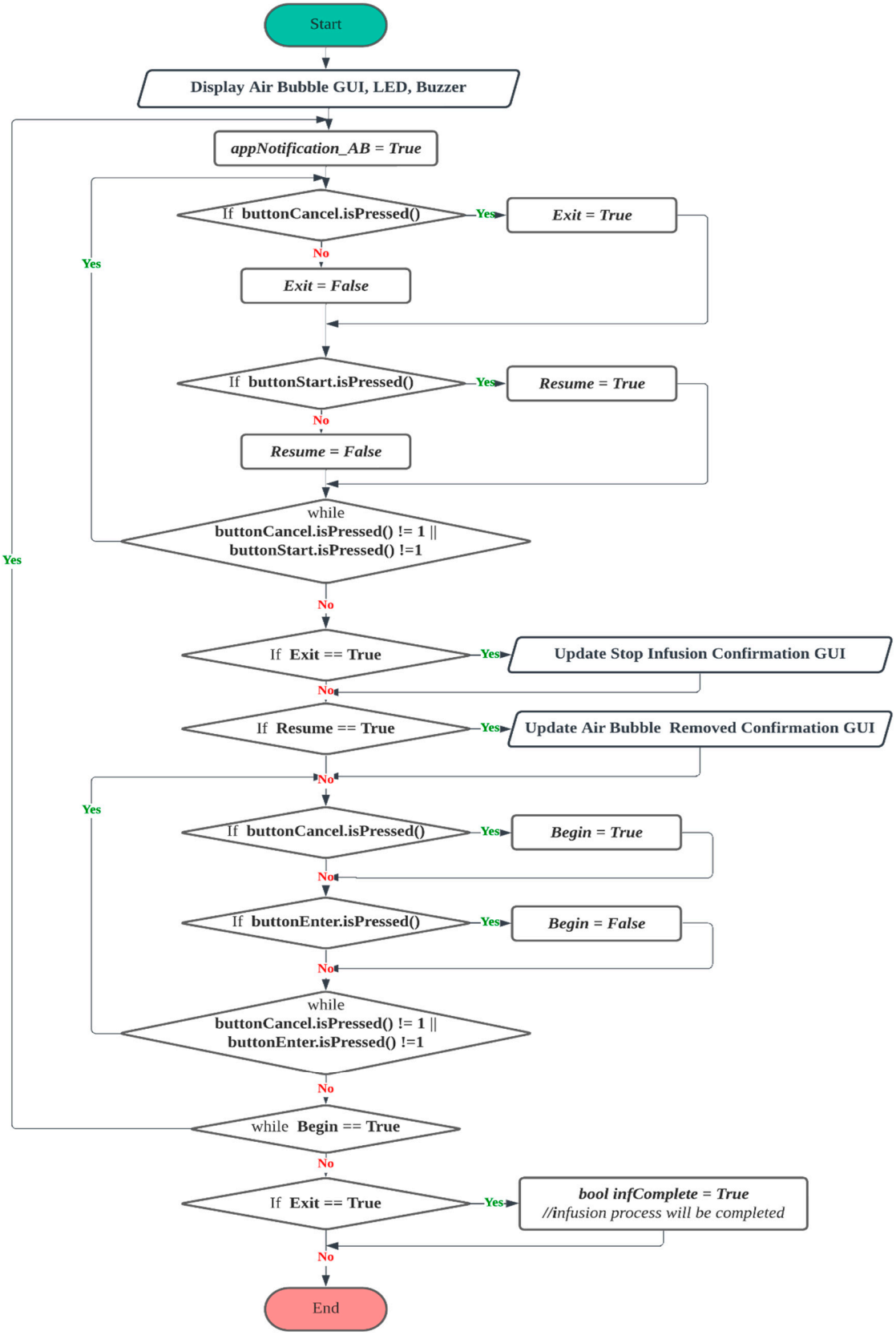


Figure 12. Interrupt algorithm flowchart.

4.6. PID Controller Design

Stepper motors are widely recognized for their precision and robust torque capabilities, essential for systems requiring accurate position control. Traditionally employed in open-loop systems for straightforward point-to-point positioning tasks, stepper motors advance to designated positions through defined steps without necessitating feedback from position sensors. This process is facilitated by generating pulse trains in varied phases to the stator windings, enabling precise movement control. Despite the inherent accuracy of this method, the open-loop approach is vulnerable to step losses when faced with excessive load torque, potentially compromising the system's precision and adaptability to fluctuations in operational demands [24].

Addressing the potential discrepancies between desired and actual flow rates necessitates the integration of a proportional–integral–derivative (PID) controller within the microcontroller framework. This advanced control mechanism refines the stepper motor's operation, significantly enhancing the system's accuracy and response to changes in flow rate requirements. The PID control mechanism's conceptual design for the infusion device is visually represented in Figure 13, utilizing Simulink to depict the intricate control processes involved.

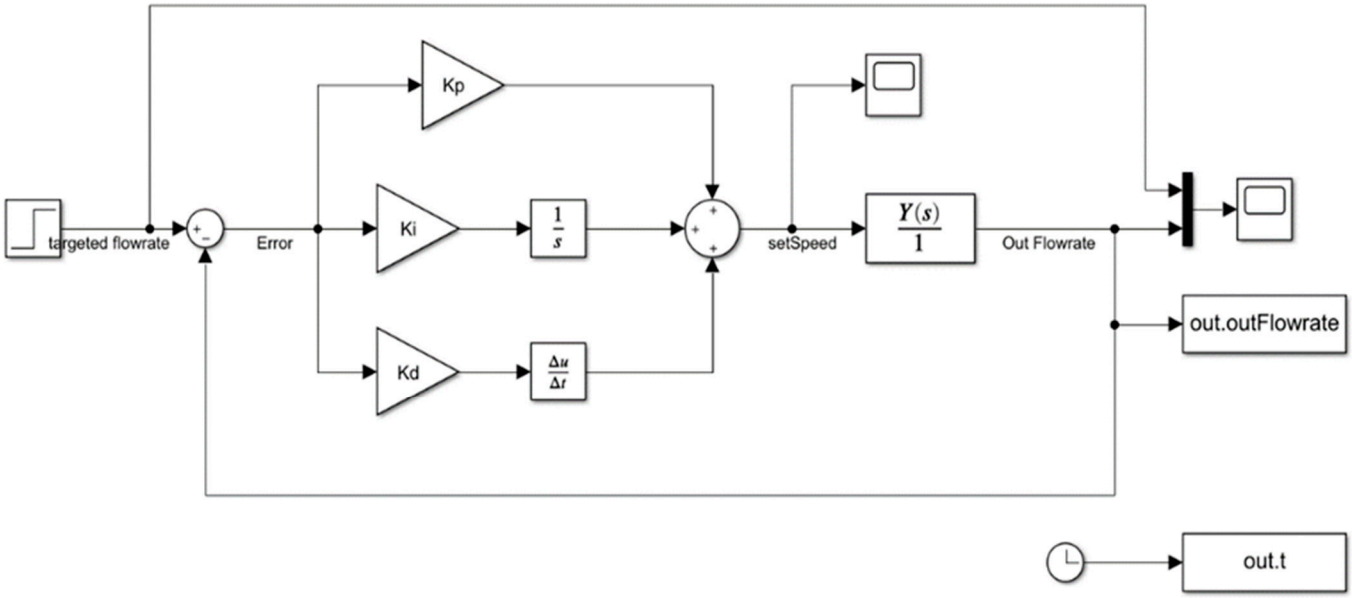


Figure 13. PID control design.

A notable challenge in this context is the non-uniform sampling intervals for feedback flowrate signals, attributable to the operational characteristics of the drip sensor. The sensor's mechanism allows for flow rate estimation only upon the detection of water droplets, thereby introducing variability in the system's response time based on the flow rate. The PID controller's role is to adjust the stepper motor's step interval timing, thereby calibrating the motor's operation to align with the current flow rate demands. This dynamic adjustment process is meticulously outlined in the PID control algorithm flowchart presented in Figure 14.

