

Design and Implementation of Intelligent Infusion Monitoring System Based on Internet of Things

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Abstract: To address the limitations of traditional infusion management models, such as reliance on manual monitoring, low efficiency, high safety risks, and poor patient comfort, this paper designs and implements an intelligent infusion monitoring system based on the Internet of Things (IoT). The system uses an STC89C52 microcontroller as the core controller, integrates dual U-shaped photoelectric sensors for drip rate detection and infusion status recognition, and employs a DS18B20 temperature sensor with a graphene heating pad to establish a closed-loop temperature control system for the medication solution. An open push-type gear-rack mechanism driven by a stepper motor is used to achieve automatic cutoff of the infusion tube. The system uploads real-time monitoring data to the OneNet cloud platform via an ESP8266 Wi-Fi module, enabling visual remote monitoring from the nurse station. Experimental results demonstrate that the system has a drip rate detection error $\leq \pm 1$ drop/min, temperature control error $\leq \pm 0.8^\circ\text{C}$, and no-liquid response time ≤ 3 seconds. This system integrates monitoring, control, communication, and temperature regulation, effectively enhancing infusion safety and nursing efficiency, and holds significant clinical application value.

Keywords: Intelligent infusion, Internet of Things (IoT), Remote monitoring, Temperature control system, Embedded system.

1. Introduction

Intravenous infusion is currently the most commonly used route of drug administration in clinical practice. According to reports released by the National Health Commission, the utilization rate of intravenous infusion among hospitalized patients in secondary and above hospitals in China ranges from 80% to 90% [1]. However, as an invasive procedure, intravenous infusion involves direct entry of medicinal solutions into the bloodstream, posing higher risks compared to other routes of drug administration. Adverse drug reaction (ADR) monitoring data indicate that injection-based drug administration accounts for a relatively high proportion of ADRs [2].

Traditional infusion management primarily relies on manual monitoring, which exhibits issues such as low efficiency and slow response. International studies have demonstrated that infusion pumps pose multiple safety hazards in practical use. A study on large-scale medical systems revealed that the incidence of upstream blockage events in infusion pumps reached as high as 29% within 6 months (112,875 upstream blockages/389,604 infusion initiations) [3]. Another study focused on the interrupt-recovery time following infusion pump alarms as a critical quality indicator requiring attention [4].

The "14th Five-Year Plan for National Health Informatization" explicitly proposes advancing the intelligent upgrading of medical equipment, with smart infusion devices listed as a key research and development direction. Existing infusion monitoring products still have room for

improvement in terms of functional integration, system interoperability, and control accuracy. Previous studies have explored the application of RFID technology in smart infusion monitoring [5], as well as intelligent infusion automatic control systems based on fuzzy control [6]. International research has also proposed solutions such as multi-channel infusion pumps [7], but their high cost makes them difficult to popularize domestically.

To address the aforementioned issues, this paper designs an intelligent infusion monitoring system based on the Internet of Things (IoT). The system's innovations include: (1) Proposing an open progressive gear-rack cutoff mechanism to enable convenient placement and reliable interruption of infusion tubes; (2) Establishing a closed-loop temperature control system for "detection-regulation-insulation" to enhance patient comfort; (3) Developing a visual monitoring interface on the OneNet cloud platform to achieve real-time remote monitoring across multiple beds. The system integrates monitoring, control, communication, and temperature regulation into a unified solution, aiming to resolve the core pain points in clinical infusion management.

2. Overall System Design

2.1. System Architecture

The intelligent infusion monitoring system adopts a master-slave modular architecture design, with the STC89C51 single-chip microcontroller as the core controller, and peripheral integrated detection sub-module, execution sub-module, display sub-module, and communication sub-module. The system structure is shown in Figure 1.

