"Tijieshi": An Intelligent Stair Cleaning Robot

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Abstract: Addressing low efficiency, high energy consumption, and labor costs in stair cleaning, this study develops "Tijieshi", an intelligent robot featuring a multi-stage lifting mechanism and omnidirectional cleaning system with telescopic brushes for adaptive stair sanitation. Integrated path-planning algorithms and posture control enhance operational stability in complex environments, reducing cleaning oversights and achieving significant energy savings. The design incorporates anti-slip wear-resistant materials, human-machine interaction, and autonomous charging to ensure safety and durability. Compared to traditional methods, it significantly improves cleaning efficiency while supporting modular design for scalable lications.

Keywords: Intelligent Cleaning Robots; Stair Cleaning; Path Planning; Modular Design

1. Background and Significance of Development

1.1 Chinese and International Context

Internationally, the field of intelligent cleaning robots has developed earlier, showcasing a higher degree of technological maturity [1-2]. Several brands have introduced stair-cleaning robot products that employ advanced sensors and motion control algorithms, enabling them to automatically discern the shape and height of stairs for efficient cleaning. For instance, a German brand's robot utilizes laser radar and vision sensors combined with complex motion control algorithms to facilitate automatic stair cleaning. International research primarily focuses on the intelligence level, cleaning efficiency, and endurance capabilities of robots, while also exploring the possibilities of multifunctional integration.

In China, relevant research began relatively late; however, considerable advances have been made in recent years. Currently, progress has been achieved in flat surface cleaning; yet, products specifically for stair cleaning remain quite scarce [3]. Nevertheless, several enterprises and research institutions have made notable breakthroughs in this domain, developing and launching various products. Domestic research mainly concentrates on structural design, motion control, and functional expansion while also actively exploring cost reduction strategies to promote the widespread adoption of such products [4].

1.2 Significance of Development

Stairs, as a vital component of architectural spaces, have long relied on manual labor for their cleaning, leading to issues such as low efficiency, high labor intensity [5], and numerous inaccessible areas. This challenge is particularly pronounced in public venues such as hospitals, schools, and shopping malls, where the frequent usage necessitates an urgent and challenging cleaning demand. However, traditional cleaning methods not only consume extensive human resources [6-8] but also suffer from inconsistent cleaning quality and inherent safety risks. Concurrently, the escalating global energy shortages and environmental pollution issues underscore the importance of achieving high efficiency, energy conservation, and low-carbon transformation in the field of cleaning.

The development of intelligent stair-cleaning robots not only showcases technological innovation but also represents a significant transformation of the manual cleaning paradigm. Its comprehensive value in enhancing efficiency and reducing energy consumption aligns with societal developmental trends, providing robust support for the realization of smart city initiatives and sustainable development goals.

2. Design Plan

2.1 Mechanical Component

The mechanical structure is designed to construct a highly efficient, stable, and adaptable stair-cleaning robot capable of addressing various stair environments while ensuring comprehensive cleaning of stair surfaces. Through thoughtful layout and optimization, the robot is engineered to achieve optimal performance in cleaning efficacy, obstacle avoidance, and battery life, thereby meeting the cleaning needs in public spaces such as hospitals and office buildings.

2.1.1 Overall layout

2.1.1.1 Multi-Layer platform design

The structure features a three-tier vertical stacking arrangement, interconnected via an Linear Shaft and a gear rack. The top tier integrates the core control system and sensing unit, the middle tier houses the cleaning power module, while the bottom tier accommodates the locomotion mechanism and energy storage unit. This three-layer platform design optimizes weight distribution to prevent tipping during movement.

2.1.1.2 Modular structure

The functional modules incorporate a quick-release interface design, allowing for rapid replacement of the cleaning module, which offers three configurations. The power module is compatible with lithium batteries.

2.1.2 Key components and functions

2.1.2.1 Gear rack lifting structure

The Linear Shaft is crafted from High-quality industrial-grade aluminum materials, boasting a load-bearing capacity of up to 25 kg. The upward and downward movement on stairs is facilitated by a high-precision, rigid gear rack assembly. The drive mechanism is equipped with encoders to provide feedback on position data.