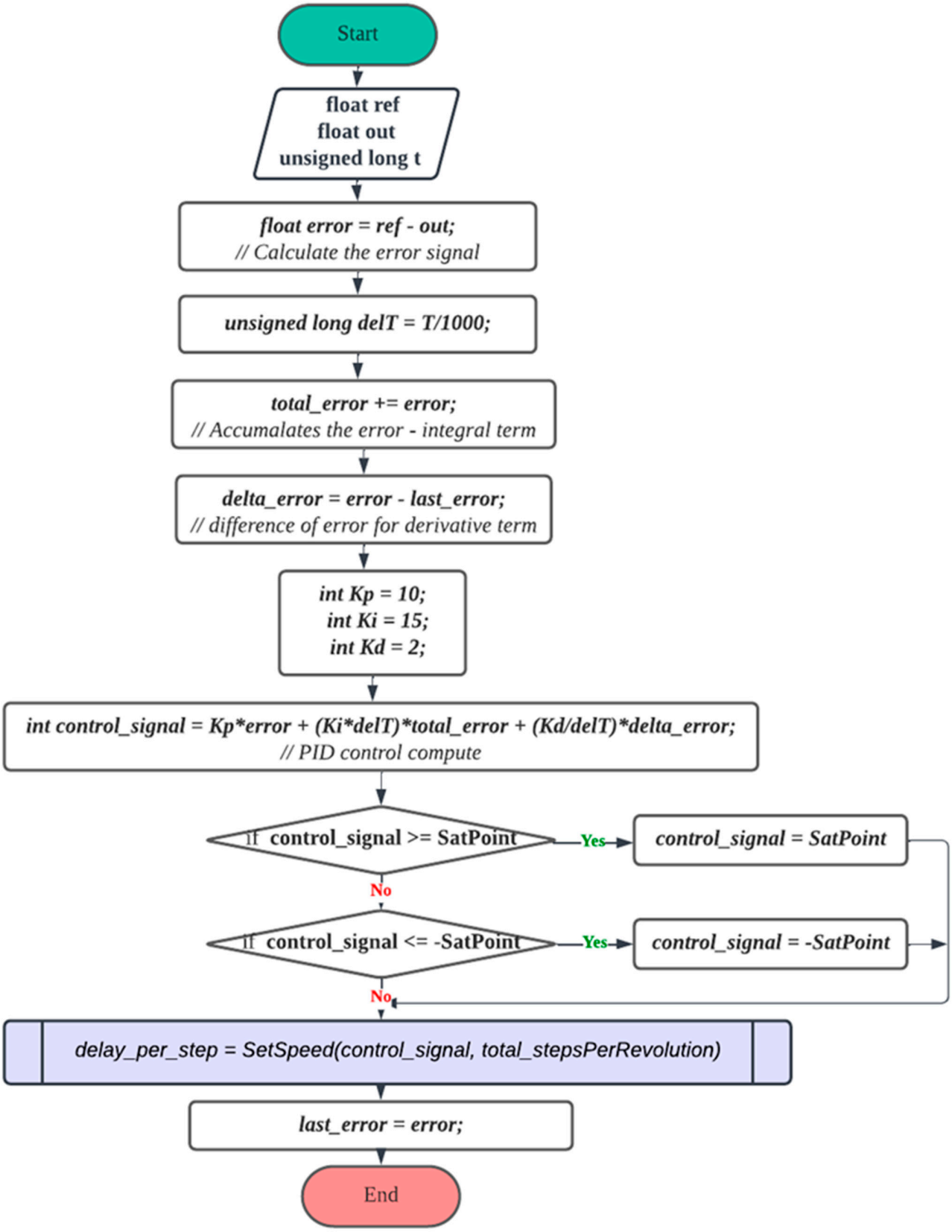


Figure 14. PID control algorithm flowchart.

5. Overall Design

The culmination of this project's design process is segmented into three primary areas: circuit design, hardware configuration, and the integration of IoT components, which include a web dashboard, mobile application, and the physical user interface of the infusion pump. This multi-faceted approach ensures a comprehensive solution that addresses both the operational and user interaction aspects of the infusion device.

5.1. IoT Platform for Infusion Pump

For the prototype's IoT functionality, the Blynk platform was chosen for its robust server infrastructure, which seamlessly integrates various components of the platform. This integration facilitates a cohesive IoT solution, encompassing a web dashboard and mobile applications compatible with both iOS and Android platforms. Through the web dashboard, medical practitioners can remotely monitor and modify the settings of the infusion device, providing a level of flexibility and control that enhances patient care.

The Blynk cloud platform is designed with multiple layers of security to shield the infusion devices from potential cyber threats, ensuring the integrity and reliability of the device's operation. At the core of its security measures, Blynk employs TLS 1.3, the latest standard in transport layer security, within its HTTPS communication protocols. This advanced level of security not only protects data in transit but also secures the communication channel between the device and the cloud server, safeguarding against unauthorized access and data breaches.

Figure 15 offers a visual representation of the IoT architecture specifically tailored for the infusion pump, detailing the critical components and their interactions within the system. This block diagram provides insight into the structured approach taken to develop a secure, efficient, and user-friendly IoT platform for the infusion pump, highlighting the significant role of the Blynk platform in achieving this integration. Through this IoT solution, the project aims to deliver a technologically advanced infusion device that meets the current demands of healthcare providers and patients, ensuring secure, accessible, and efficient patient care.

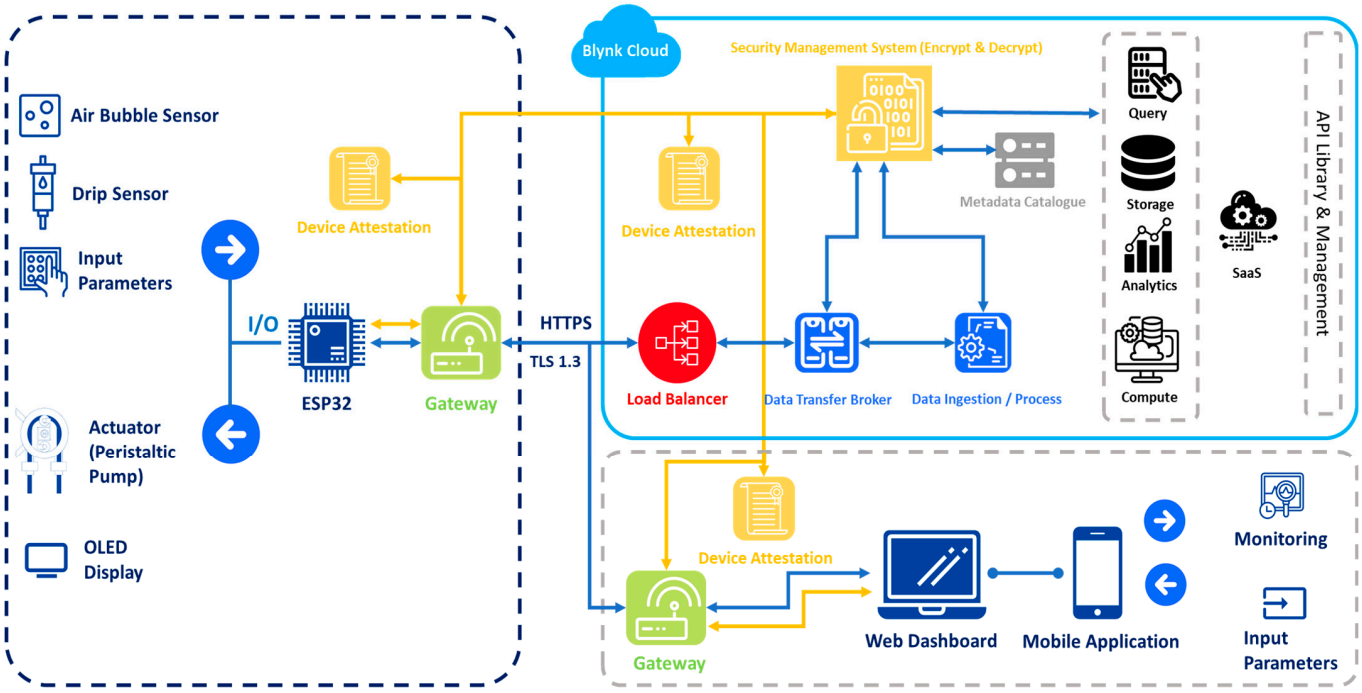


Figure 15. IoT architecture for the infusion pump.