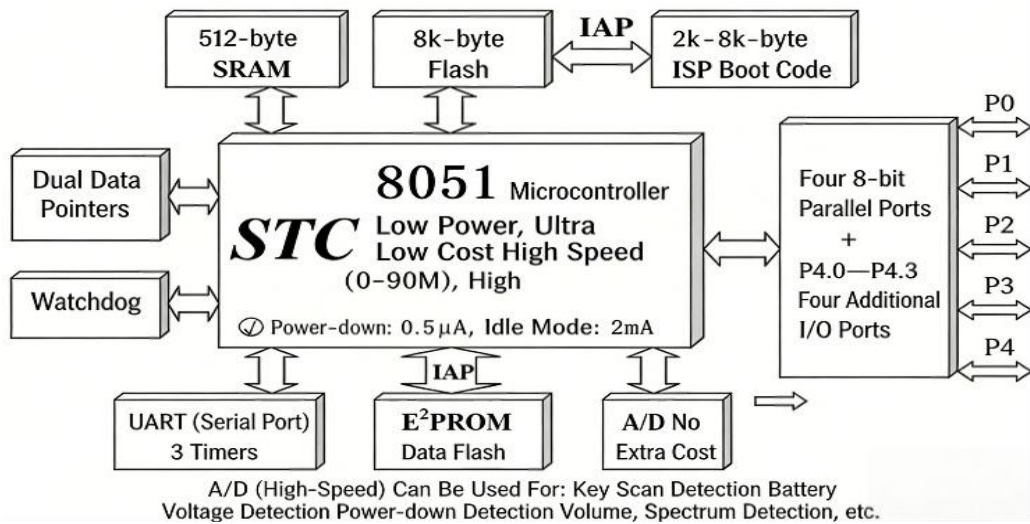


Figure 1. Core Controller System Architecture

Detection Submodule: Comprising dual U-shaped photoelectric sensors (for droplet rate and liquid level detection) and a DS18B20 temperature sensor (for pharmaceutical solution temperature acquisition).

The execution sub-module includes a step motor-driven cutoff mechanism, a graphene heating plate, and a buzzer.

Display Submodule: The LCD1602 module displays the dripping rate, temperature, and operational status in real time.

Communication Submodule: Transmits data to the OneNet cloud platform via the ESP8266 Wi-Fi module.

The workflow of the system is as follows: data acquisition by detection module → processing and analysis by main controller → action execution by control module → local display by display module → remote synchronization by communication module.

2.2. Working Principle

The system collaboratively identifies three infusion states through dual sensors:

Normal infusion state: Both upper and lower sensors detect liquid, the system calculates the drip rate in real time and displays the temperature;

Abnormal infusion status (e.g., tube blockage): The upper sensor shows no signal while the lower sensor detects a signal, triggering the system's audible and visual alarm.

Infusion completion status: No signals detected from both upper and lower sensors, the system triggers a sound and light

alarm and activates the stepper motor to cut off the infusion tube.

Temperature control employs a threshold comparison method: Users set the upper and lower temperature limits (default 25°C~40°C) via buttons. The DS18B20 continuously monitors the temperature of the medicinal solution. When the temperature falls below the lower limit, the microcontroller activates full-power heating of the graphene heating element. When the temperature exceeds the upper limit, heating is stopped to achieve constant temperature control.

The communication module encapsulates data such as drip rate, temperature, and alarm status into JSON format and uploads it to the OneNet platform via the MQTT protocol. The nurse station can monitor the infusion status of multiple beds in real time through a visual interface.

3. Hardware System Design

3.1. Main Control Unit

The system employs the STC89C51 microcontroller as the main control chip. This chip integrates 8 KB of Flash memory and 512 B of RAM, operates at 5 V, and supports ISP online programming. The microcontroller connects to peripherals via ports P0 to P3. The device's pin connection diagram is shown in Figure 2, with detailed pin assignments illustrated in Figure 3.

