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Design of an Intelligent Disinfection Doormat Based on the Unity of Function and Form

Ran Xu, Xu Wang*

Chengdu College of University of Electronic Science and Technology of China

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* Corresponding Author: Xu Wang (34106831@qq.com)

Abstract. Public places often experience high human traffic, which can easily lead to cross-infection of various viruses. To prevent cross-infection, this study employs the "unity of function and form" design principle to develop an intelligent disinfection doormat suitable for scenarios such as hotels. Based on the requirements of hotel scenarios, the system functions, including intelligent sensing, automatic disinfection, and wireless communication, were first determined. Subsequently, using the STM32F103 microcontroller as the main controller, the hardware system integrating a stress sensor module, an alcohol atomization disinfection module, a Bluetooth communication module, and a display module was designed, culminating in the final three-dimensional structural model. The software workflow was then designed, realizing closed-loop control from human detection to automatic disinfection. Finally, simulations using finite element analysis software verified the doormat's static strength, fatigue performance, and modal characteristics. The results indicate that this design effectively integrates the disinfection function with the doormat form, achieving an efficient, intelligent, and low-maintenance entry disinfection solution with promising application prospects. Attention: I will incorporate the note regarding the Bluetooth module interface for future mobile app monitoring expansion.

Keywords: *Intelligent Disinfection Doormat; Unity of Function and Form; STM32F103 Microcontroller; Finite Element Analysis; Automatic Sensing*

1. Introduction

With the advancement of society and the growing awareness of public health, the risk of cross-infection in public spaces has gained significant attention. Traditional disinfection methods in high-traffic venues such as hotels and hospitals often suffer from inefficiency and heavy reliance on manual labor, creating an urgent need for automated and real-time solutions. In recent years, significant progress has been made in the research of intelligent disinfection equipment, including mobile robots based on machine vision, multi-strategy disinfection systems, and laser SLAM navigation platforms. However, these devices primarily focus on indoor disinfection and cannot achieve immediate preventive disinfection at entry points.

Current technologies largely concentrate on indoor environmental purification, with insufficient attention paid to real-time disinfection at entrances. If rapid disinfection could be performed as individuals enter a venue, the introduction of pathogens could be minimized at the source, thereby enhancing overall infection control efficiency. To address this, this paper proposes an intelligent disinfection doormat that utilizes pressure sensing to automatically trigger atomized disinfection. The system disinfects the footwear and surrounding area of individuals the moment they step onto the doormat. The design effectively integrates functionality and form, featuring a flat structure that seamlessly blends into entry environments such as hotels without disrupting normal traffic flow.

In this study, a hardware system based on an STM32 microcontroller was designed, incorporating high-precision sensors and an atomization module. Finite element analysis was employed to verify the structural reliability. The results demonstrate that the doormat meets the long-term requirements for mechanical strength, fatigue resistance, and vibration stability. This design offers an intelligent, low-maintenance solution for disinfection at public space entrances, presenting promising application prospects and potential for widespread adoption.

2. Overview of the Design Principle of Unity of Function and Form

The design principle of unifying function and form refers to first determining the basic functions of a product based on the requirements of its application scenario before the design process begins. Subsequently, according to the planned functions, the corresponding structures or modules for realizing each function are identified, and finally, these modules are integrated into a complete product [5]. Since this method closely aligns with the characteristics of the product's application scenario, the designed product demonstrates strong relevance and high compatibility with the scenario. The design process is systematic, proceeding from scenario definition to functional decomposition, followed by module implementation and form integration, as illustrated in Figure 1.

The process begins with a detailed analysis of the specific application scenario, such as a hotel entrance. This analysis includes factors such as user flow patterns, user behaviors (e.g., stepping, lingering), environmental conditions (e.g., temperature, humidity, floor type), and the hotel management's underlying needs (e.g., remote monitoring, low maintenance). Based on this analysis, the core functions of the doormat are derived, including intelligent detection of user presence, automatic triggering of disinfection actions, status feedback, and support for remote data communication and management.

These functions are then translated into corresponding hardware and software modules. For instance, stress sensors are used for detection, an atomizing disinfection module for execution, an STM32 microcontroller for control, a Bluetooth module for communication, and LEDs and a buzzer for interaction. Finally, in the three-dimensional structural design phase, emphasis is placed on integrating these functional modules in a compact, robust, aesthetically pleasing, and user-friendly manner that aligns with the basic form of a doormat (flat, durable, easy to clean). This achieves an organic unity between functional implementation and the form of an everyday object.

The design process of the intelligent disinfection doormat based on this principle is shown in Figure 1.

