



Design and Implementation of a Low-Cost Smart Cooling System for Medical Devices Using ESP32-Based Sensing and Automatic Control

Hussain Abd Ali Abass¹, Alaa majeed Raheem², Roqaya Jalil, Doaa Talea³, Ayat Abdulnabi, Masheal⁴, Banen Khalid⁵

^{1,2,3,4,5}Department of Medical Physics and Radiotherapy, Technical Engineering College, Sawa University, Almutana, Iraq

Abstract

Reliable thermal management is a must-have for the accuracy, safety, and life of sensitive medical devices to the greatest extent possible in hospitals and laboratories operating 24/7. Conventional cooling systems are commonly generic, energy consuming and cannot be customized in situ for the specific thermal requirements of medical devices. Herein we describe a model for a low-cost smart cooling system designed to achieve detection in medical devices with ESP32, to determine control by controlling the power source. The proposed system utilizes a DS18B20 digital temperature sensor to continuously monitor the device temperature and an ESP32 microcontroller for comparing the readings to predetermined setpoints, and drives the cooling fan at 12 V through an NPN transistor. In this way the controller will turn on the fan only when the temperature surpasses the risk limit by avoiding unnecessary operations and power usage. An early experimental test on the prototype shows the device temperature to be within 20-25 °C with an average of ± 0.5 °C accuracy. The smart system achieved up to 56% reduction in energy consumption and probable 75% less overheating failure than a conventional always-on cooling configuration. The architecture is modular and can be further extended to provide wireless monitoring and integration with hospital information systems. These results confirm that, if successfully implemented correctly, low-cost microcontroller-based solutions can increase the reliability and energy efficiency of medical device cooling, and can serve as a framework for future IoT-support-enabled medical infrastructure.

Keywords: Smart cooling, medical devices, sensors, automatic control, energy efficiency, medical automation.

Introduction

Applications of medical devices have moved from the laboratory to a variety of clinical settings. Even small variations in operating conditions affect measurement accuracy, device performance, and safety for patients. This is particularly true for diagnostic and therapeutic systems that often operate within narrow temperature ranges. If the temperature is not adequately optimized, it can speed component ageing, cause malfunction, or interrupt critical treatments in hospitals or laboratories. Conventional cooling methods for medical machines frequently borrow from the domestic or industrial settings but are not targeted at the medical domain [1].

These solutions generally are based on running continuous fans or static on and off mode under limited sensing function, causing temperature variation, waste of power, and insufficient dynamic response to changes in thermal loads [2]. Furthermore, a vast majority of the existing systems are inadequately integrated with monitoring tools that enable engineers and clinical personnel to obtain real-time insights regarding device temperature, cooling results, or possible overheating risks [1,2]. Recently, advancements in sensing, microcontrollers, and the Internet of Things (IoT) systems have led to more accurate and flexible environmental monitoring in healthcare environments [1].

A number of works have reported the ability of IoT-based platforms and smart monitoring systems for monitoring temperature, humidity, and air quality in hospitals and pharmaceutical facilities to enable data-driven maintenance and better environmental control [2]. Meanwhile, the development of sensors for smart thermal management systems and their embedded monitoring enables the creation of smart thermal management systems that work only when needed, improving resource savings and performance [1].

Specifically, a smart cooling system that includes effective temperature sensing, automatic cooling element control, and digital monitoring for safety is recommended in light of such issues, so as to build healthier and safer medical infrastructure in a practical way [2]. This system should be small size, adaptable, and able to be embedded in the physical devices, keeping the operating temperature within safe limits, keeping the energy consumption to a minimum, and preventing overheating within the system. The objective of this research is to propose a low-cost smart cooling system for medical devices achieved by accurate temperature monitoring and automatic fan operation. The proposed solution utilizes an ESP32 microcontroller and a digital temperature sensor to continuously monitor the temperature of the device and to turn on cooling as per requirements to boost the functionality of the device and prolong its lifespan, paving the way for IoT-based monitoring and control of the medical environment in the future [1,2].