Initiating the connectivity sequence, the ESP32's integrated Wi-Fi module connects to the gateway network, setting the stage for secure communication with the Blynk cloud server. To verify the authenticity and security of the connection, the server requests the device's attestation key, ensuring that only trusted hardware can establish a connection. This is followed by a TLS handshake between the ESP32 and the server, employing TLS 1.3 encryption to secure the communication channel. This handshake process involves the exchange of the 'Key Share' and 'Key Share Certificate', establishing a robust encryption algorithm and secure connection for the subsequent data transmission via HTTPS.

Integrating multiple infusion devices to the same cloud network and application can help healthcare workers control and monitor the infusion process of multiple patients on a single system seamlessly. This can be enacted by allocating part of the database storage for each unique infusion device, where each infusion device will have its authentication key to differentiate it from the others. The concept art for this design is illustrated in Figure 16, where each infusion device will be connected to the same server and the infusion process input and output parameters are displayed on its device page. This design further reduces the workload of the healthcare workers, as they can control and monitor all the infusion processes in a centralized space.

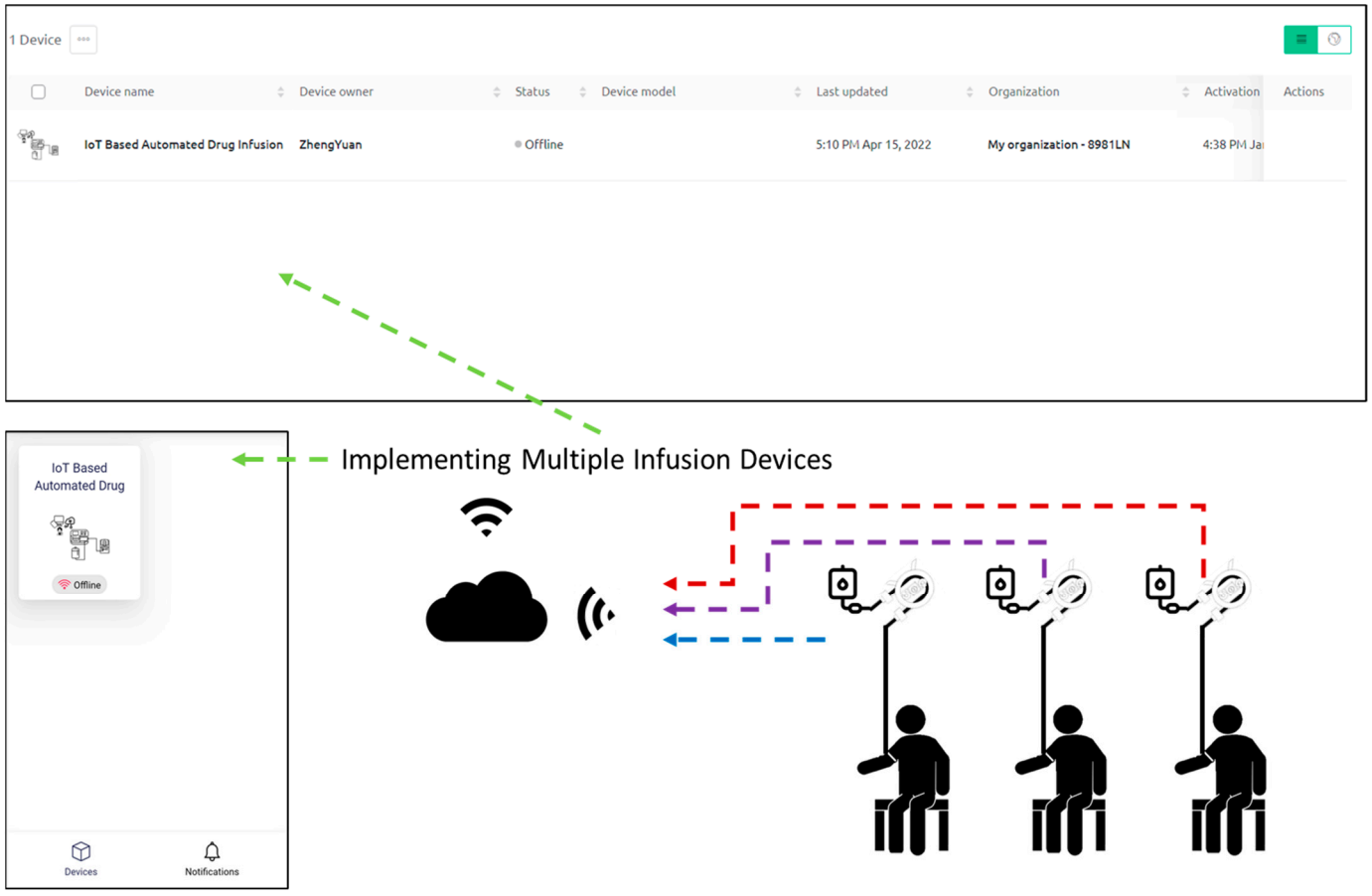


Figure 16. IoT network for multiple devices.

5.2. Overall Circuit Design

The circuit layout of the infusion device is methodically organized into two broad categories: the primary circuitry of the infusion system and the circuitry for energy supply. The primary circuit includes user input switches, output components and sensors as depicted in Figure 17. This layout ensures seamless interaction with the device's functional components and accurate monitoring of the infusion process.

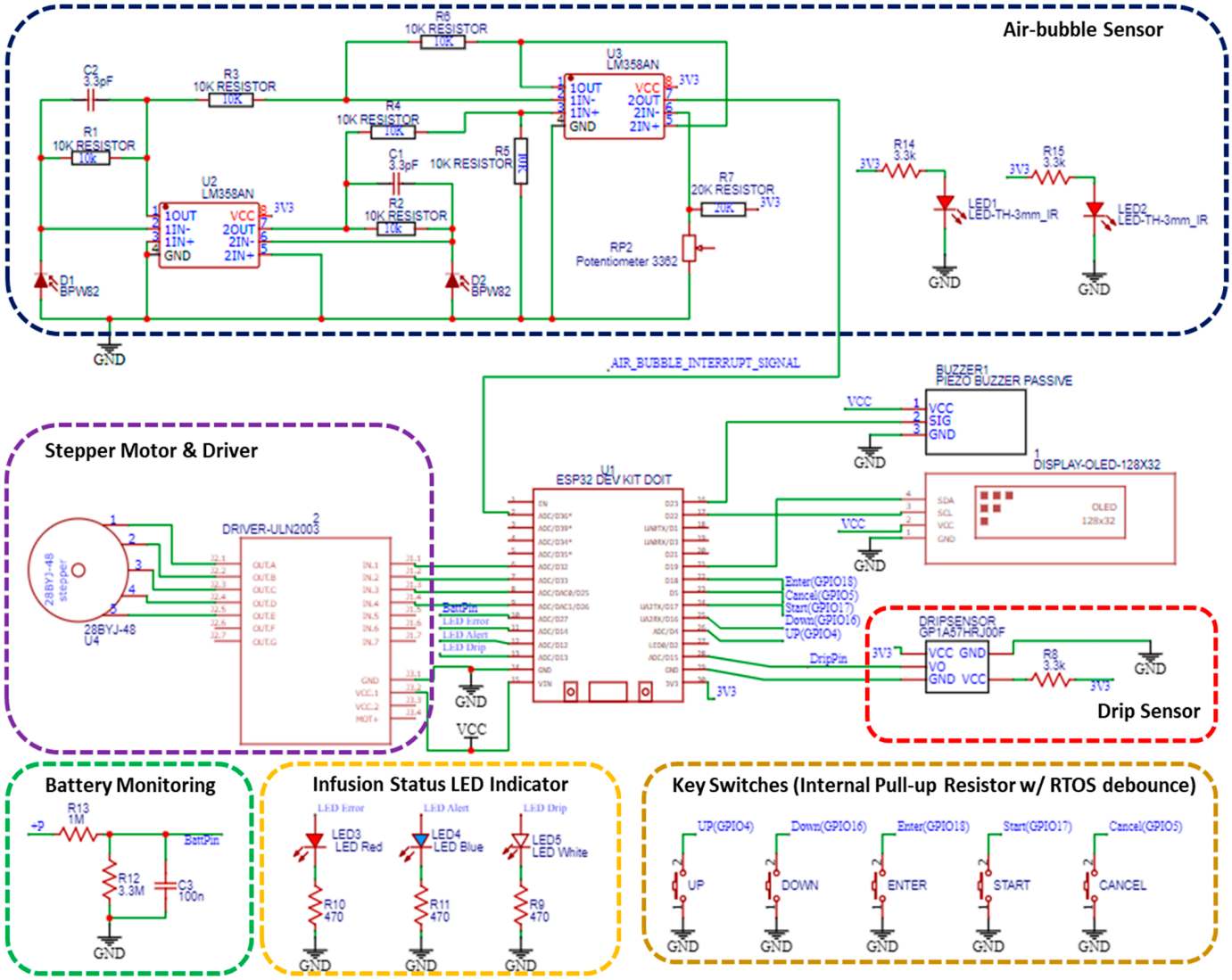


Figure 17. Main circuit design.