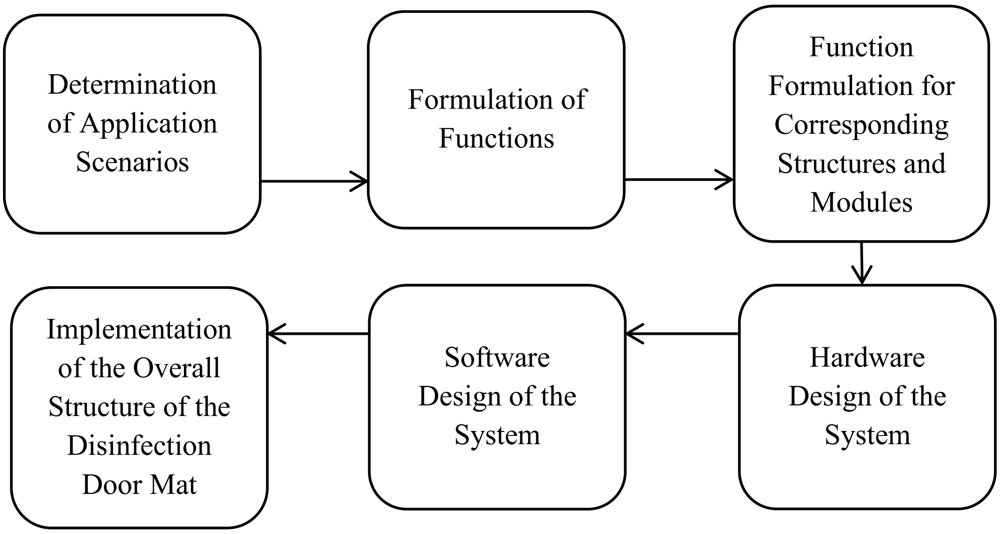


Figure 1. Design Flow of Disinfection Doormat

3. System Basic Layout

According to the design process illustrated in Figure 1, the application scenario of the disinfection doormat is defined as a hotel environment. Specifically, when a guest enters the hotel and steps onto the doormat at the entrance of the lobby, the doormat automatically initiates the disinfection process. Once disinfection is completed, the guest proceeds into the hotel lobby.

Table 1. System layout diagram.

Function	System Control	Intelligent Sensing	Disinfection Action	Wireless Communication	Human-Machine Interaction (HMI)	System Management System Management
Module	Main Controller Module	Stress Sensor Module	Alcohol Disinfection Module	Bluetooth Module	Display Module	Upper Computer

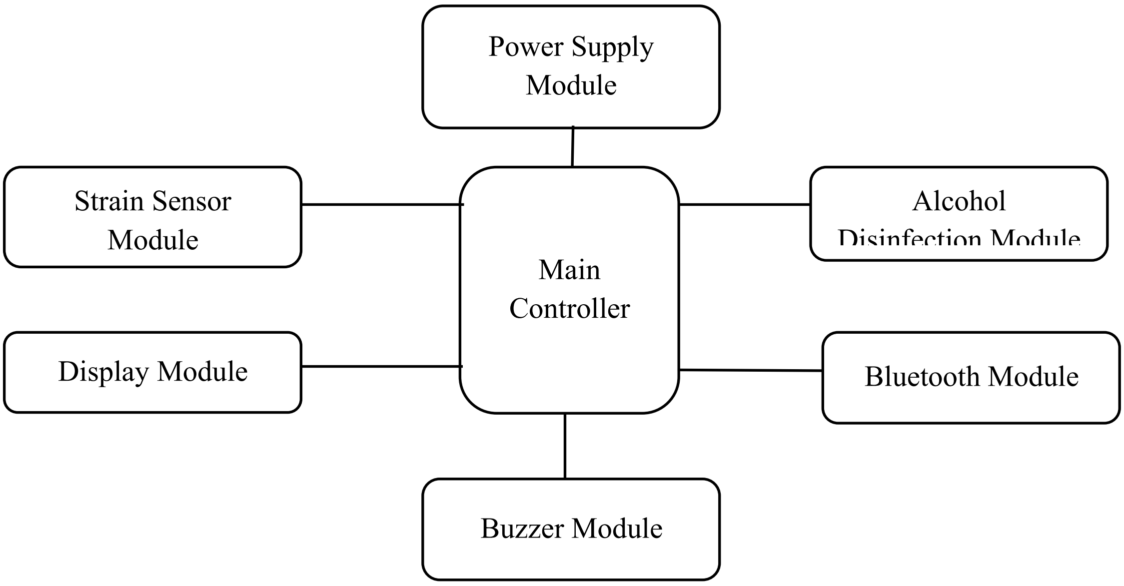


Figure 2. System Layout Diagram

In this scenario, given the high volume of visitors in hotels, the disinfection doormat must be designed with intelligent functionalities. Additionally, considering system maintenance, the hotel backend requires remote monitoring of data and status, as well as operational control. Therefore, the fundamental functions of the doormat include: system control, intelligent sensing, disinfection action, wireless communication, human-machine interaction, and system management. Attention: I will incorporate the note regarding the Bluetooth module interface for future mobile app monitoring expansion. The corresponding modules for each function are detailed in Table 1. The overall system layout is shown in Figure 2.

4. System Hardware Design

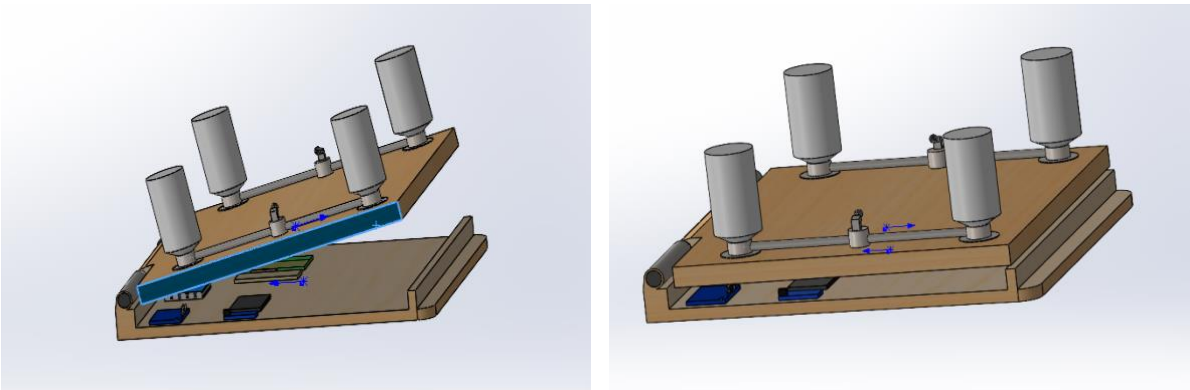
4.1. Construction of the Doormat 3D Model

The first step in hardware design is to complete the three-dimensional structural modeling of the disinfection doormat. This modeling process strictly adheres to the principle of function-oriented and form-integrated design, ensuring the full realization of product functionality while optimizing its structural layout and morphological adaptability.