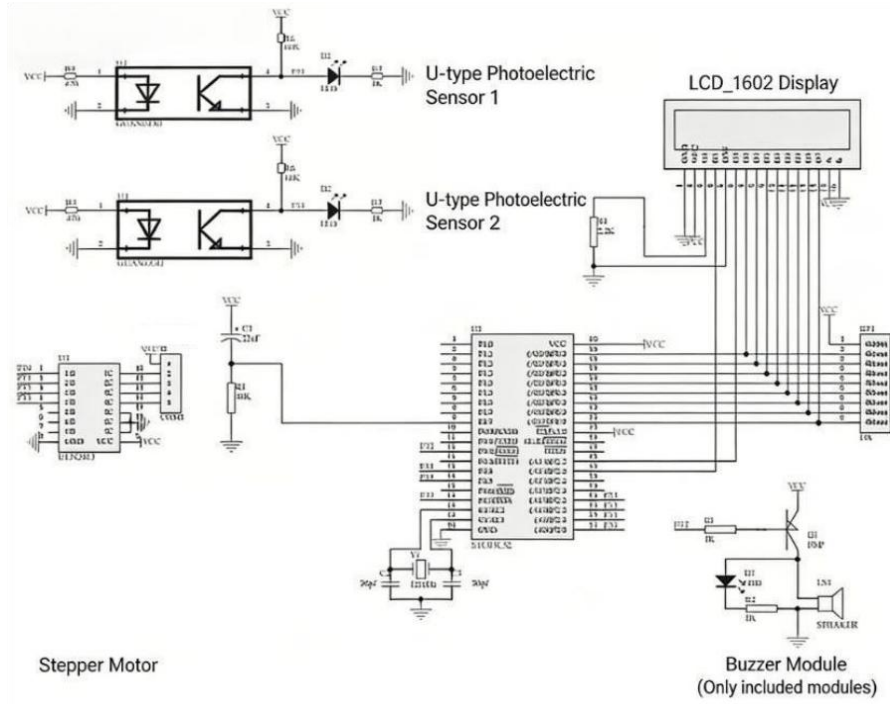


Figure 2. Device Pin Connection Diagram

Peripheral Modules	Pin Connections	Function Description
Photoelectric Sensor 1	P1*7	Droplet Detection
Photoelectric Sensor 2	P1*4	Liquid Level Detection
Photoelectric Sensor 2	P3*7	Temperature Acquisition
DS18B20	P1*5	
Graphene Heating Sheet	P2*0~P2*3	Heating Control
Stepper Motor	P2*5	Truncation Control
Buzzer	P2*5	Acousto-optic Alarm
LCD1602	P0*0~P0*7	Data Display
ESP8266	P3*0(RX)/P3*1(TX)	Wireless Communication

Figure 3. Pin Assignment

3.2. Dual Photoelectric Sensor Module

To achieve precise detection, an innovative dual-displacement U-shaped photoelectric sensor layout was adopted. The upper sensor's infrared beam detects droplet descent along the diameter of the dropper's cross-sectional plane, with droplet counts calculated every 5 seconds and converted into dripping rate (drops/min). The lower sensor's infrared beam intersects the dropper's cross-sectional plane at an acute angle to detect the presence of a liquid column.

The key to distinguishing three states with the dual-sensor layout lies in: during normal infusion, droplets continuously fall and a liquid column exists; during blockage, no droplets fall but the liquid column persists; upon completion of infusion, neither droplets nor liquid column is present. The detection circuit operates on a 5 V power supply, with a working current of 20 mA and a response time ≤ 50 ms.

3.3. Open Pushing Type Truncation Mechanism

To address the inconvenience of handling in the first-generation enclosed structure, this paper innovatively designs a gear-rack type open propulsion mechanism. The mechanism consists of a 28BYJ-48 stepper motor (five-step four-phase), a 3D-printed active gear, and a rack blocking block. The front

end of the rack is designed as a pointed tip, and the device housing is equipped with an open groove where the infusion tube can be directly inserted.

When the infusion is detected to be complete, the microcontroller controls the stepper motor to rotate. The motor drives the gear to rotate, which in turn moves the rack forward. The pointed rack then compresses the infusion tube against the inner wall of the groove, achieving complete occlusion. The motor rotates 5 steps (each step 1.8°), and the push rod moves 0.8 mm to complete the cutoff. This design reduces the time required for tube retrieval and placement from the original 15 seconds to 3 seconds, significantly improving usability.

3.4. Temperature Control Module

The temperature control module consists of a DS18B20 temperature sensor and a graphene heating element. The DS18B20 employs a single-bus protocol, with a measurement range of -55°C to 125°C , precision of $\pm 0.5^\circ\text{C}$, and resolution of 0.0625°C . The graphene heating element (5 V/10 W) is attached to the exterior of the teapot, with heating power regulated by a PWM signal.

The temperature control algorithm employs hysteresis loop comparison control: when temperature T is below the set lower limit $T_{\text{set, min}}$, full-power heating is applied; when T exceeds the set upper limit $T_{\text{set, max}}$, heating is stopped. With a control cycle of 1 second, this prevents frequent on-off cycles.

3.5. Wireless Communication Module

The system utilizes an ESP8266-01S Wi-Fi module for remote data transmission. Operating in STA mode, the module communicates with the microcontroller via UART protocol (115200 baud rate) and supports 802.11b/g/n networks. The microcontroller connects to the Wi-Fi hotspot through AT commands and establishes a connection with the OneNet cloud platform using the MQTT protocol to enable transparent data transmission. Similar solutions have been implemented in IoT medical devices [7].

4. Software System Design

4.1. Main Program Flow

The system software adopts a modular design. Upon power-on, the system first completes initialization of all modules (LCD, timer, interrupt, sensor, Wi-Fi), followed by entering the main loop. In the main loop, the following tasks are executed sequentially: temperature acquisition and processing, drip rate detection and calculation, status judgment and alarm, LCD display update, and data upload.

The system uses timer interrupts for precise timing, with Timer 0 configured to interrupt every 1 ms for dripping rate counting and time reference.

4.2. Temperature Monitoring and Control

The temperature detection subroutine reads DS18B20 temperature values via a single-bus protocol. Each conversion takes 750 ms. To avoid system response delays, a timed polling method is employed, with conversions and readings initiated every second. The temperature control subroutine activates or deactivates the heating element based on preset thresholds. The code is as follows (in C language):

```
void Temp_Control(void) {float temp = DS18B20_ReadT();
if(temp <temp_low) {HEATER = 1; // Start heating
else if (temp> temp_high) {HEATER = 0; // Stop heating}}
```

4.3. Drip Rate Detection Algorithm

The droplet rate was measured using the sliding window counting method. The number of droplets (N) was counted every 5 seconds, with the droplet rate $V = N \times 12$ (droplets/min). To enhance anti-interference capability, the program was configured with a minimum pulse width filter, counting only when the low-level duration of the photoelectric signal exceeded 10 ms. Similar detection protocols have been applied in prior studies [6].