The power section incorporates a voltage divider within the battery monitoring segment to adapt the NCR18650B Li-ion battery's maximum 4.2V charging voltage to a level suitable for the ESP32's ADC input range. Additionally, it features an IP3005 Li-ion protection IC for comprehensive battery safeguarding against potential electrical issues. The inclusion of a Type-C connector facilitates easy charging and power supply through a USB Type-C port. A designated power button enables straightforward device activation and shutdown, enhancing the device's user-friendliness. The detailed power circuit design is showcased in Figure 18, illustrating the thoughtful integration of power management and safety features within the device's architecture.

5.3. Overall Hardware Design

The physical construction of the infusion device encompasses the peristaltic pump mechanism and the device's enclosure, both designed using the FreeCAD open-source software. This 3D CAD approach allows for precise modeling of components, which are then converted to STL format for 3D printing. The hardware prototypes, primarily fabricated using FDM technology with PLA material, except for the 'rotor holder', which requires SLA printing due to structural considerations, exemplify the practical application of 3D printing in medical device prototyping.

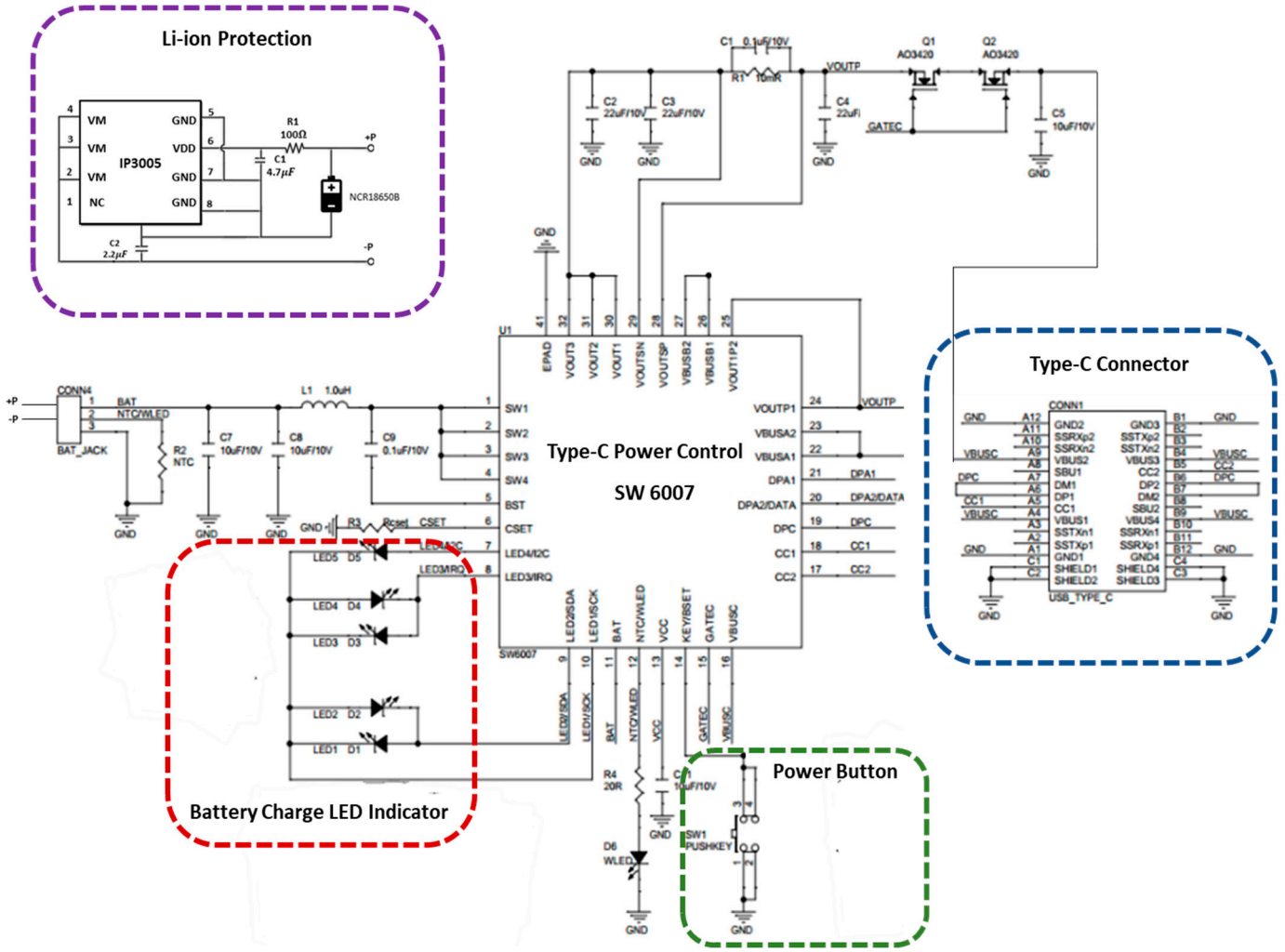


Figure 18. Power circuit design.

The device's enclosure is engineered to compactly house all circuit components, as illustrated in Figure 19. It features a snap-fit lid design for easy assembly and air vents to promote circulation, mitigating the risk of overheating, especially for the stepper motor. This comprehensive approach to hardware design underscores the infusion device's functionality and user-centric design, facilitating reliable and efficient medication delivery in clinical settings.

The comprehensive design and functionality of the drug infusion device are showcased in Figure 20, encapsulating the culmination of intricate hardware and software integration efforts. This physical design representation serves as a prelude to the rigorous experimental validation and testing phases aimed at ensuring the device's operational efficacy and reliability in healthcare settings.