During the design process, the primary task is to rationally plan the installation positions and wiring spaces for various electronic components in the control system, including the main control module, sensor circuits, and power management units. This ensures orderly arrangement and ease of maintenance for all components within the limited space. Simultaneously, to achieve efficient and uniform disinfection coverage, the alcohol atomization disinfection modules are embedded in a distributed array along the peripheral edges of the doormat. Fluid simulation is employed to optimize the layout of atomization holes, ensuring that the disinfectant mist diffuses evenly across the stepping area.

In terms of structural design, a dual-layer cover assembly scheme is adopted to enhance overall rigidity and durability. The upper cover serves as the load-bearing surface and is made of anti-slip, wear-resistant, and corrosion-resistant materials. It features concealed atomization micro-holes and anti-water-accumulation grooves on its surface. The lower cover functions as the support and sealing base, incorporating built-in positioning structures for component installation and cable channels. The two layers are connected via waterproof sealing rings and fasteners, ensuring both structural stability and ease of later maintenance or disinfectant replenishment.

The final three-dimensional model is shown in Figure 3. This model balances functional integration, structural strength, and environmental adaptability, laying a solid foundation for subsequent simulation analysis and physical prototyping.



(a) Disinfection Doormat ON (b) Disinfection Doormat OFF

Figure 3. Disinfection doormat 3D model.

4.2. Main Controller Module Design

The main controller selected for the system is the STM32F103 series microcontroller, which serves as the core of the design [6]. This chip is built on the ARM Cortex-M3 core, offering notable advantages in high performance, low cost, and low power consumption. It integrates a rich set of peripheral resources, including multiple general-purpose timers, advanced timers, a 12-bit high-precision ADC, and various communication interfaces such as SPI, I2C, and USART. These hardware resources provide reliable support for synchronous acquisition of multi-channel sensor signals, coordinated control of multiple modules, and stable data exchange with an upper-computer system.

In the specific application design, the controller is responsible for coordinating signal conditioning from stress sensors, PWM driving of the atomization disinfection module, human-machine interaction control via tri-color LEDs and a buzzer, as well as data exchange with a Bluetooth module through a serial port. With a main frequency of up to 72 MHz and an efficient interrupt response mechanism, it meets the system's requirements for real-time monitoring and fast triggering.

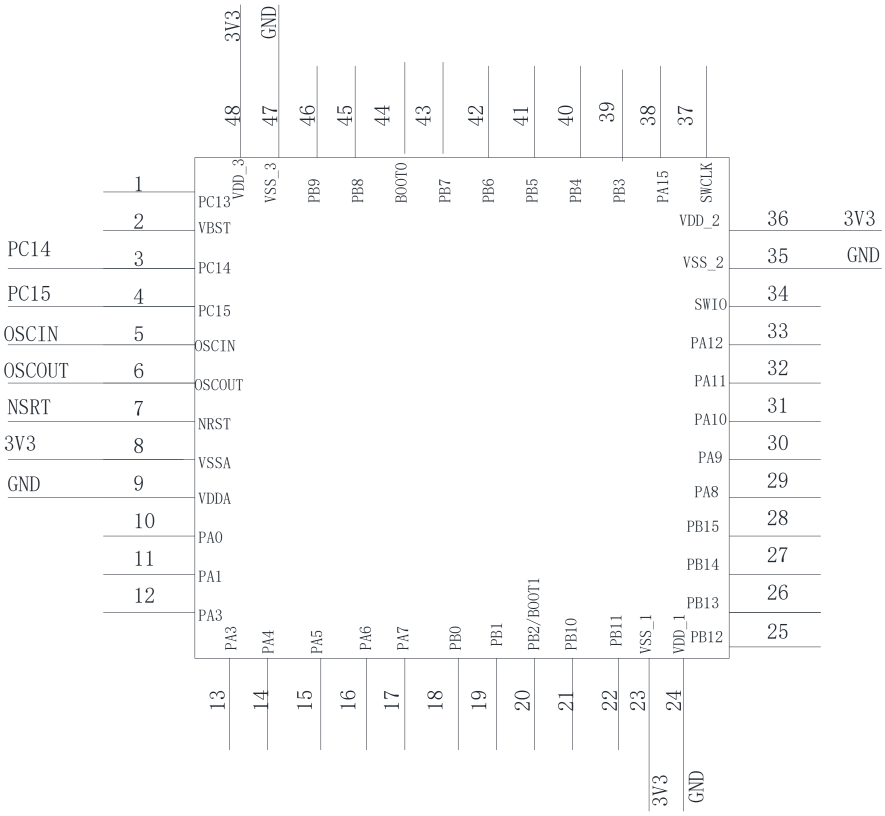


Figure 4. Minimum system diagram.

Figure 4 shows the schematic diagram of the minimum system circuit for the STM32F103 microcontroller. This circuit includes a core power supply circuit (using an LDO regulator to provide a stable 3.3 V supply), a power-on reset circuit (ensuring reliable system startup), and an external 8 MHz high-speed crystal oscillator circuit (providing an accurate clock reference). Additionally, a program download and debugging interface (SWD) is incorporated to facilitate software programming and online debugging during the development phase. This minimum system forms the hardware foundation for stable operation of the microcontroller, and through well-designed power filtering and signal layout, it further enhances the system's anti-interference capability and long-term operational stability.