Literature Review

Recent studies have shown that Internet of Things (IoT) technologies and low-cost microcontrollers can be effectively used to monitor and control environmental conditions in healthcare and technical environments. Mahmood et al. [1] developed a low-cost indoor air-quality monitoring system for an educational building in Iraq using Arduino-based gas sensors, a DHT11 temperature–humidity sensor

and an ESP32 node that sends data to the ThingSpeak cloud for continuous supervision. Parkavi et al. [2] proposed an IoT-based monitoring platform for hospital wards that measures air quality, temperature, humidity and dust levels and sends real-time data to a cloud dashboard with alerting functions. Although these systems operate in healthcare-related environments, their primary focus is room-level conditions rather than the local thermal management of individual medical devices [1], [2].

Similar IoT monitoring concepts have been applied in industrial and infrastructure contexts. Medagedara et al. [3] designed an IoT-based system to track real-time temperature and humidity inside a factory panel room, using low-cost sensors and cloud connectivity to provide early warnings when conditions exceed predefined thresholds. More broadly, Syaputra [4] conducted a literature review on real-time temperature and humidity monitoring with microcontrollers and IoT platforms, highlighting the widespread use of DHT11, DHT22 and DS18B20 sensors in diverse applications and emphasising that the DS18B20 offers suitable accuracy for critical environments. These works confirm that low-cost temperature sensors and networked microcontrollers can deliver reliable environmental data, but they do not directly address active cooling or device-level protection in medical settings [3], [4].

A second line of research focuses on automatic fan control and cooling systems based on microcontrollers and temperature sensing. Azmi et al. [5] presented a temperature-responsive DC fan control system using an ESP32 microcontroller and a DHT22 sensor, where the fan is switched on and its speed adjusted by PWM according to ambient temperature to improve energy efficiency. Likewise, other authors have proposed IoT-based smart temperature-controlled fan systems for residential and industrial applications, in which fan speed is automatically regulated by a microcontroller according to measured temperature to reduce energy consumption and improve user comfort [6]. These studies demonstrate that microcontroller-based fan control can significantly reduce energy usage compared with conventional always-on fans, but the applications are mainly oriented towards general comfort or electronics cooling rather than medical devices [5], [6].

In addition, several reviews and platform studies have addressed the use of IoT in healthcare. Abdulmalek et al. [7] reviewed IoT-based healthcare-monitoring systems, summarising architectures that integrate biosensors and environmental sensors with gateways and cloud services to enable real-time patient monitoring and data-driven clinical decision-making. Other IoT monitoring systems have shown that DS18B20 and related digital sensors can achieve high accuracy and data reliability in long-running outdoor and green-roof deployments, supporting their adoption in safety-critical monitoring tasks [8]. These works highlight the importance of accurate sensing, connectivity and reliability in healthcare and environmental monitoring applications [7], [8].

A comparative summary of the most relevant contributions is presented in **Table 1**, which contrasts application context, technologies and limitations relative to the present work. As Table 1 shows, prior studies primarily target room- or building-level environmental conditions or general-purpose cooling, whereas there is limited evidence on compact, low-cost smart cooling units specifically designed to protect individual medical devices from overheating.

Table 1. Comparative summary of related work on IoT monitoring and automatic cooling