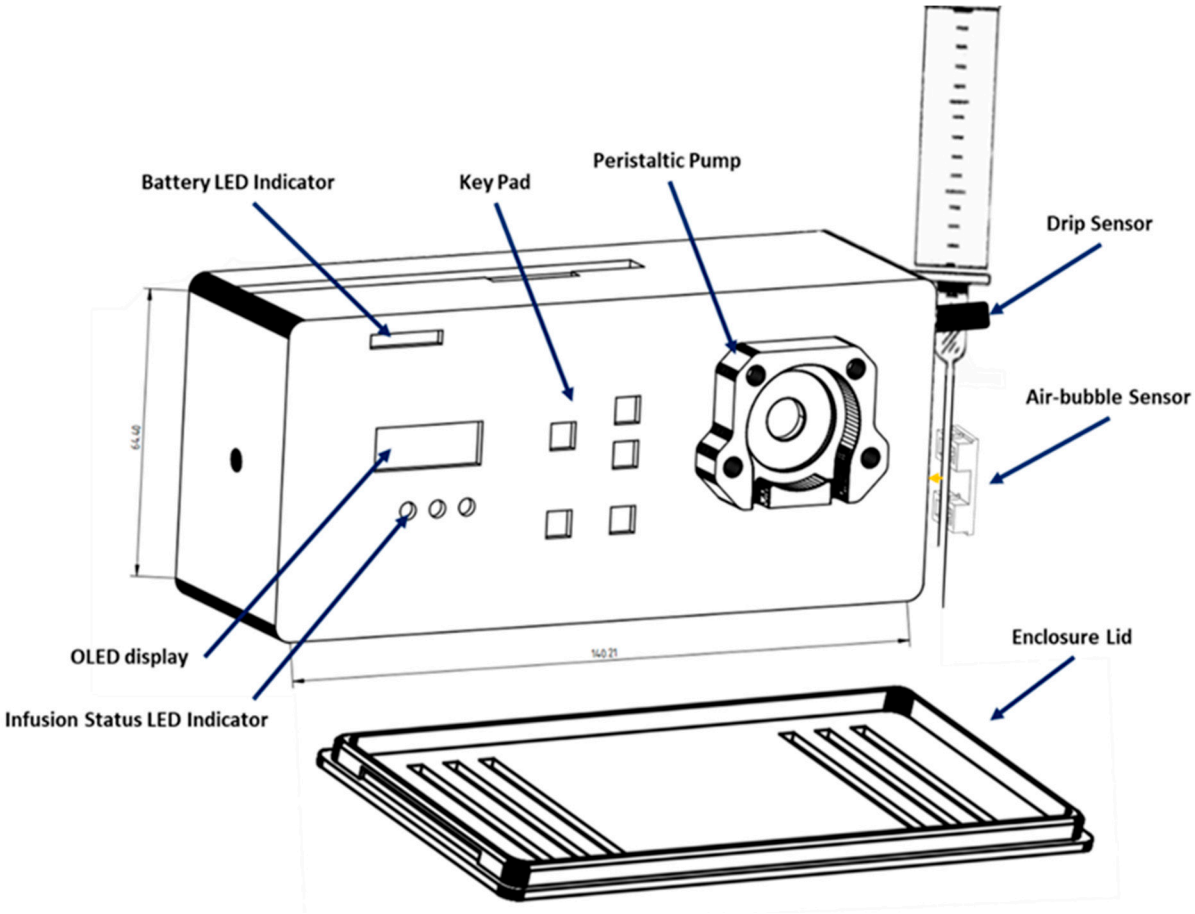


Figure 19. Overall hardware design of the infusion device.

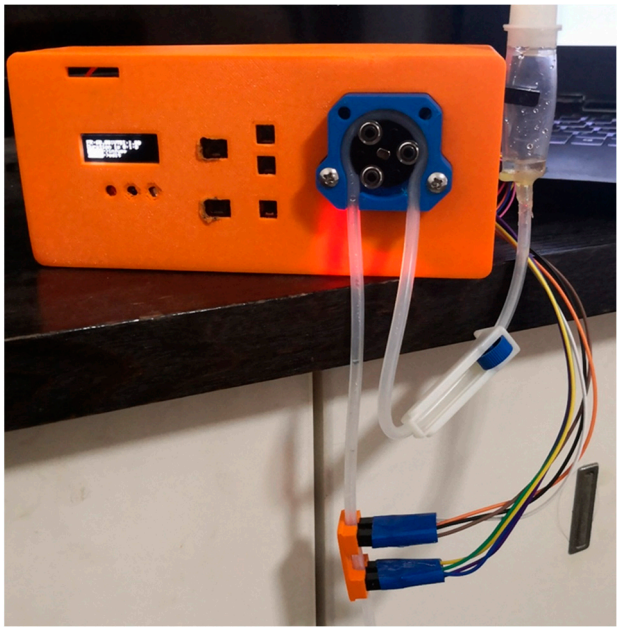


Figure 20. Physical design of the IoT-based automated drug infusion device.

6. Measurement Results and Discussion

6.1. Measurements

The development process involved extensive testing of individual components to verify their performance and suitability for integration into the final system design. Detailed investigations into component functionalities, such as liquid displacement efficiency of the peristaltic pump and electrical properties of circuit elements, laid the groundwork for assembling a coherent and functional device prototype.

A crucial step in the prototype development was conducting comprehensive PCB testing to identify and rectify potential issues like short circuits, component defects, or incorrect connections. Utilizing tools such as soldering irons, desoldering pumps, digital multimeters, and oscilloscopes facilitated meticulous examination and validation of the circuit design both prior to and following the component soldering process. Orientation and pinout accuracy of IC components were scrupulously checked to prevent damage and ensure correct assembly. Continuity tests conducted post-soldering helped detect any undesired open or short circuits, ensuring the integrity of the circuit connections. The setup for the final PCB testing, showcasing the use of an oscilloscope to verify the functionality of microcontroller inputs/outputs and sensor operations, is depicted in Figure 21.

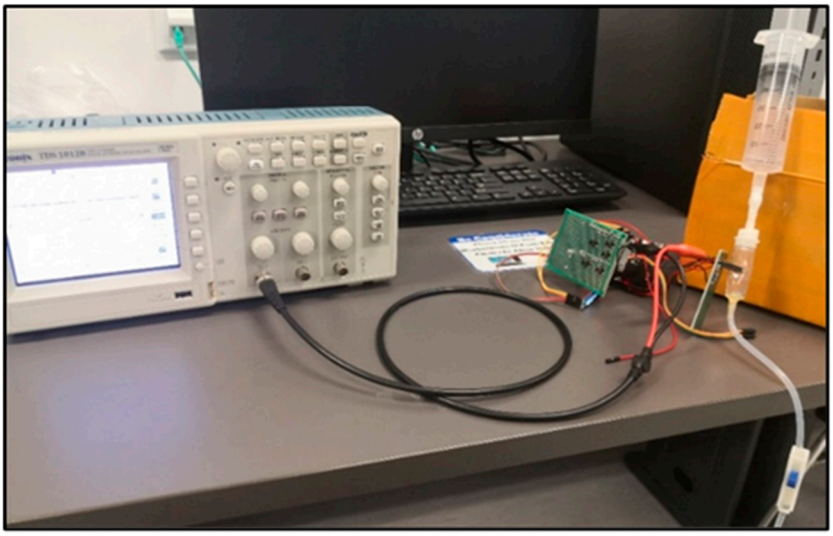


Figure 21. PCB circuit testing setup.

For an IoT device targeted at healthcare applications, the ability to accurately and reliably transmit real-time data such as infusion rates and volumes is paramount. Equally critical is the device's capability to issue timely notifications for potential issues, necessitating thorough testing of IoT performance and data integrity. Real-time performance verification was conducted to assess the device's responsiveness and reliability in communicating with the cloud database, illustrated in Figure 22. This included evaluating the consistency and accuracy of data transmission and reception across varying intervals to ensure the integrity and authenticity of the data.

Connectivity testing addressed the device's ability to maintain consistent and reliable communication with healthcare providers throughout the infusion process. This involved assessing Wi-Fi signal strength and network responsiveness under different conditions using API protocols and the PuTTY terminal, with test results presented in Figure 23. Such testing is critical for affirming the device's readiness for deployment in clinical environments, where uninterrupted connectivity is crucial for patient safety and effective treatment management.