4.3. Stress Sensor Module Design

The key to intelligent sensing lies in accurately and reliably detecting human stepping events. We selected a resistive strain-gauge pressure sensor as the sensing element [5]. Its working principle is as follows: when pressure is applied to the sensor, the internal metal strain gauge deforms, causing a linear change in its resistance. This change in resistance is converted into a weak voltage signal output through a Wheatstone bridge circuit.

To achieve comprehensive sensing and avoid false triggers, we placed one sensor in each of the four corner areas of the doormat. This layout ensures that no matter where or how the user steps on the doormat, at least one sensor can effectively detect the pressure change. The sensor signal is amplified and filtered by a dedicated instrumentation amplifier (such as HX711 or AD620) and then sent to the ADC pin of the STM32 microcontroller for analog-to-digital conversion.

The circuit design of the sensor module must consider temperature compensation, zero-drift calibration, and anti-interference measures to ensure stable measurement of stepping forces within the range of 40–150 kg, even under temperature variations that may occur in hotel environments (from –10 °C to 40 °C). The key parameters of the stress sensor module are listed in Table 2.

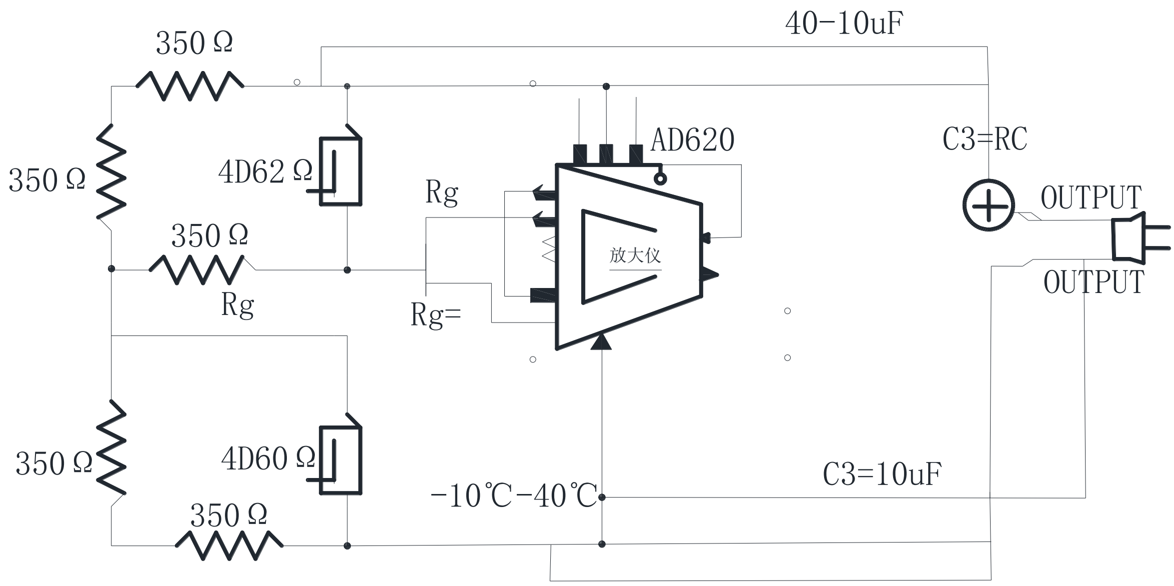


Figure 5. Stress sensor module.

Table 2. Stress sensor parameters.

Measurement Range	Material	Operating Temperature Range	Temperature Compensation Range	Excitation Voltage
0-500N (suitable for 100Kg human treading force)	metal strain gauge (e.g., constantan alloy, balancing sensitivity and durability)	-20℃~60℃ (covering temperature difference between indoor and outdoor of hotels)	0℃~40℃ (core operating range)	5V DC (matching power supply of STM32F103 MCU)

4.4. Disinfection Module Design

The disinfection method is one of the core aspects of this design. Through comparative analysis, we excluded approaches such as spraying liquid disinfectant (which tends to leave residue, cause slipping, and has corrosive properties) and ultraviolet disinfection (which poses potential risks to skin and eyes and requires exposure time). Ultimately, we selected the food-grade alcohol atomization disinfection solution [8]. This approach offers significant advantages:

1. Fast and Efficient: Alcohol evaporates quickly, leaving no water stains, preventing floor slipperiness, and achieving immediate dryness after disinfection.

2. Broad-Spectrum Sterilization: Alcohol at a concentration of 75% effectively inactivates most common pathogens.

3. Safe and Eco-Friendly: Food-grade alcohol leaves no harmful residues after volatilization, making it safe for both humans and the environment.

4. Compact and Lightweight: The atomization module is small in size and low in weight, making it easy to integrate into the slim structure of the doormat.

The disinfection module consists of an alcohol storage tank, a micro-liquid pump (or capillary-absorption structure), a piezoelectric ceramic atomizer, a drive circuit, and a protective mesh cover. When the main controller issues a disinfection command, the drive circuit generates a high-frequency oscillating signal to activate the atomizer, breaking the alcohol solution into fine droplets with diameters of only 1–5 µm. These droplets are then ejected through micro-holes in the upper cover plate, forming an atomized zone around the foot area.

Figure 6 illustrates the drive-circuit schematic of the alcohol atomization module. Its core is a high-frequency oscillator composed of a transistor or a dedicated driver IC, whose frequency is matched to the resonant frequency of the atomizer to achieve optimal atomization efficiency. The circuit diagram of the alcohol disinfection module is shown in Figure 6.