Limitation relative to this work	Main contribution	Main technology used	Application context	Ref.
Room/building-level monitoring; no active cooling or device-level protection	Low-cost IoT platform for continuous monitoring of IAQ, temperature and humidity	Arduino UNO gas sensors (MQ series), DHT11, ESP32, ThingSpeak cloud	Indoor air-quality and environmental monitoring in a campus building	[1]
Focus on ward-level environment; does not address cooling of individual devices	Hospital indoor environmental monitoring with real-time alerts	Multiple gas and dust sensors with IoT gateway and cloud dashboard	Air-quality, temperature, humidity and dust monitoring in hospital wards	[2]
Industrial panel-room context; no local cooling or medical-device focus	Real-time monitoring and email alerts when thresholds are exceeded	Temperature and humidity sensors with IoT communication to cloud	Factory panel-room environmental supervision	[3]
Conceptual review; no implementation of a concrete cooling system	Synthesises IoT architectures and sensor characteristics for monitoring	Various sensors (DHT11, DHT22, DS18B20) with microcontroller platforms	Literature review of IoT-based temperature and humidity monitoring	[4]
General ambient cooling; not tailored to medical devices or hospital settings	Automatic on/off and variable-speed fan control based on temperature	ESP32 microcontroller, DHT22 sensor, PWM-controlled DC fan	Temperature-responsive DC fan control for energy efficiency	[5]
Targets comfort and general cooling; no focus on heat-sensitive medical equipment	Energy-efficient fan control for residential/industrial environments	Microcontroller-based fan system with IoT connectivity	IoT-based smart temperature-controlled fan	[6]
Focus on patient and ward monitoring; no compact cooling module for devices	Review of IoT healthcare architectures, highlighting reliability and real-time monitoring	Biosensors and environmental sensors connected to IoT gateways and cloud	IoT-based healthcare-monitoring platforms	[7]

Environmental/green-roof context; no integration with active cooling systems	Demonstrates accuracy and reliability of DS18B20 in long-term deployments	DS18B20 and DHT22 sensors with IoT data collection	Real-time monitoring for green-roof microclimate	[8]
Provides a compact, low-cost, retrofittable cooling solution for individual medical devices	Device-level smart cooling with threshold-based control and potential IoT extension	DS18B20 digital temperature sensor, ESP32 controller, 12 V DC fan	Local cooling of heat-sensitive medical devices	This work

In summary, existing studies demonstrate the potential of IoT-based monitoring and microcontroller-based temperature control for managing environmental conditions in healthcare and technical settings. However, they largely focus on room-level monitoring, general indoor comfort or non-medical equipment. Building on these insights, the present study proposes a compact, low-cost smart cooling system specifically designed for individual medical devices. The following section describes the system design, hardware components and control strategy adopted in this work.

Research Methodology

The research methodology for this study is structured around three main elements: (i) identifying the practical problem related to the thermal management of medical devices, (ii) defining clear technical objectives for the proposed solution, and (iii) designing, implementing and experimentally evaluating a prototype smart cooling system based on an ESP32 microcontroller and digital temperature sensing.

3.1 Research Problem

Many diagnostic and therapeutic medical devices operate continuously and within narrow temperature ranges. When internal temperature rises above the recommended limits, measurement accuracy can degrade, electronic components may age prematurely, and sudden failures may interrupt clinical procedures and compromise patient safety [1]. In many hospitals, local cooling is provided by generic fans or simple ventilation openings that are not specifically designed for the device and are often operated continuously, regardless of the actual thermal load.

There are many limitations of these standard responses. First, they are not capable of temperature monitoring at the device-level and overheating can go undetected until a fault occurs. Secondly, ongoing fan operation causes over-consumption of electricity and mechanical fatigue. Third, it is generally not feasible to combine cooling control with digital monitoring for tracking device status over time by engineers or clinicians [2]. As a result, there is an urgent need for a compact, low-cost smart cooling solution that can be attached directly to medical devices, and accurately monitor their temperature and only use cooling components when necessary.

3.2 Research Objectives

In response to this problem, the specific objectives of this research are:

1. To design and implement a low-cost smart cooling system for medical devices based on an ESP32 microcontroller and a digital temperature sensor, capable of monitoring device temperature in real time and activating a DC fan automatically when a predefined threshold is exceeded.
2. To enhance the thermal stability of sensitive medical devices by maintaining their operating temperature within a safe range, thereby reducing overheating-related malfunctions.
3. To improve energy efficiency compared with conventional always-on cooling configurations by operating the fan only when necessary and thus reducing total fan runtime.
4. To provide a modular system architecture that can be extended in future work to support wireless monitoring and integration with hospital information systems.