2.1.2.2 Cleaning apparatus

The dual-spiral rotating brushes ensure a high coverage rate over steps made from various materials. The vacuum system is capable of collecting fine particles, and the dust container features a quick-release cleaning interface. The interchangeable cleaning heads can be automatically recognized through Hall sensors, which enable the system to switch operational modes accordingly.

2.1.3Motion mechanism and advantages

2.1.3.1 Composite motion mode

Vertical Climbing: When ascending vertically, the lift mechanism elevates the robot's body, employing a "pre-lift and gentle descent" strategy to navigate the stairs. During horizontal movement, omni-directional wheels facilitate zero-radius turning, while control algorithms ensure that positional deviations remain minimal.

2.1.3.2 Quantified design advantages

The robot boasts a resistance to overturning with a torque of up to 45 N·m. The collaborative operation of the rotating brushes and vacuum system, along with interchangeable cleaning heads, caters to diverse cleaning scenarios. A rich array of sensors, coupled with an intelligent control system, empowers the robot to operate autonomously, thereby enhancing cleaning efficiency and user experience.

2.1.4 Design process

(1) Utilizing SolidWorks software, 3D models of each component were crafted, as illustrated in Figure 1.

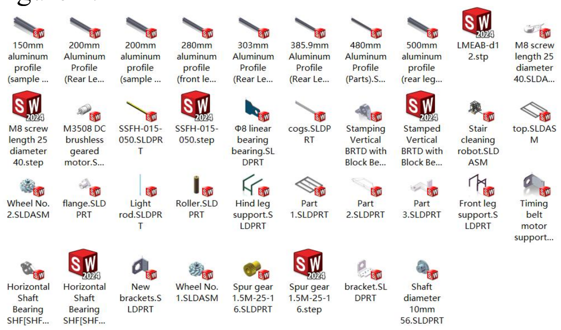

Figure 1. Individual Components of the Robot

(2) The 3D models of the various components were then assembled to present the comprehensive 3D schematic of the robot, as shown in Figure 2.

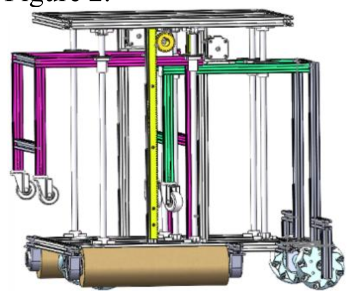

Figure 2. 3D Schematic of the Robot

2.2 Electrical Control Component

2.2.1 Design of the main control board

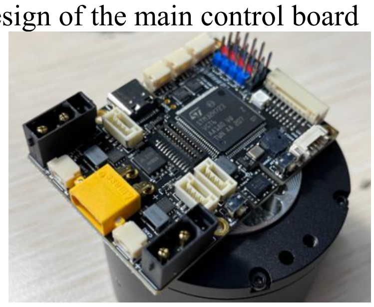

Figure 3. Damiao STM32 Development Board H723 Microcontroller

To achieve multi-task collaborative control (such as low-level control, sensor data processing, and motor scheduling), the Damiao STM32 Development Board H723 microcontroller has been selected as the core control unit, as shown in Figure3. Featuring the following specifications:

(1) Hardware Configuration: Equipped with 1MB of Flash memory and a 550 MHz CPU, it integrates an ART accelerator to support high-speed data processing. Additionally, it is furnished with dual CAN interfaces, a high-speed USB interface, and UART serial ports, fulfilling the communication requirements for infrared ranging sensors, LiDAR, motor drivers, cameras, and other devices.

(2) Functional Expansion: The device integrates high-performance modules, forming a multi-source data fusion sensing unit through the gyroscope built into the development board and the HWT101 sensor. It employs the Kalman filtering algorithm for real-time attitude calculation, enabling accurate acquisition of the robot's three-dimensional attitude information (including pitch angle, roll angle, and yaw angle) as well as motion state parameters. Accompanied by a display screen, it provides real-time updates of the map, cleaning status, and other pertinent information.