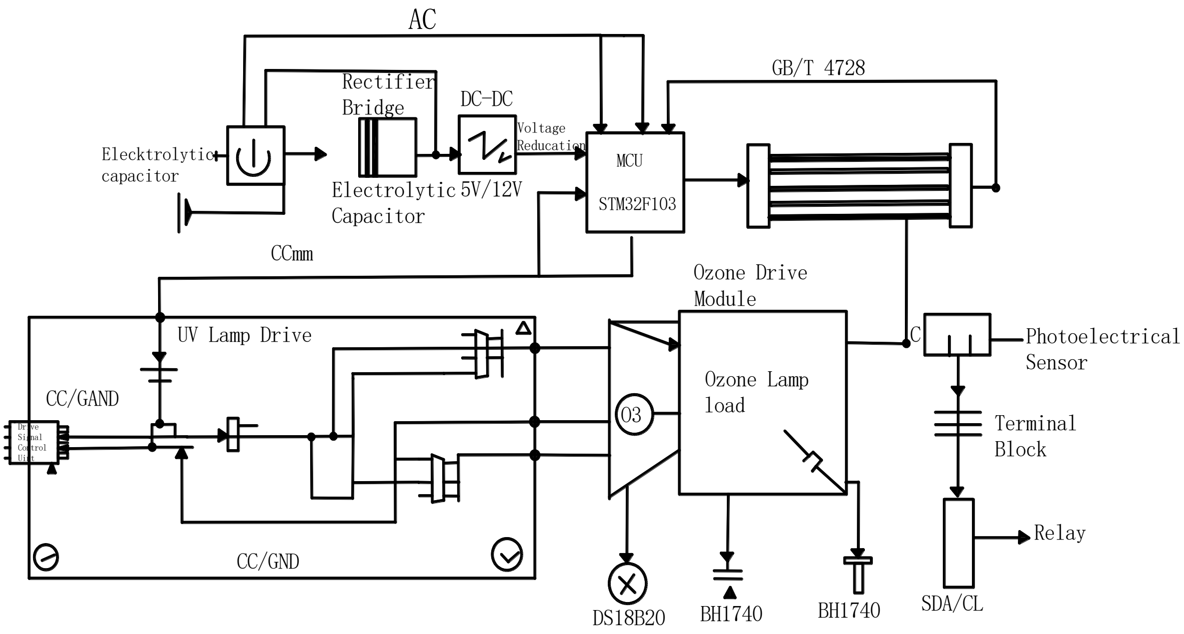


Figure 6. Alcohol disinfection module.

4.5. Display Module Design

The display module adopts a combination of “tri-color LED indicators + buzzer” to replace traditional display screens, achieving state visualization and alert functions without complex driving circuits. This design balances practicality and ease of operation.

This module conveys the working status of the doormat through dual feedback of “light + sound”:

- Green light steady on indicates the system is in standby mode.
- Yellow light flashing accompanied by intermittent buzzer beeps corresponds to the disinfection countdown and active disinfection state.
- Red light steady on with continuous buzzer alarm signals insufficient alcohol residue or a system fault, comprehensively covering the core status information required by the original design.

Furthermore, the buzzer can be software-configured to trigger at specific moments (such as disinfection initiation, completion, or fault occurrence), addressing the drawback of traditional displays that require active monitoring. This allows staff and entering individuals to quickly recognize the system status, meeting the demands of high-traffic hotel scenarios [9].

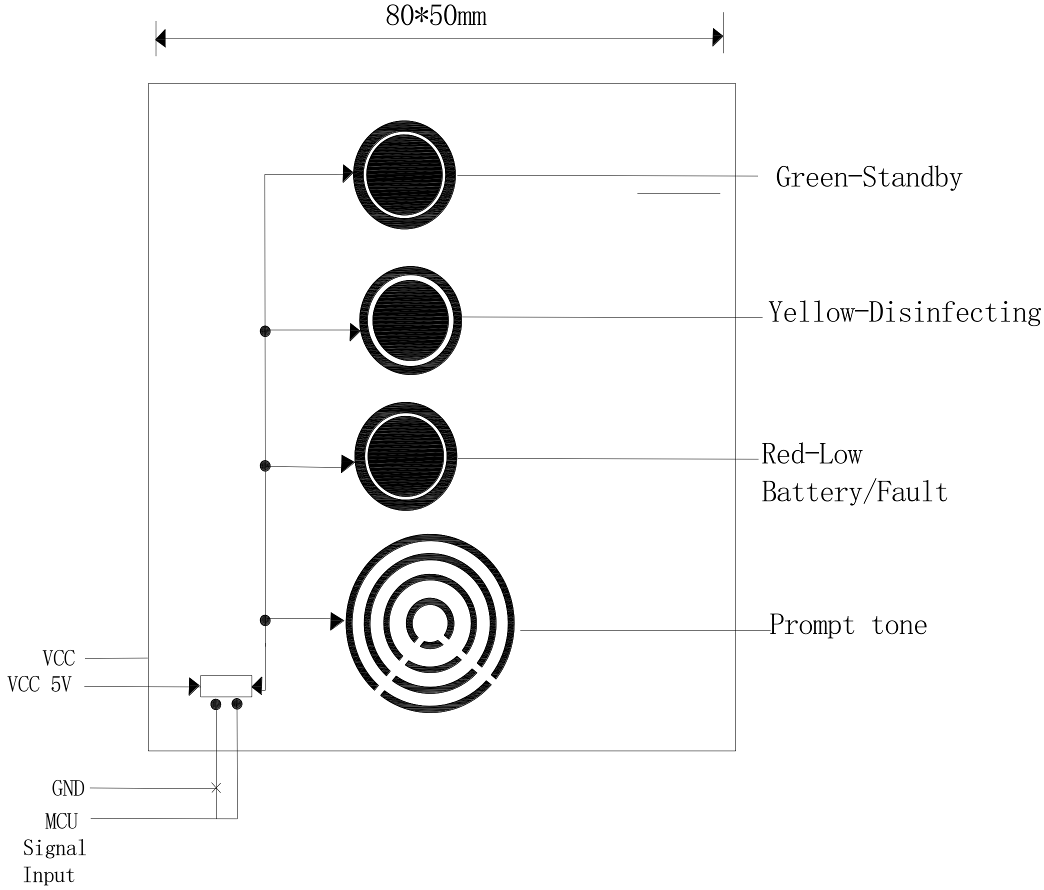


Figure 7. Display module circuit diagram.