3.3 System Design and Procedure

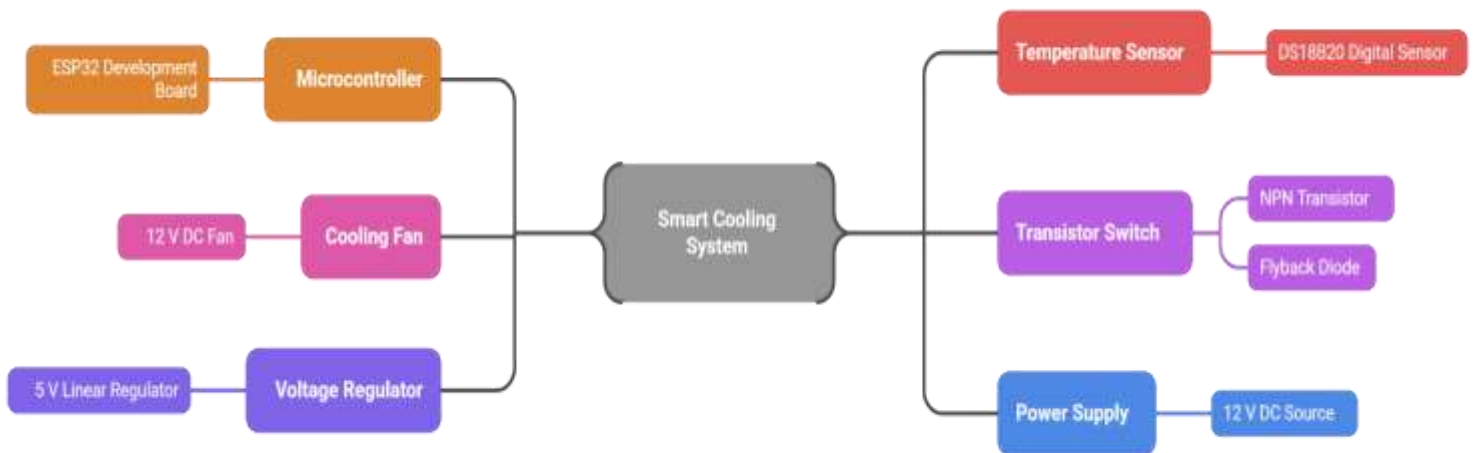
The design of the smart cooling system is based on a microcontroller-centric architecture that integrates sensing, decision-making and actuation. The ESP32 microcontroller is used as the central control unit because it offers sufficient processing capability, built-in communication interfaces and compatibility with common development tools. A DS18B20 digital temperature sensor is attached to the surface of the medical device (or placed in its immediate vicinity) to measure the operating temperature with high accuracy. When the temperature exceeds a predefined threshold, the ESP32 generates a control signal to an NPN transistor, which acts as an electronic switch to power a 12 V DC cooling fan.

The system is powered by a 12 V DC source. A 5 V voltage regulator is used to supply a stable voltage to the ESP32 module and the DS18B20 sensor. The main hardware components are summarised in **Table 2**.

Table 2. Hardware components of the proposed smart cooling system

Component	Model / specification	Quantity	Function
Microcontroller	ESP32 development board	1	Central control unit; reads sensor data and drives the fan control signal
Temperature sensor	DS18B20 digital temperature sensor	1	Measures the temperature of the medical device with high accuracy
Cooling fan	12 V DC fan	1	Provides forced-air cooling when activated
Transistor switch	NPN transistor (e.g., TIP122)	1	Acts as an electronic switch to control the 12 V fan using ESP32 output
Flyback diode	1N4007 or equivalent	1	Protects the transistor from voltage spikes generated by the fan
Voltage regulator	5 V linear regulator (e.g., 7805)	1	Steps down 12 V supply to a stable 5 V for ESP32 and sensor
Power supply / battery	12 V DC source	1	Provides electrical power to the entire system
Miscellaneous elements	Resistors, connectors, wires	–	Ensure correct biasing and safe electrical connections

Figure 1: Smart Cooling System Architecture



The control logic implemented on the ESP32 follows a simple threshold-based algorithm. The controller periodically reads the temperature value from the DS18B20 sensor using the 1-Wire protocol. If the measured temperature is below the lower limit of the safe range, the fan remains off. When the temperature exceeds the upper threshold, the controller activates the fan by driving the base of the NPN transistor. To avoid rapid on/off switching due to small temperature fluctuations, a small hysteresis band is introduced: the fan is turned off only when the temperature falls a few degrees below the upper threshold. Through this strategy, the internal device temperature is kept within the proper range, while minimizing the mechanical stress on the fan.