4.4. Wi-Fi Communication Protocol

The ESP8266 is controlled via the AT command set, with the system designed to employ a non-blocking state machine for communication processing, thereby preventing blocking of the main program. Data upload is formatted as JSON, containing fields such as device ID, temperature, drip rate, and alarm status, which are published to a designated topic on the OneNet platform via the MQTT protocol. The nurse station monitoring interface subscribes to the topic to obtain real-time data.

5. System Testing and Result Analysis

5.1. Test Environment and Methods

To verify system performance, an experimental testing platform was established. The testing equipment included: standard infusion stand, disposable infusion set (diameter 3.2 mm), normal saline, stopwatch (accuracy 0.01 s), and infrared thermometer (accuracy $\pm 0.1^\circ\text{C}$). The testing contents included: drip rate detection accuracy, temperature control accuracy, no-liquid response time, and communication stability.

5.2. Testing of Drip Rate Measurement Accuracy

Five different drip rates (20,40,60,80, and 100 drops per minute) were set, with 10 tests conducted in each group. The

system display values were recorded and compared with manual counts. The test results are shown in Table 1.

Table 1. Test results of dripping rate detection accuracy

Set value (drops/min)	Mean measurement (drops/min)	Absolute Error (drops/min)	fractional error (%)
20	19.8	-0.2	1.0
40	40.3	+0.3	0.75
60	60.1	+0.1	0.17
80	79.7	-0.3	0.38
100	99.5	-0.5	0.50

The test results show that the detection error of the system is less than ± 1 drop/min and the relative error is less than 1.0%, which is better than the accuracy of ± 5 drop/min of the traditional product.

5.3. Temperature Control Performance Test

The temperature threshold was set at 30°C – 35°C , and the entire process from heating initiation to stable temperature control was tested under a room temperature of 25°C . The temperature change curve was recorded, as shown in Table 2.

Table 2. Temperature change curve

Time (seconds)	temperature ($^\circ\text{C}$)	explain
0	25.0	Start heating
30	26.2	heating-up
60	27.8	heating-up
90	29.1	heating-up
120	30.4	First time exceeding 30°C
150	32.5	Continue to rise
180	34.2	Approaching the upper limit
200	35.0	The limit has been reached, but the heating inertia persists.
210	35.6	peak (overshoot)
240	34.8	Stop heating and let it cool down.
270	33.7	descend
300	32.5	descend
330	31.8	Approaching the lower limit
360	30.5	Reheat below the lower limit
390	31.9	Raising the temperature again
420	33.2

The system heated from 25°C to 30°C in approximately 120 seconds, with a overshoot of 0.6°C . Under steady-state conditions, the temperature fluctuation range was $\pm 0.5^\circ\text{C}$, and the control accuracy met medical requirements (within $\pm 0.8^\circ\text{C}$).

5.4. Liquid-free Response Time Test

Simulate the completion of an infusion scenario, recording the time from the disappearance of the droplet to the system triggering an alarm and cutoff. The average response time across 10 tests was 2.7 seconds, with a maximum response time of 3.1 seconds and a minimum of 2.4 seconds, meeting the design requirement of ≤ 3 seconds.

5.5. Communication Stability Test

The system ran continuously for 72 hours, uploading data

every 10 seconds. During testing, 25,920 uploads were made, with 25,901 successful uploads and a packet loss rate of 0.073%. After network interruption, the automatic reconnection success rate was 100%, with an average reconnection time of 8.5 seconds.

6. Conclusion

This paper designs and implements an intelligent infusion monitoring system based on the Internet of Things (IoT). The system features the following characteristics: (1) Dual photoelectric sensors are employed to achieve precise drip rate detection and status recognition, with a detection error $\leq \pm 1$ drop/min; (2) An innovative open push-type gear-rack cutoff mechanism is designed to facilitate convenient placement and reliable interruption of infusion tubes; (3) A closed-loop temperature control system is established, with a control error $\leq \pm 0.8^\circ\text{C}$, enhancing patient comfort; (4) Remote visual monitoring is achieved via the OneNet platform, supporting centralized management of multiple beds.

The experimental results demonstrate that all performance indicators of the system meet the design requirements, effectively reducing infusion safety risks and alleviating the workload of medical staff. Subsequent work will focus on: (1) integrating each functional module into a PCB board to achieve device miniaturization; (2) optimizing the layout of heating elements to enhance heating efficiency; (3) improving cloud platform functionality by adding historical data analysis and voice alarms.

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