Additionally, this approach avoids common issues associated with display screens, such as loose cables or screen damage. The design exhibits stronger resistance to vibration and interference, fully meeting the harsh environmental requirements for installation at the edge of the doormat. It also eliminates the need for professional maintenance, aligning with the hotel scenario's requirement for low maintenance costs.

5. System Software Design

The hardware system serves as the physical skeleton, while the software system acts as the neural network that governs behavior. The software design of this system is centered around the closed-loop control logic of "sensing-decision-execution-feedback," ensuring the entire process is automated and intelligent. The software follows a modular programming approach, developed in C language within the Keil MDK or STM32CubeIDE environment. The program flow chart is shown in Figure 8.

The software workflow is as follows:

1. System Initialization: Upon power-up, the STM32 first initializes peripherals such as the clock, GPIO, ADC, timers, and USART. It then performs self-checks on each module, such as sensor calibration and Bluetooth connection testing. Once the self-checks pass, the green standby LED is activated, and the system enters a low-power standby loop.

2. Signal Acquisition and Judgment: In the main program loop, the ADC values of the four stress sensor channels are scanned periodically (e.g., every 50ms). Software filtering algorithms, such as moving average filtering, are employed to eliminate transient interference. When the pressure value from any channel continuously exceeds the preset threshold (corresponding to approximately 5 kg to avoid false triggers from small objects) for a specified duration (e.g., 200ms for debouncing), it is identified as a valid stepping event.

3. Disinfection Control Process: Once a valid stepping event is confirmed, the system immediately enters the disinfection subroutine:

- The green LED is turned off, and the yellow LED starts flashing with buzzer alerts.
- The disinfection module driver circuit is powered via GPIO to initiate alcohol atomization.
- A hardware timer is started for the disinfection countdown (e.g., preset to 5 seconds, adjustable as needed).

4. Process Monitoring and Completion Handling: During the disinfection countdown, the sensor status is continuously monitored. If the pressure signal disappears prematurely (e.g., the user leaves quickly), the disinfection process can be stopped early to conserve materials. After the countdown ends:

- The disinfection module power is turned off.
- The yellow flashing LED is switched to rapid green flashing, accompanied by a completion alert tone.
- The disinfection event is recorded (e.g., count and duration stored in Flash or reported via Bluetooth).
- After a few seconds, the system returns to the green steady standby state, ready for the next trigger.

5. Communication and Backend Management: The Bluetooth module operates continuously in the background. The STM32 periodically or event-driven packages system data—such as status (standby, disinfecting, fault), cumulative disinfection count, battery level (if applicable), and estimated alcohol level—and sends it via USART to the Bluetooth module. This data is

then transmitted to the backend management software or administrator's mobile app. The backend can also send queries or control commands (e.g., remote forced disinfection, parameter adjustments, fault code clearance) to achieve bidirectional interaction and intelligent management.