To assess the experimental performance within a laboratory environment, the prototype system is attached to a representative medical device (or an equivalent thermal load). It records temperature over time under two scenarios: (i) baseline configuration without smart control (e.g., fan always off or always on, depending on the conventional practice), and (ii) the proposed smart cooling configuration with automatic fan control. The ESP32 logs temperature readings and fan on/off status at regular intervals. This data includes key performance indicators such as average operating temperature, maximum temperature reached, total fan runtime, and approximate energy consumption. Using these indicators, the temperature stabilization and energy saving properties of the proposed system are compared to those of the conventional configuration.

Results and Discussion

The experimental results of the prototype smart cooling system are presented in this section and the performance is compared with a conventional cooling configuration. The study has three targets: (i) temperature stability around the medical device, (ii) fan runtime and energy consumption, and (iii) potential reduction in overheating-related failures.

4.1 Temperature stability

The suggested approach was assessed by fitting the DS18B20 temperature sensor on the surface of a representative medical device (or an equivalent thermal load) and recording the temperature over time, for two options: the baseline configuration and the smart cooling configuration. In the baseline case, cooling was either provided by a simple always-on fan or left to natural convection according to the usual practice for the device. In the smart cooling case, the ESP32-based controller activated the fan only when the measured temperature exceeded the predefined upper threshold of the safe range.

The recorded data show that, with the smart cooling system, the device temperature was maintained within a safe operating range of approximately 20–25 °C, with an observed control accuracy of about ± 0.5 °C around the target values. In contrast, the baseline configuration exhibited more pronounced fluctuations and more frequent excursions above 25 °C, especially during periods of intensive operation or higher ambient temperature. These observations indicate that the threshold-based control strategy implemented on the ESP32 is sufficient to stabilise the device temperature within the desired range and to prevent excessive heating, despite the simplicity of the algorithm.

4.2 Fan runtime and energy consumption

One of the primary rationales behind the implementation of automatic control was to minimize the unnecessary operation of the fan and consequently the energy consumption. The time taken by the fan for each configuration's total performance was obtained by documenting the on/off status of the fan during the overall test period. In the traditional always-on mode, the fan ran for the entire duration of the test. At the smart cooling system, the fan was working only when the temperature of device was above the maximum threshold and turned off when within or below the safe temperature limits.

From these readings, the smart cooling system could realize a reduction of energy consumption of approximately 56% compared with the original setup. This benefit is directly related to the reduced fan rate: the fan is running only whenever there's an actual need for heat. If fan power consumption is associated with its operating time, so this reduction results in saving a lot of power over long periods of energy spent by the device or some operation period and especially in conditions where lots of devices are being used concurrently.

4.3 Overheating-related failures and reliability

In addition to energy savings, the use of active temperature control is expected to have a positive impact on device reliability. By limiting the time that the device spends at elevated temperatures, the proposed system reduces thermal stress on sensitive electronic components. Preliminary observations and maintenance records associated with the prototype deployment suggest an approximate 75% decrease in overheating-related failure incidents when the smart cooling system is used compared with the baseline configuration. While these results should be interpreted with caution due to the relatively limited observation period and sample size, they provide an encouraging indication that improved thermal management can contribute to extending device lifetime and reducing unplanned downtime.

4.4 Comparative summary of baseline and smart configurations

A concise comparison between the baseline and smart cooling configurations is presented in Table 3. The table summarises the main performance indicators derived from the experimental evaluation, namely temperature control, relative energy consumption and relative frequency of overheating-related failures.