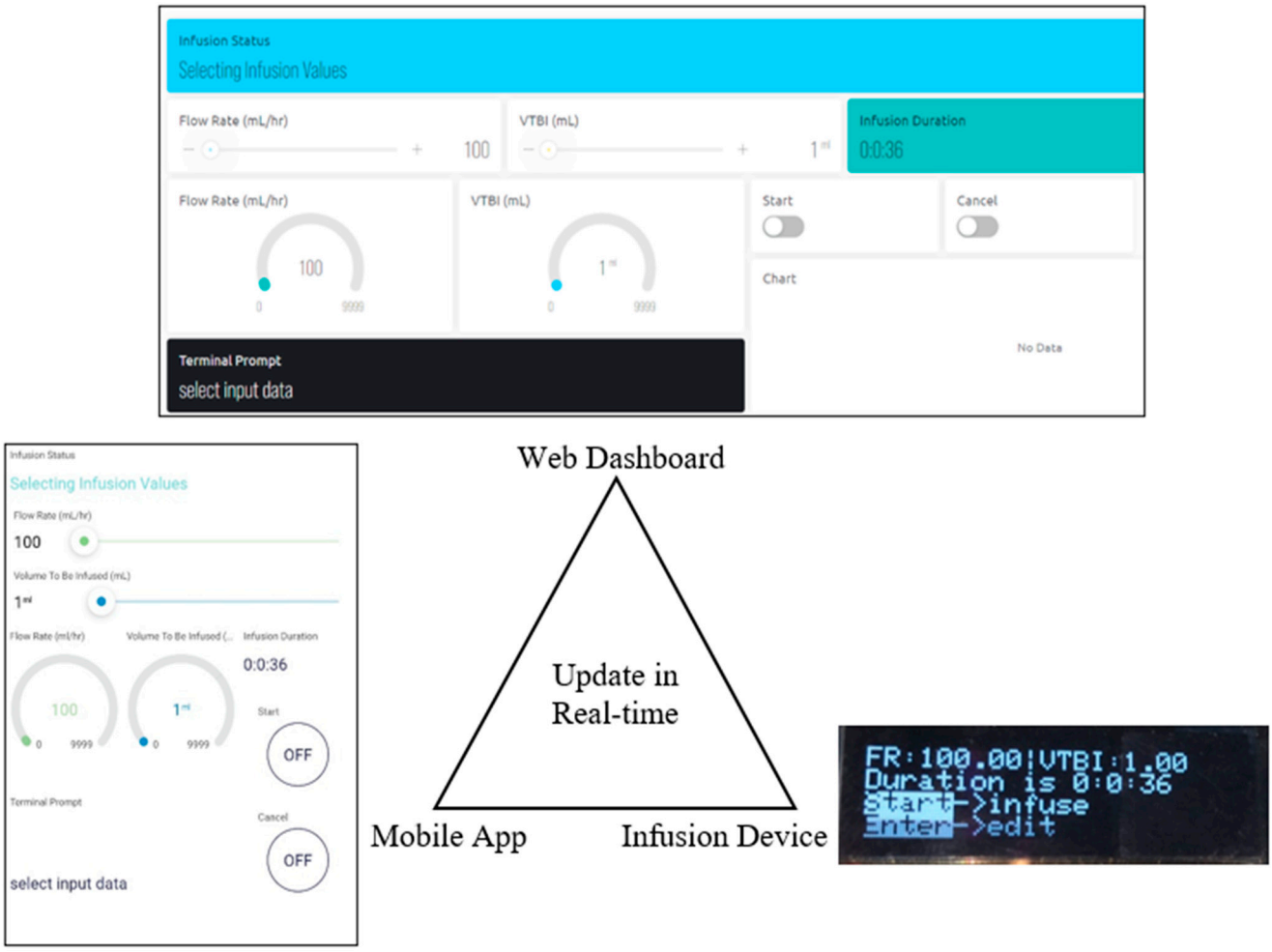


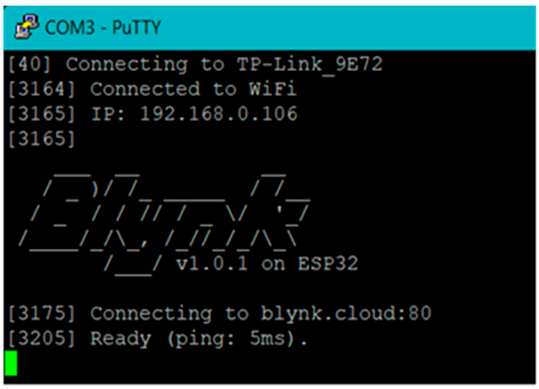
Figure 22. IoT real-time performance test.

The Infusion accuracy test plays an important role in validating the overall performance of the IoT-based automated drug infusion device, focusing specifically on its precision in achieving predefined infusion parameters such as duration and volume. This test utilizes the following:

- Electronic weighing scale: Leveraging the fact that water has a density of 1 kg/L, this tool enables the precise measurement of small liquid volumes.
- Measuring cylinder: Positioned atop the electronic weighing scale, the cylinder collects the infused fluid, allowing for volume quantification.
- Stopwatch: Employed to measure the actual duration of the infusion process, ensuring the device's adherence to prescribed time frames.

The core objective is to calibrate the device's output—both in terms of infused amount and the time taken—with the expected parameters, utilizing feedback from the drip sensor and the device's computational algorithms to estimate the outcomes of each infusion session. The setup for conducting this crucial accuracy assessment is illustrated in Figure 24, showcasing the arrangement of tools and the device under test.

Additionally, the operational demands of the device's various components vary, leading to differential current consumption rates during use. To provide insights into the device's energy efficiency and operational demands, Table 6 compiles the average current consumption for each component within the system. These data are essential for understanding the device's power requirements and optimizing its design for energy efficiency without compromising performance.



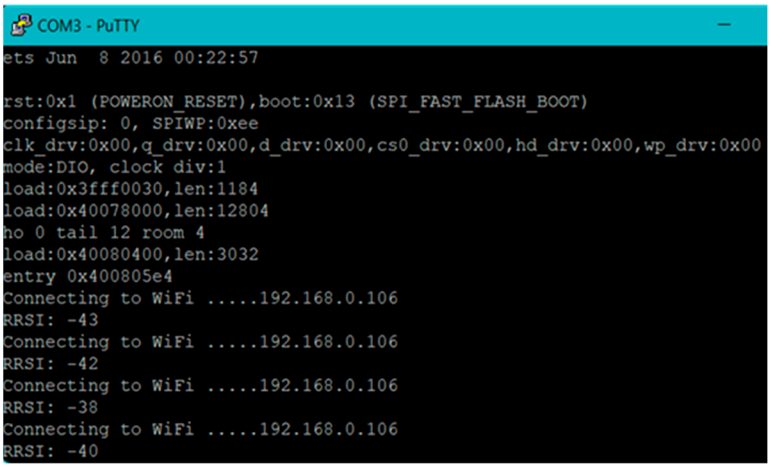


Figure 23. Wi-Fi connectivity test.

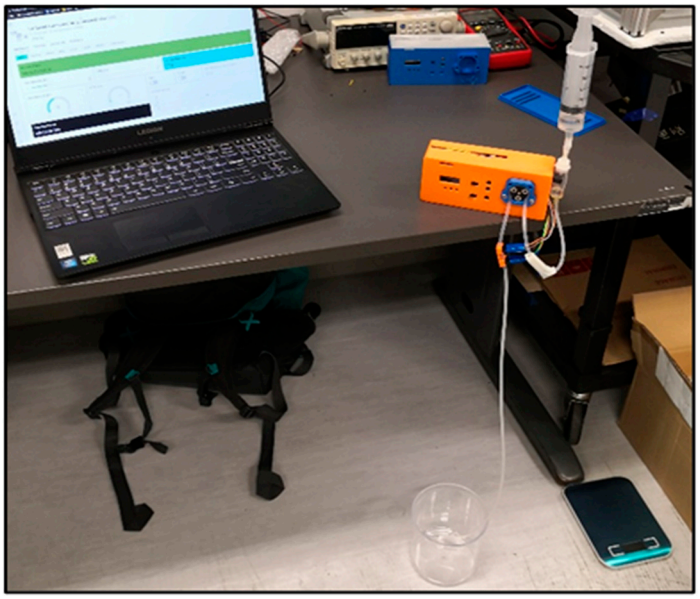


Figure 24. Testing apparatus of the accuracy test.

Figure 25 provides a detailed graphical representation of the infusion device's power consumption profile over time, illustrating the varying energy demands during different operational phases. The graph is segmented into distinct periods:

- Time 'y' represents the duration when the device displays the menu screen, a phase characterized by relatively static power consumption as the user navigates the device's interface.

- Time 'y-z' denotes the period of user interaction for selecting and calibrating input parameters. This phase might exhibit slight variations in power usage due to the engagement of additional interface elements and processing.
- Time 'x-z' captures the critical phase of drug infusion, where the device actively administers medication. This period is likely to show a more pronounced power consumption profile, reflecting the operational demands of the infusion process, including motor activity and sensor monitoring.

Table 6. Components current consumption.