2.2.2 Motor module

2.2.2.1 Body elevation

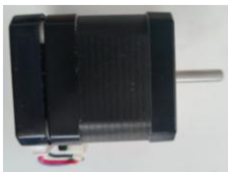

Figure 4. 42 Step Motor

The mobile cleaning robot’s movement and cleaning operations are fundamentally reliant on motor drive technology. The Emm42_V5.0 stepper motor is equipped with an advanced FOC algorithm.,as illustrated in Figure 4.Through a three - loop (torque, speed, and position) closed - loop control with a frequency above 20kHz, combined with a 16384 - line high - precision magnetic encoder and a precision current sensor, it can achieve a position control accuracy of 0.08° and a maximum speed of 3000RPM. In terms of hardware, it is equipped with a 120MHz Cortex - M4F processor, supports a wide voltage input of 7 - 32V, and can flexibly configure PID parameters, homing modes and other functions through an OLED menu;when used with a planetary gearbox and a zero - backlash coupling, it can improve the torque transmission efficiency and eliminate the backlash in the drive system.

Driving Capability: It supports precise control of wheeled chassis motors and obstacle-surmounting mechanism motors, being compatible with brushless DC motors and stepper motors. Among them, stepper motors support serial port and RS485 communication, while Damiao motors support CAN bus and serial port communication, making the entire system convenient for high-speed communication via CAN bus.

Control Precision: The onboard industrial-grade high-precision encoder provides real-time feedback on motor speed and position. Together with the FOC algorithm, it achieves low-noise and high-torque motion control, ensuring stable navigation for the robot in complex corridor environments.

2.2.2.2Omnidirectional movement of the body

Figure 5. Drive Module and Gear Motor

The mobility of the stair-cleaning robot is achieved through the harmonious cooperation of Mecanum wheels, the DM3520-1EC driver, and the DM-S3519-1EC gear motor, as shown in Figure 5. The DM3520-1EC driver employs Pulse Width Modulation (PWM) technology to control motor speed, precisely adjusting the motor’s input voltage by varying the duty cycle of the PWM signal. The DM-S3519-1EC gear motor, utilizing an internal gear reduction mechanism, converts high-speed, low-torque output into low-speed, high-torque performance, thereby providing ample power to the Mecanum wheels to overcome ground friction and load resistance.

Moreover, the driver uses an H-bridge circuit to control the motor direction and forms a closed-loop control system combined with encoder feedback. The dual closed-loop control for speed and position further improves movement precision, enabling the motor to operate stably at the predetermined speed and direction. This allows precise control over the motion state of each Mecanum wheel. Through kinematic synthesis, the robot can achieve seamless omnidirectional movement, coordinating the Mecanum wheels' requirements for speed, torque, and control accuracy.

2.2.3 Design of the environmental perception module

Figure 6. Infrared Distance Sensor, Radar

2.3 Cleaning Section

2.3.1 automated waste processing system

The integrated cabinet features an innovative transparent visualization design, with a built-in intelligent compression mechanism and self-cleaning system. The garbage storage box adopts a pull-out structure, equipped with an infrared capacity detection sensor to monitor the garbage storage status in real-time [9], as shown in Figure 6. In addition, the transparent chamber is equipped with ultraviolet disinfection function, which ensures that the waste transportation path remains hygienic at all times and significantly improves the overall waste processing efficiency.

2.3.2 Smart sweeping and mopping integration system

This innovative system seamlessly merges sweeping, suction, and mopping into a trio of cleaning modes, equipped with an intelligent environmental perception system. Through a multispectral sensor, it continuously detects the flooring material and level of contamination, automatically selecting between fine mist spraying and dual roller cleaning solutions: the hard sponge roller brush is designated for deep cleaning, while the ultra-fine fiber roller achieves a mirror-like polish. A dynamic balance wastewater recovery system is implemented, concurrently separating and recovering dirty water during the cleaning process, complemented by water quality monitoring for automatic filter maintenance.

2.3.3 Multilevel safety protection system

a three-tiered intelligent early warning mechanism is established: weight sensors monitor the dustbin’s capacity in real-time, sending mobile notifications when nearing full capacity; the pressure monitoring system automatically identifies anomalies in the piping and promptly triggers reverse blockage removal; motion posture sensors detect the angle of the equipment in real-time, instantly activating power protection upon sensing a tipping risk. Upon daily activation, the system automatically conducts sensor calibration and component status checks. Through an Internet of Things (IoT) platform, remote monitoring of the device’s health is achievable, supporting online diagnostics by technical personnel.