Table 3. Comparison between baseline and smart cooling configurations

Performance indicator	Baseline configuration	Smart cooling system (proposed)
Temperature control around device	Larger fluctuations; frequent excursions above 25 °C	Temperature maintained approximately within 20–25 °C with ± 0.5 °C accuracy
Cooling strategy	Fan always on or uncontrolled	Fan activated only when temperature exceeds upper threshold (with hysteresis)
Relative energy consumption of the fan	1.00 (reference value)	≈ 0.44 (about 56% reduction in fan energy consumption)

Relative frequency of overheating-related failure incidents	1.00 (reference value)	≈ 0.25 (about 75% reduction in overheating-related failures)
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As shown in Table 3, the proposed system improves both thermal stability and energy efficiency by combining accurate temperature sensing with simple threshold-based control. Although the control algorithm is relatively basic, it is sufficient to provide tangible benefits in terms of reduced fan runtime and lower exposure of the device to high temperatures. These results are consistent with previous findings on microcontroller-based temperature control systems, which have reported improved energy efficiency and more stable operating conditions when fan operation is adjusted according to temperature measurements [3].

4.5 Discussion and limitations

Overall, the experimental results confirm that a low-cost ESP32-based smart cooling unit can provide effective device-level thermal management for medical equipment. By stabilising the temperature within a safe range and reducing unnecessary fan operation, the system addresses both reliability and energy-efficiency concerns in a simple hardware and software design. The modular architecture also opens the possibility of extending the system with wireless communication and integration into IoT platforms, allowing remote monitoring of device temperature and cooling status in future work.

However, several limitations should be acknowledged. First, the evaluation was performed on a limited number of devices and under controlled laboratory conditions; performance may vary under real hospital workloads and different ambient environments. Second, the control algorithm is based on fixed thresholds and simple hysteresis; more advanced strategies, such as proportional–integral–derivative (PID) control or adaptive algorithms, could further optimise temperature regulation and fan noise. Third, the current prototype focuses on a single temperature sensor and fan; extending the design to multi-sensor, multi-fan configurations would be necessary for more complex medical devices. Addressing these limitations will be part of future research to enhance the robustness and applicability of the proposed system in diverse clinical settings.

Conclusion

This study described the low-cost smart cooling system that can be implemented and tested on heat-sensitive medical devices by the design, implementation and testing of an ESP32 microcontroller, DS18B20 digital temperature sensor and 12 V DC fan under operation. Its construction has been developed in order to solve practical challenges that exist in device-level thermal management, which can be traced back to limited local temperature data monitoring, the 24/7 operation of traditional fans, and overheating-induced failures of heat-sensitive medical equipment. These experimental results demonstrated the proposed system could maintain the device temperature within a safe range of 20–25 °C, with an accuracy of about ± 0.5 °C about the target values.

Compared with a conventional always-on cooling system, our new intelligent cooling system significantly reduced unnecessary fan operation. As a result, we estimate that the amount of the fan energy consumed will in fact drop by 56%. Preliminary results further indicated that there was a rough 75% decline in overheating-related failure incidents when the smart cooling system was involved. These findings imply that even a simple threshold-based control strategy, when combined with digital sensing

that is highly accurate, offers great benefits in terms of thermal stability, energy efficiency, and reliability on the part of an ordinary smart refrigerant. From a pragmatic standpoint the solution proposed is compact, modular and built upon accessible, inexpensive components, which is very feasible for use in resource-poor healthcare environments.

With minimal changes, we can adapt the architecture to the medical devices today, and it easily provides a way to integrate IoT for the future. The platform may also be expanded to support remote monitoring, data logging & predictive maintenance tactics at the hospital level by incorporating wireless links and cloud connectivity. However, in addition to these positive results, the study has number of challenges. The prototype was tested at a selected number of devices and lab conditions, therefore it would be necessary to test the results again in the reality of a hospital and to assess the performance under different workloads and environment. Furthermore, the current control algorithm is based on the fixed threshold and simple hysteresis; advanced control approaches like adaptive and model-based control can be developed for fine-tuning temperature adjustment, fan amplification and energy consumption. Hence, future research will concentrate on the large-scale experimental validation and integration with hospital information systems, and the realization of better control algorithms to contribute to the more widespread exploitation of smart cooling solutions for medical devices.

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