Components		Current Consumption
ESP 32	Menu screen Wi-Fi: Tx and Rx enable (polling) Dual-core processing With drip sensor receiver	160 mA
	Selecting values and calibration Wi-Fi: Tx enable Dual-core processing With drip sensor receiver	100 mA
	Infusion Wi-Fi: Tx (2nd Core) and Rx enable Dual-core processing With drip sensor receiver	80 mA
Air Bubble Sensor		2.36 mA
Drip Sensor (Emitter)		661 µA
28byj-48 stepper motor and ULN2003	Infusion Idle	270 mA 300 mA

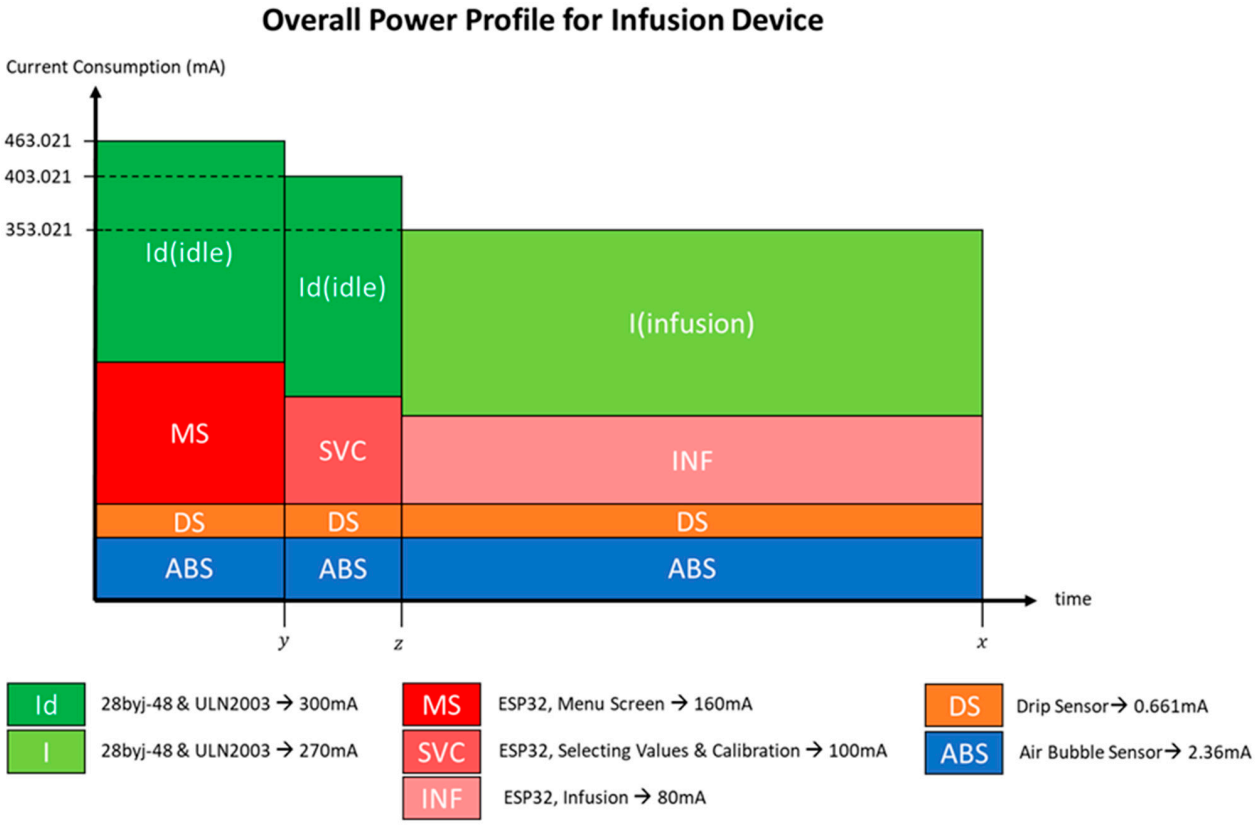


Figure 25. Overall power profile for infusion device.

6.2. Results and Discussion

The comprehensive testing regime applied to the IoT infusion device prototype yielded promising results, underscoring the device's reliability and effectiveness. A pivotal aspect of this evaluation was the data integrity test, the outcomes of which are summarized in Table 7. The findings from this test highlight a critical operational parameter—maintaining a minimum 50 ms interval between consecutive request protocol commands ensures the accuracy and completeness of data transmitted to and from the cloud database. This insight has significantly informed the algorithmic strategy of the infusion system, optimizing data communication routines to safeguard the integrity of transmitted information.

Table 7. Data integrity test.

Request Methods	Requests Time Intervals	Data Integrity
GET	500 ms	Successful
	100 ms	Successful
	50 ms	Accurate but with data missing
POST	500 ms	Successful
	100 ms	Successful
	50 ms	Accurate but with data missing

This optimization is crucial for maintaining seamless and reliable data exchanges between the device and the cloud infrastructure, a foundational requirement for ensuring that the device operates within the expected parameters and that healthcare practitioners receive timely and accurate information. The careful consideration of data communication intervals exemplifies the meticulous approach to device design and functionality, aiming to deliver a dependable and efficient solution for automated drug infusion in clinical settings.

The infusion device's testing phases have elucidated its foundational strengths and highlighted areas for enhancement, notably in Wi-Fi connectivity, infusion accuracy, and battery longevity.

The device showcases reliable connectivity within a 6 m range, even when obstructed by walls and doors, as noted in the results from Table 8. Beyond this range, with additional obstacles, signal stability drops, indicating potential disconnection risks. This insight is critical for ensuring the device's operational efficacy in clinical environments, where sustained connectivity is crucial for uninterrupted monitoring and infusion control.

Table 8. Wi-Fi signal test results.

Obstructing Object	Distance from Router (m)	Average Wi-Fi Signal Strength Over 10 Readings (dBm)
No obstruction	1.5	−37
	5.0	−42
Stainless steel material covers the antenna	1.5	−46
	5.0	−57
Device in an enclosed room	2.5	−43
	6.0	−73

Accuracy tests have shown an average volume error of 6.47%, with this rate including scenarios involving minimal infusion amounts like 1 mL, where the scale's sensitivity limit impacts precision. The error rate improves to 4.7% for volumes above 10 mL, underscoring better accuracy for typical infusion quantities. The design of the drip chamber, which equates 20 drops to approximately 1 mL $\pm$ 0.1 mL, led to an average estimated volume error of 2.2%, demonstrating the device's capability to monitor infusion rates effectively. These results are discussed with reference to Tables 9 and 10, which detail the outcomes of the accuracy tests for volume and duration, respectively.

Table 9. Infusion volume accuracy test results.

Target Speed	Target Volume	Actual Volume	Infused Error	Estimated Volume through Device	System Error	Estimated Error
10 mL/h	1 mL	1 mL	-	0.95 mL	5%	5%
	10 mL	10.4 mL	4%	10.55 mL	5.5%	1.44%
	50 mL	48.3 mL	3.4%	49.10 mL	1.8%	1.65%
60 mL/h	1 mL	1.1 mL	10%	1.05 mL	5%	4.55%
	10 mL	10.6 mL	6%	10.4 mL	4%	1.89%
	50 mL	52 mL	4%	53.25 mL	6.5	2.4%
100 mL/h	1 mL	0.8 mL	20%	0.8 mL	20%	-
	10 mL	9.8 mL	2%	9.9 mL	1%	1.02%
	50 mL	46.5 mL	8.8%	47.35 mL	5.3%	1.83%
Average infusion volume error			6.47%	Average estimated error		2.2%

Table 10. Infusion timing accuracy test results.

Target Speed	Target Volume	Target Duration	Actual Duration	Timing Error
10 mL/h	1 mL	6 min	5 min 58 s	0.56%
	10 mL	60 min	59 min 57 s	0.08%
	50 mL	300 min	299 min 49 s	0.06%
60 mL/h	1 mL	1 min	1 min 1 s	1.67%
	10 mL	10 min	10 min 1 s	0.16%
	50 mL	50 min	50 min 4 s	0.13%
100 mL/h	1 mL	36 s	36 s	-
	10 mL	6 min	5 min 59 s	0.28%
	50 mL	30 min	29 min 55 s	0.28%

The battery's endurance was verified through a stress test, confirming the device's capability to function for approximately 19.24 h on a full charge, aligning with the theoretical battery life. This test, extending just beyond this duration until battery depletion, affirms the device's longevity for daily operational needs, as evidenced by the automatic shutdown facilitated by the power control SW6007 IC. This durability is crucial for the device's utility in healthcare settings, offering assurance of its reliability over extended use periods.

The collective findings from these evaluations provide a solid performance basis for the IoT-based automated infusion device, signaling its readiness for clinical application and the necessity for further optimizations. Ensuring stable Wi-Fi connectivity within clinical settings and refining measurement accuracy for small-volume infusions are pertinent steps toward enhancing the device's utility. The infusion device's confirmed accuracy for standard volume infusions and its demonstrated operational longevity are promising aspects, suggesting its potential to improve patient care through precise and reliable medication administration.