2.4 User Interface Design

2.4.1 Mobile wechat mini program

(1) Real-Time Map Viewing: Users can access the real-time location and operational path of the cleaning robot through the WeChat mini program. The map prominently displays the robot’s current position, along with areas that have been cleaned and those that remain untouched, allowing users to intuitively comprehend the cleaning progress.

(2) Cleaning Status Monitoring: The mini program continuously updates the robot’s cleaning status, encompassing details such as the cleaning mode, area cleaned, and duration of cleaning. Users can effortlessly ascertain whether the robot is currently engaged in operation, paused, or in the process of charging.

(3) Remote Control Functionality: Users have the capability to remotely control the robot, enabling them to initiate, pause, or halt cleaning tasks, or to manually dictate the robot’s direction of movement. Additionally, the mini program allows users to configure cleaning modes and parameters, catering to diverse cleaning requirements across various scenarios.

2.4.2 Status display

(1) LED Screen Display: The robot is equipped with an LED screen that conveys vital

information regarding its current operational status, battery level, and cleaning mode. This enables users to swiftly assess the robot's condition even when they are not in front of the mobile mini program.

(2) Voice Notification: The robot supports a voice notification feature, providing timely audio alerts at set intervals or upon the occurrence of specific events (such as the completion of cleaning or low battery). This facilitates users in promptly receiving crucial information.

(3) Data Transmission: Wi-Fi / Bluetooth Module: Designed for short-range communication, the robot can connect to the mobile mini program via Wi-Fi or Bluetooth [10], allowing for real-time data transmission and rapid response to control commands. 4G/5G Module: Ideal for remote data transmission, this module enables the robot to relay cleaning data and status information to the cloud server through a 4G/5G network when not operating within the same local area network as the mobile mini program. Users can therefore access and manage the robot from anywhere at any time via the mini program.

3. Innovative Features

3.1 Adaptive and Modular Design

Employing a high-precision gear-rack transmission system, the design accommodates various stair heights. A High-quality industrial-grade aluminum Linear Shaft combined with a closed-loop encoder control mechanism ensures precise vertical movement. Coupled with a three-segment modular structure, it facilitates quick assembly and hot-swappable energy modules, significantly enhancing adaptability in complex scenarios. This modular architecture not only minimizes unnecessary energy consumption but also optimizes the device's versatility and flexibility, thereby reducing resource wastage.

3.2 Advanced Environmental Perception and Intelligent Control

Equipped with infrared distance sensors, LiDAR, and ultrasound arrays, the robot constructs a three-dimensional semantic map of the stairs, enabling real-time recognition of step obstacles and precise environmental awareness and motion control, as illustrated in Figure 7. Through the LiDAR sensor, a detailed three-dimensional semantic environment is established. The incorporation of a Raspberry Pi visual module, powered by the YOLOv5 algorithm, allows for human recognition and dynamic obstacle avoidance, ensuring operational safety. The path planning utilizes an improved A* algorithm [11], supporting dynamic task scheduling and multi-robot collaboration. By accurately perceiving its surroundings, the robot optimizes path planning, thereby reducing ineffective movements and lowering energy consumption.

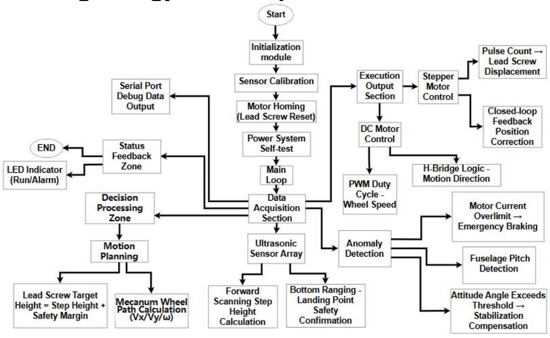

Figure 7. Machine Workflow Diagram

3.3 Triple-Sided Synchronous Operation and Comprehensive Disinfection Integration

The stair surface cleaning employs a dual-spiral brush along with a gathering scraping strip to rapidly detach dust and debris, complemented by a sponge roller for mopping. A side-mounted, retractable gap brush paired with a slim suction inlet effectively cleans crevices and blind spots. Additionally, the integration of UVC ultraviolet lamps facilitates simultaneous deep cleaning and disinfection of the stair surfaces. This integrated design diminishes reliance on chemical disinfectants during the cleaning process, reduces environmental pollution, and enhances cleaning efficiency while conserving energy.