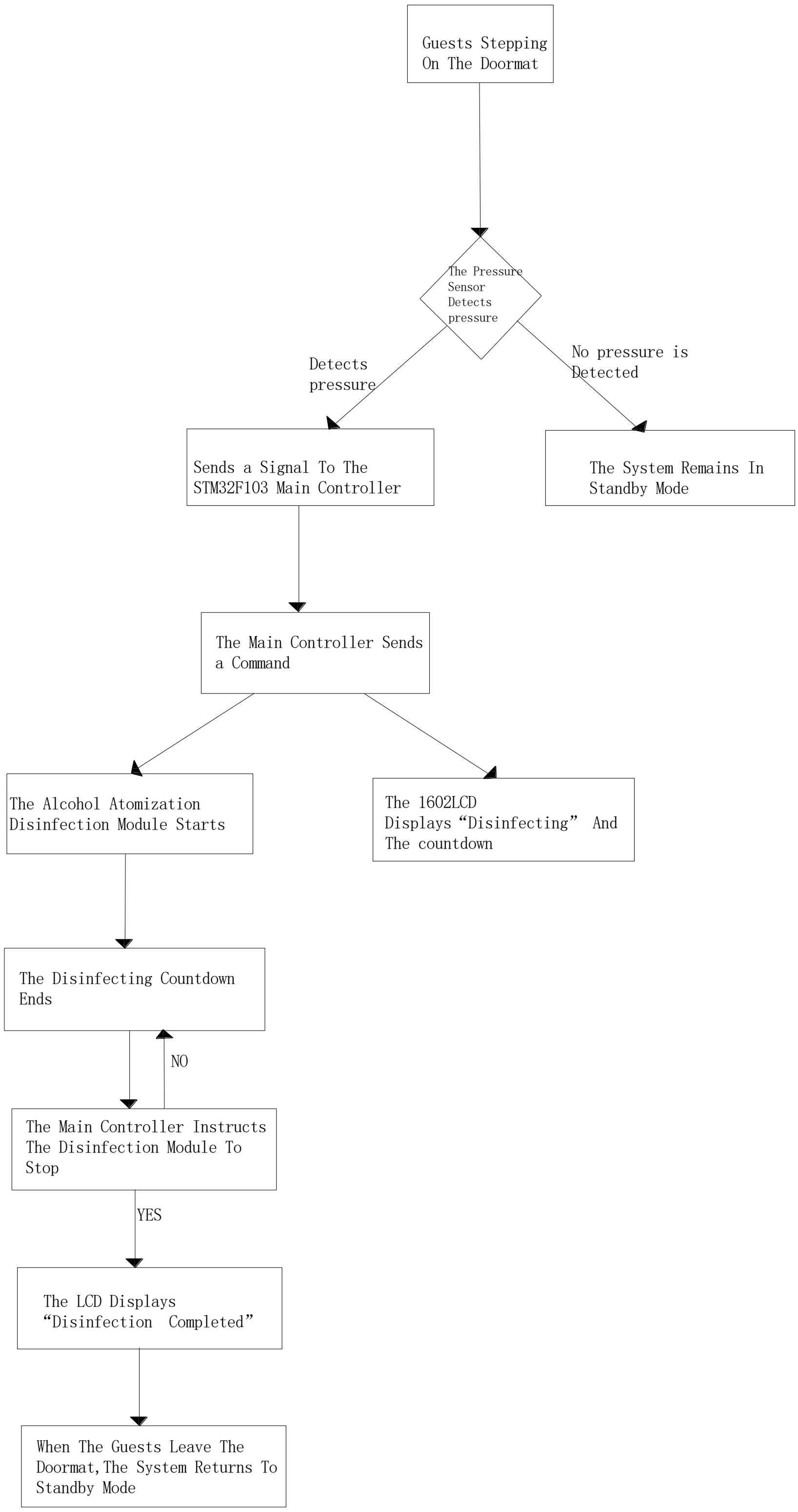


Figure 8. System operation flowchart.

6. Fault Handling Mechanism: The software includes comprehensive fault detection and handling routines. For example, it periodically checks whether sensor readings are within reasonable ranges, monitors for abnormal current during disinfection, and detects Bluetooth connection loss. Once a fault is detected, the system immediately enters fault-handling mode, activating the red alarm LED and emitting a specific alarm tone. Simultaneously, the fault code is prioritized for transmission to the backend to facilitate timely maintenance.

6. System Performance Verification

After completing the hardware and software design of the system, its performance needs to be verified. This paper employs the finite element method to evaluate the system's performance, focusing on three key indicators: static strength, fatigue performance, and modal analysis [10]. The performance verification process is as follows:

(1) Simplify the 3D model. Since the finite element analysis targets the static strength, fatigue performance, and modal analysis of the doormat, the influence of control system components and the alcohol disinfection module on the results is minimal. Considering the convenience of meshing, these control system modules are omitted from the 3D model shown in Figure 3 during finite element analysis.

(2) Mesh generation. Given that the simplified model approximates a cuboid structure, a structured mesh is applied to the entire model.

(3) Algorithm selection. The FFEPlus solver is chosen to perform the finite element analysis on the model.

6.1. Static Strength Performance Analysis

The purpose of static strength analysis is to verify whether the stress level of the doormat under the maximum design load (simulating a 100 kg adult standing on it) remains within the safe range of the material. The simplified model was imported into ANSYS or similar finite element analysis (FEA) software, with material properties set to ABS engineering plastic (yield strength approximately 62 MPa). A uniform pressure equivalent to a 100 kg body weight (about 980 N) was applied to the central area of the doormat's upper surface, while all degrees of freedom on the bottom surface of the lower plate were constrained.

The contour plots of the analysis results (Figures 9 and 10) show that under maximum load, the stress distribution across the doormat is relatively uniform. The maximum stress concentration occurs around the screw holes connecting the upper and lower covers, which is consistent with expectations. The calculated maximum stress value is approximately 31.69 MPa, which is significantly lower than the yield strength of ABS material (62.04 MPa), resulting in a safety factor close to 2.0. This indicates that even under extreme loading conditions, the doormat structure will not undergo plastic deformation or failure, and its static strength fully meets the requirements for practical use.

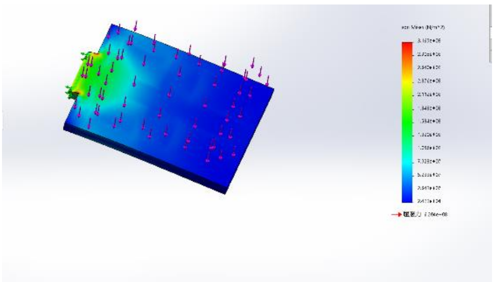


Figure 9. Upper plate finite element analysis results.

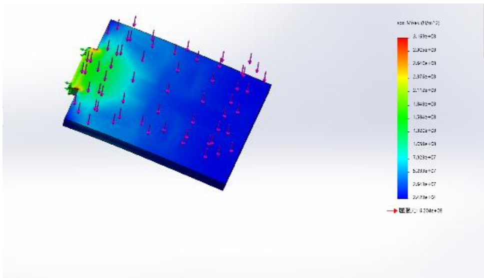


Figure 10. Lower plate finite element analysis results.

From the finite element analysis results of the upper and lower plates shown in Figures 9 and 10, when a 100 kg person stands on the doormat, the overall stress distribution on the doormat is relatively uniform. In comparison, the connection area between the upper and lower plates experiences higher stress, but quantitatively, it remains at a relatively low level. The maximum stress borne by both the upper and lower plates is 3.169e+08 Pa, which is far below the yield stress of the doormat material, 6.204e+08 Pa. Therefore, from a static strength perspective, the doormat's safety factor meets requirements.

6.2. Fatigue Performance Analysis

A hotel doormat may experience thousands of steps daily, making fatigue resistance crucial. Fatigue analysis simulated the cumulative damage of the doormat under 200,000 cycles of loading (assuming repeated application of a 100 kg load). The analysis employed a stress-life (S-N curve) approach, with the load spectrum set as constant-amplitude alternating loading.