6.3. Advantages over Existing Infusion Device

The IoT-based drug infusion device introduces a suite of advancements and benefits, positioning it as a competitive alternative within the medical device landscape, particularly in the infusion device category. These key advantages underscore the device's potential to enhance patient care and operational efficiency in various healthcare settings:

- Portability: Weighing approximately 335 g and boasting a compact design, the infusion device stands out for its portability. This feature significantly enhances its usability across different environments, from clinics to home settings, offering flexibility and convenience that surpasses many existing products.
- Exceptional battery life: The device's battery life is notable, lasting about 19 h on a full charge. This endurance, coupled with its small form factor, makes the device exceptionally well suited for extended use in various settings, ensuring continuous, reliable operation without frequent recharging.

- Advanced Sensing Capabilities: Integration of air bubble and drip sensors represents a critical technological enhancement. The air bubble sensor mitigates the risk of air embolism by preventing air from entering a patient's vein, while the drip sensor monitors the real-time infusion rate, facilitating accurate volume-to-be-infused (VTBI) calculations and flow rate adjustments. This sensor feedback is crucial for the device's controller to compensate for any discrepancies, ensuring precise infusion delivery.
- IoT Connectivity: The device's connection to an IoT platform elevates its functionality, enabling remote control and monitoring through a web dashboard or mobile application. This feature not only enhances user interaction but also supports the storage of real-time infusion data in a cloud database for subsequent analysis and review, promoting data-driven patient care.
- Cost Efficiency: The production cost of the prototype infusion device is competitively low, totaling approximately SGD 46.60 (excluding the cost of 3D printing filament and services).

The Alaris GH Plus Guardrails Syringe Pump and Moog CURLIN 6000, which comes as a standard in the market, are known for their functionality but not for their portability and user convenience. Our system stands out due to its compact design (about 335 g) and extended battery life (19 h) making it suitable for use in different healthcare settings, from clinics to home care. This mobility advantage is in line with the increasing popularity of remote patient monitoring and the trend of decentralized healthcare which is driven by the need for care at home [35]. Moreover, our system consists of the latest sensing techniques which are not usually employed in many of the existing pumps. The combination of air bubble and drip sensors, in particular, greatly improves the patient's safety by reducing the probability of air embolism and by making the VTBI calculations accurate through real-time flow monitoring. This is in accord with the recent improvements in infusion technology that focus on closed-loop systems and automatic error detection to achieve accuracy in medication delivery [36]. Among the features of our system are the IoT connectivity and data management capabilities, which are its key differentiators. Contrary to the existing market instruments, we use the IoT (Internet of Things) to assist in controlling and monitoring the system using a web dashboard or mobile app. This feature enables healthcare providers to carry out their work more flexibly and also allows them to make data-driven decisions by using cloud storage and analysis of infusion data. It fits in the trend of telehealth and remote patient management becoming more prevalent in healthcare. The last factor we have taken into account is the cost of production (SGD 46.60 per unit). Such cost-effectiveness is a factor that makes our system an option that is more affordable than some commercially available ones; thus, it can be a solution that will expand access to advanced infusion technology for many healthcare providers.

IoT-based infusion monitoring, which was first studied by Oros, D et al. [37], is mostly concerned with monitoring aspects of intravenous drug administration. Our system exceeds monitoring by providing full automation for drug infusion which is able to be operated remotely and is very precise. This system of features makes our system a more sophisticated solution which simplifies the whole infusion process. Furthermore, Preethi et al.'s [24] research, which deals with IoT for healthcare monitoring and flow control, is also addressed. Their work is good and it gives us a better understanding of what we need to do, but we have expanded the range of functions. Our system is a more advanced one, encompassing not only control and monitoring but also data management through cloud storage, which makes it possible for retrospective analysis and better care strategies. In the end, Al-Sheikh and Ameen [25] analyze mobile healthcare monitoring systems based on IoT technology. Whereas their research is for healthcare monitoring systems, the infusion device is not the target area. On the other hand, our design places user experience at the core of infusion therapy implementation by combining portability and long battery life. Such an approach that is user-centric is applicable to the particular requirements of both healthcare providers and patients. Our cloud-enabled, IoT-based drug infusion system tackles the limitations of existing devices in the market and research

by providing a one-of-a-kind combination of portability, advanced sensing abilities, remote control functionalities, data management features and low expenses. This all-embracing solution makes it a strong candidate in the field of automated infusion technology, which has the possibility to revolutionize patient care, improve operational effectiveness, and increase access to advanced infusion therapy in different healthcare settings.

6.4. Regulatory Requirements

As per the regulatory requirements, this prototype is considered a medical device that needs to be registered with the Health Sciences Authority (HSA) in Singapore before it can be effectively deployed. There are certain factors that need to be considered in order to determine the risk classification of medical devices, such as the intended purpose of the device, the expertise required to use the device which in this prototype refers to a professional level of expertise, the importance of the information to the diagnosis of the disease, which is not relevant to this prototype and impacts of the results to the individual or the public health. Based on the factors, it is deemed that this prototype would most probably fall under Class B—low-moderate risk, thereby requiring a full evaluation route to pass the regulation of medical devices [38].

7. Limitations

The IoT-based drug infusion device brings innovative solutions to healthcare, yet it faces limitations that must be addressed to meet medical device regulations and enhance its functionality. These limitations include:

- Lack of Occlusion Pressure Sensors: Essential for detecting blockages in the IV tubing, the absence of occlusion pressure sensors limits the device's ability to ensure smooth liquid flow and detect occlusions.
- No Bolus Functionality: The device's current stepper motor (28byj-48) limits the maximum infusion rate to 150 mL/h, which is insufficient for bolus injections. A more powerful motor, like the NEMA 17, could overcome this limitation.
- Sensor Vulnerability to Spoofing Attacks: The air bubble and drip sensors are susceptible to spoofing, where external signals can manipulate sensor readings, potentially leading to dosage errors or air embolism risks. Enclosing the sensors could mitigate this vulnerability.
- Drip Chamber Splash Issue: Splashes in the drip chamber may obstruct sensor readings, causing the device to mistakenly halt the infusion. Adding additional sensor pairs could help distinguish between actual overflow and splash interference.
- Limited Drip Sensor Angle: The device's drip sensor requires the drip chamber to be nearly vertical. A tilt beyond 30 degrees compromises the sensor's ability to detect drips, affecting the accuracy of infusion monitoring.
- Absence of an Automated Free Flow Clamp: Currently, the prototype relies on a manual clamp to prevent overflow, identified by the drip sensor. Incorporating an automated solenoid pinch valve could offer a more reliable solution to halt flow automatically.

8. Conclusions

This study showcases the development of a cloud-based embedded solution for an automated drug infusion device within the Internet of Things (IoT) realm. This innovative device offers both local and remote-control capabilities via a web dashboard and a mobile application, specifically tailored for seamless operation. The prototype excels in accurately monitoring the infusion process, providing real-time data on flow rates and infused volumes directly to its onboard display, as well as remotely via web and mobile platforms. Moreover, it is equipped with mechanisms to detect and alert users to any irregularities during infusion sessions, enhancing patient safety and operational oversight. Key features include an air bubble sensor designed to prevent air embolism by detecting air bubbles larger than 6.28 mL in the IV tubing, alongside a drip sensor that monitors

infusion volume, enabling the onboard processor to estimate flow rates accurately. These capabilities are bolstered by the implementation of a real-time operating system (RTOS) in the firmware design, which orchestrates task execution to ensure timely completion of all operational tasks. The device's portability is another significant advantage, attributed to its compact size and the exceptional battery life of up to 19 h, making it a versatile solution for various settings, from hospitals to home care. Additionally, the production cost of the prototype is notably low at SGD 46.60, making it an economically viable option. The infusion accuracy of the prototype stands at $\pm$6.47%, slightly below the precision of some market counterparts. However, for volumes greater than 1 mL, the accuracy improves to $\pm$4.57%, attributed to the enhanced correction capabilities of the PID controller based on increased feedback signal estimation. Despite its promising attributes, the prototype's maximum flow rate limitation of 150 mL/h presents a challenge for delivering bolus doses, indicating an area for future enhancement. Overall, the IoT-based automated drug infusion device represents a significant advancement in healthcare technology, offering potential solutions to longstanding challenges in IV infusion treatment. By supporting healthcare workers and caregivers, this device aims to improve the efficiency and safety of patient care across diverse environments.

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