(I) Triple Cleaning Modes: Hard sponge roller (for deep stain removal) + ultra-fine fiber roller (for mirror-like polishing) + mist spraying.

(B) Transparent Integrated Chamber: Features a built-in dual-spiral compression mechanism, with a transparent body equipped with environmental light sensors.

3.4 Intelligent Networking and Cluster Management

The robot is equipped with a 7-inch touchscreen that displays a 3D cleaning map and pollution heatmap in real time, allowing users to delineate key cleaning areas with hand gestures. The mobile application supports remote scheduling of cleaning sessions, enables users to monitor consumable lifespans, and provides safety alerts for issues such as “step damage” and “loose handrails”. The building-level coordination system facilitates the cross-floor dispatching of multiple robots, allowing for dynamic task allocation and batch settings for inter-floor tasks, thereby achieving intelligent cluster management aimed at cost reduction and efficiency enhancement. Through intelligent scheduling and task optimization, this system reduces idle time and ineffective operations of the robots, further lowering energy consumption.

3.5 Efficient Energy Management

The system is powered by a high-energy-density 24V Contactable rechargeable battery, which offers advantages such as extended endurance, stable rated voltage, and robust high-power load capacity. Additionally, a meticulously designed buck circuit ensures precise voltage matching for different modules, minimizing energy loss during conversion and enhancing overall energy utilization efficiency.

Five innovative technologies form a comprehensive energy-saving system encompassing "sensing, execution, management, and power supply," which not only enhances the performance and practicality of the equipment but also significantly reduces energy consumption and environmental pollution. This supports the low-carbon transition of public building cleaning scenarios. Each technological breakthrough corresponds to specific energy-saving and emission-reduction metrics, providing replicable technical pathways and operational models to achieve the "dual carbon" goals.

4. Application Prospects

The "Tijieshi" intelligent stair-cleaning robot, with its innovative design and energy-saving and emission-reduction principles, is poised to play a significant role in multiple fields, demonstrating broad application prospects.

4.1 Market Prospects Analysis

4.1.1 Market Scale and Growth Potential

Stair-cleaning robot technology is transitioning from flat-surface cleaning to three-dimensional space management. It can address complex environments, such as multi-story buildings, through collaborative robotic arms or specialized stair-climbing mechanisms, resolving traditional cleaning blind spots. With the integration of intelligent sensing and AI technologies, its stability and adaptability to diverse scenarios continue to improve. The market is optimistic about its application potential in multi-story residential buildings, commercial complexes, and other areas. As technology matures and costs are optimized, its adoption rate is expected to further increase.

4.1.2 Driving Factors

(1) Policy Support: Government authorities are actively promoting policies to enhance public environmental hygiene standards, accelerating the installation and application of cleaning equipment in public spaces. This has created significant opportunities for the stair-cleaning robot market. For instance, regulations on improving hygiene management at urban rail transit stations have driven increased investment in cleaning equipment at subway stations, boosting demand for stair-cleaning robots as a key component. (2) Technological Innovation: With the continuous development and deep application of cutting-edge technologies such as AI and the Internet of Things (IoT), stair-cleaning robots have achieved qualitative leaps in intelligence. Remote monitoring functions allow managers to track the robot’s operational status in real-time via mobile or computer applications, accessing information such as cleaning paths and progress. Precise path-planning algorithms ensure efficient and thorough cleaning of stair areas, avoiding redundant cleaning or omissions, thereby significantly improving cleaning efficiency and quality, further stimulating market demand. (3) Demographic and Cost Pressures: As China’s aging population grows and the proportion of the labor force declines, labor costs continue to rise. Traditional stair-cleaning tasks in shopping malls, office buildings, and similar venues require substantial manpower and incur high costs. Stair-cleaning robots can effectively replace manual labor, enabling 24-hour continuous operation and significantly reducing operational costs, thus driving robust market demand.