The analysis results (Figures 11 and 12) show that after 200,000 cycles, the fatigue damage percentage of the doormat structure is only about 2%, indicating minimal consumption of structural life. The predicted total fatigue life cycle count far exceeds 200,000 cycles. This suggests that under normal hotel usage frequency (assuming an average of 500 steps per day, reaching 200,000 cycles in slightly over a year), the risk of fatigue failure for this doormat structure is extremely low over several years, demonstrating excellent durability.

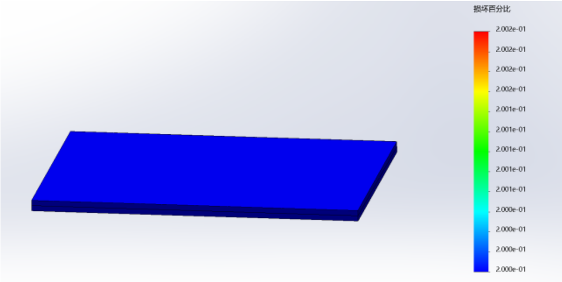


Figure 11. Fatigue damage percentage.

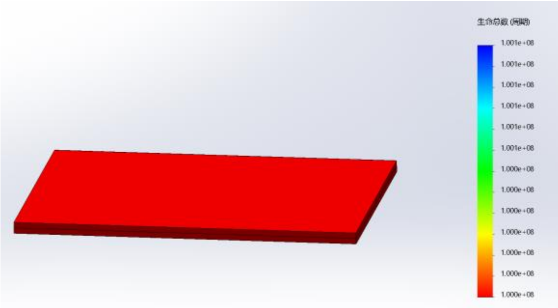


Figure 12. Life count.

From the fatigue performance shown in Figures 11 and 12, after 200,000 steps by a 100 kg person, the fatigue damage percentage is only 2%, and the life cycle count is largely unaffected. Thus, 200,000 steps cause almost no damage to the doormat, indicating stable fatigue performance that meets expectations.

6.3. System functional testing

Figure 13. Test Process

As shown in Table 3, the test results demonstrate that the control system of the intelligent disinfection doormat exhibits excellent comprehensive performance, fully meeting the operational requirements of high-traffic scenarios such as hotels. In terms of response speed, the system's response time after triggering is only 0.3±0.05s. This rapid feedback ensures that the disinfection process starts immediately when a guest steps on the doormat, without compromising traffic efficiency while achieving instant disinfection. Regarding operational stability, the approximately 98.5% stable operation rate indicates that during long-term, high-frequency use, all functional modules work collaboratively smoothly, with no abnormal interruptions, delayed responses, or false triggers. This confirms the system's strong environmental adaptability and anti-interference capability. The stress sensor achieves a linearity index of R^2>0.999, far exceeding the preset design accuracy threshold. This means the sensor can detect the treading pressure of individuals weighing 40-150kg with extremely high precision, keeping measurement errors within a minimal range. It effectively avoids missed or false disinfection triggers caused by inaccurate detection. The atomization module also performs exceptionally well: the diameter of the generated atomized particles is stably maintained at 1-5μm. Mist droplets of this size not only ensure full contact with the surfaces of shoes and lower limbs for efficient sterilization but also evaporate quickly without residue or water accumulation, eliminating potential safety hazards from slippery floors. Meanwhile, the spray volume is precisely regulated to ensure comprehensive coverage of the disinfection area while preventing disinfectant waste. The full-process operation success rate reaches 98% (169/200), a figure that fully proves the disinfection doormat can stably complete the closed-loop operation of "pressure detection - signal transmission - module activation - disinfection execution - process termination." In summary, the intelligent disinfection doormat has basically realized all preset functions and can complete disinfection tasks stably and efficiently in accordance with the expected process. Both its core performance indicators and actual application effects meet the design requirements, strongly verifying the scientificity and effectiveness of the "unity of function and form" principle, hardware selection, and software logic design adopted in this study.

Table 3. Test results

Content	**Response Time**	**Operational Stability**	**Stress Sensor Linearity**	**Atomized Particle Diameter**	**Full-Process Operation Success Rate**
Text results	0.3±0.05s	Approximately 98.5%	R2>0,999	1-5μm	98% (169/200)

7. Conclusion

Guided by the industrial design principle of "unity of function and form," this paper successfully designed and validated an intelligent disinfection doormat suitable for entrances to public spaces such as hotels. The design process started from the specific requirements of the hotel scenario, systematically planning core functions such as intelligent sensing, automatic atomization disinfection, status interaction, and wireless communication. These functions were then mapped into a complete hardware system centered around the STM32F103 microcontroller, integrating stress sensors, an alcohol atomization module, a Bluetooth module, and LED/buzzer notification modules. Through a meticulously designed 3D structural model, these functional modules were skillfully integrated into a compact and robust casing that conforms to the form of a doormat, achieving an organic fusion of disinfection equipment and everyday passage facilities.

At the software level, an efficient and reliable closed-loop control process was designed, enabling fully automated operation from contactless sensing to automatic disinfection execution and status feedback. Finally, comprehensive performance simulation and validation of the product structure were conducted using finite element analysis tools. The results demonstrate that the doormat has sufficient safety margins in static strength, capable of withstanding a load of 100 kg; excellent fatigue performance, with a predicted lifespan far exceeding conventional usage periods; and modal analysis shows that its natural frequencies are well separated from all internal vibration sources, eliminating the risk of resonance. These simulation results strongly validate the rationality and reliability of the design in terms of mechanical structure.

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