4.2 Application Scenarios and Demand Structure

4.2.1 Commercial Dominance

Currently, commercial scenarios dominate the application of stair-cleaning robots, with large public venues such as shopping malls, subway stations, and airports accounting for over 70% of their usage. (1) Hospitals: As densely populated environments, hospitals require efficient stair cleaning while ensuring hygiene and safety. The "Tijieshi" robot offers a new cleaning solution, equipped with UVC ultraviolet lamps to disinfect stair handrails and steps, aiding in preventing pathogen transmission and contributing to a clean and safe hospital environment. (2) Office Buildings: Stairs in office buildings are frequently used, and manual cleaning is time-consuming and less efficient. The "Tijieshi" robot can perform automated cleaning tasks at preset times, achieving rapid sweeping and mopping of stair surfaces. It is expected to contribute to maintaining a clean and aesthetically pleasing office environment while reducing cleaning costs for businesses. (3) **Schools**: Stairs in schools are critical pathways for students and staff, making cleaning tasks essential. The "Tijieshi" robot can efficiently complete stair-cleaning tasks, providing a clean and tidy learning and living environment for students and faculty while minimizing disruptions to teaching activities caused by manual cleaning, thus enhancing the intelligent management level of campuses. (4) Shopping Malls and Retail Centers: Shopping malls and retail centers feature numerous stairs and high foot traffic, resulting in substantial cleaning workloads. The "Tijieshi" robot can navigate flexibly between staircases on different floors, performing rapid cleaning and disinfection, thereby supporting mall cleaning operations, enhancing the customer shopping experience, and reducing operational costs. (5) Nursing Homes: For elderly residents with limited mobility, the safety and cleanliness of stair areas are critical. The robot can perform stable and meticulous stair cleaning, reducing the risk of slips and other accidents for the elderly.

4.2.2 Growing Household Demand

With the upgrading of consumer spending, the demand for high-quality household cleaning has risen, driving the gradual penetration of stair-cleaning robots into residential scenarios. As product performance improves, prices become more affordable, and consumer awareness grows, the adoption rate in households is expected to continue expanding. This is particularly relevant for households with stairs, such as duplexes and villas, where stair-cleaning robots can alleviate cleaning burdens and meet the demand for convenient and efficient cleaning solutions.

4.3 Energy Saving, Emission Reduction, and Sustainability

In the context of global advocacy for energy saving, emission reduction, and sustainable development, the "Tijieshi" robot employs high-energy-density lithium batteries, offering long endurance and high energy efficiency. Its optimized design reduces energy waste and lowers consumption. Additionally, intelligent path planning and precise control algorithms further enhance energy utilization efficiency, minimizing unnecessary energy consumption. Moreover, the robot reduces reliance on chemical cleaning agents during operation, lowering environmental pollution and aligning with green principles, thus providing a reference for the green transformation of the cleaning industry.

4.4 Advantages of Intelligence and Cluster Management

The "Tijieshi" intelligent stair-cleaning robot is equipped with smart connectivity features, enabling remote control, status monitoring, and task scheduling via mobile applications or touchscreens. Its building-level collaborative system supports cross-floor scheduling of multiple robots, enabling cluster operations and improving cleaning efficiency. This advantage makes it highly valuable in large public venues and multi-story buildings, meeting the cleaning demands of complex environments and enhancing management efficiency and intelligence levels.

In summary, the "Tijieshi" intelligent stair-cleaning robot, with its high-efficiency cleaning, energy-saving and emission-reduction features, and intelligent control capabilities, is poised to play a significant role in public spaces, household markets, and sustainable development. It offers new perspectives for the cleaning industry and contributes to the realization of a green cleaning future.

Acknowledgments

This paper was supported by Student innovation and entrepreneurship training program of Southwest Minzu University (Project Number: 202510656033).

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