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Design and Research of a Low-Cost Intelligent Housekeeping Robot System Based on ROS2 and Multi-Sensor Fusion

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ABSTRACT: *With the acceleration of people's daily lives, household structures becoming smaller, and population aging deepening, household cleaning, environmental monitoring, and in-home care have become significant demands within the smart home domain. Addressing the problems of manual dependence for traditional cleaning tools, limited obstacle avoidance for common robotic vacuums, unfriendly interaction modes, and high costs for premium housekeeping services, this paper examines a low-cost intelligent housekeeping robot named "Huiwu Helper." We propose a system design that integrates cleaning operations, environmental perception, human–robot interaction, and smart home linkage. The system uses ROS2 as the software framework and combines a Mecanum-wheel omnidirectional chassis, multi-sensor fusion for obstacle avoidance, SLAM mapping, path planning, machine-vision-based dirt detection, and offline voice interaction to achieve autonomous mobility, dynamic obstacle avoidance, and targeted cleaning in complex indoor environments. This solution enhances the robot's adaptability to household scenes under constrained hardware budgets and offers a practical reference for low-cost intelligent housekeeping device development.*

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I. INTRODUCTION

In recent years, technologies for smart homes and service robots have advanced rapidly[1], and the demand for automation in household scenarios continues to grow[2]. Although routine domestic cleaning is not technically complex, it is repetitive, time-consuming, and often unpleasant[3]. Especially in dual-income households, single-occupant elder households, pet-owning homes, and small apartments, cleaning efficiency, environmental safety, and ease of operation remain unresolved by simple tools alone. Conventional cleaning tools require continuous user intervention; typical robot vacuums still struggle with low-profile obstacles[4], carpet adaptability, hair entanglement, and complex path planning; while premium housekeeping services are constrained by budget and scheduling, limiting their applicability as a universal household solution.

Against this background, intelligent housekeeping robots for home service scenarios hold clear research value[5]. Drawing on the "Huiwu Helper" project, this study focuses on a multifunctional integrated design for a low-cost hardware platform. The system not only performs sweeping and mopping tasks, but also integrates environmental monitoring, voice interaction, anomaly alerts, and smart home linkage to support multi-task, multi-object, and multi-user household needs. From a systems engineering perspective, the design integrates ROS2, SLAM, multi-sensor fusion, machine vision, and embedded control, aiming to demonstrate a practical approach to building low-cost service robots.

II. Overall System Architecture

The "Huiwu Helper" intelligent housekeeping robot centers on the triad of cleaning, monitoring, and interaction. The overall system comprises mechanical structure, hardware control, software algorithms, and human–machine interaction. The mechanical subsystem includes a Mecanum-wheel mobile base, cleaning actuators, sensor mounting, and a modular shell. The hardware control subsystem consists of the main controller, motor drivers, power management, sensor acquisition, a voice module, and communications hardware. The software stack is built on ROS2 with a layered control architecture responsible for mapping and localization[6], path planning, dynamic obstacle avoidance, and task scheduling. The human–machine interaction subsystem provides local voice control, LED status feedback, and a smartphone application for control and visual feedback.

System design must balance the complexity of household scenes with low user operation thresholds. Household environments introduce furniture legs, scattered cables, shoes, carpets, pet hair, and narrow passages; relying on a single sensor often leads to missed detections, false positives, or entrapment. Therefore, this design employs a hybrid perception scheme fusing vision, ultrasonic, infrared, and bumper sensors to improve environmental awareness. A Mecanum-wheel chassis enables lateral translation, in-place rotation, and tightradius maneuvers, making it well-suited to small apartments and cluttered areas. Offline voice commands and one-touch start features reduce operational barriers for the elderly and children.

Table 1 summarizes the system modules and their functions.

Module	Major Components	Function
Mobility chassis	Mecanum wheels, motors, drivers	Achieve omnidirectional movement, in-place rotation, and precise positioning
Environmental perception	Camera, ultrasonic, infrared, bump sensors	Detect obstacles, edges, and support obstacle avoidance
Cleaning actuators	Roller brush, water tank, mop, suction unit	Perform sweeping, mopping, and targeted cleaning
Control & decision	ROS2, SLAM, path planning	Handle mapping, localization, path generation, and task scheduling
HMI	Voice module, LEDs, smartphone app	Provide voice control, status feedback, and remote management
Environmental sensing	Temperature–humidity, PM2.5, formaldehyde, VOC sensors	Monitor indoor environment and trigger smart-home linkage

III. Mechanical Design and Hardware System

Mechanical design directly affects the robot's passability, stability, and maintainability in real households. We adopt a Mecanum-wheel omnidirectional chassis to enable sideways movement and zero-radius rotation, reducing path failures caused by insufficient turning space. The cleaning mechanism uses an integrated sweep-and-mop setup with a roller brush, mop plate, and water tank, and supports adjustable cleaning modes for different scenarios. For example, standard vacuuming is appropriate for general flooring, while greasy or watery kitchen spots trigger higher mop frequency and increased water flow. Pet-owning households require enhanced hair-collection capability and brush designs that minimize entanglement.

The hardware emphasizes low cost, extensibility, and serviceability. An STM32 or similar microcontroller can handle motor control, sensor sampling, and basic low-level execution, while an upper-layer compute platform runs ROS2 nodes, image processing, and path planning. Sensor placement balances field-of-view coverage and mechanical constraints: forward cameras recognize obstacles and dirty spots, ultrasonic sensors measure distance reliably, infrared sensors detect edges and nearby obstacles quickly, and bump sensors provide a final safety layer. Power management must trade off runtime, weight, and safety.

Compared with high-end commercial robots, this design prioritizes integration and algorithmic compensation over simply adding expensive sensors. Given limited compute and sensing budgets, the system improves performance through sensible mechanical layout, algorithmic optimization, and modular design. The modular approach simplifies maintenance and upgrades: users can replace the mop, water tank, brush, or specific sensors independently, lowering lifecycle costs.

IV. Navigation, Obstacle Avoidance, and Intelligent Cleaning Strategies

Navigation and obstacle avoidance determine the robot's ability to complete cleaning autonomously. The system builds a ROS2-based software framework that separates perception, localization, planning, execution, and interaction into cooperating nodes communicating via messages. In indoor settings, the robot uses SLAM to construct a map and localize itself; user-defined cleaning zones then drive global path generation. Global planning may use A* to find efficient traversable routes, while local planning adopts Dynamic Window Approach (DWA) or similar reactive planners to adapt motion in response to dynamic obstacles.

Multi-sensor fusion for obstacle avoidance is the core strategy for handling household uncertainty. Visual sensors are suitable for recognizing cords, footwear, and pet items but are vulnerable to lighting changes and occlusion; ultrasonic sensors provide stable distance measurements but struggle with small or soft objects; infrared sensors excel at near-range boundary detection; bump sensors serve as a final safety net. By aggregating these sensor streams, the robot can better distinguish traversable areas, low-profile obstacles, transparent barriers, and items that can cause entanglement, thereby reducing missed coverage, entrapment, and collisions.

For intelligent cleaning, the system incorporates machine-vision-based dirt detection to classify typical household dirt types such as dust, water stains, oil spots, and hair accumulations. Under constrained compute resources, the detection model should be lightweight; options include compact detection networks like YOLOv5n or highly pruned networks with quantization. Additional acceleration can be achieved via preprocessing and selective inference to reduce computation. When the system detects a heavy-dirt area, the cleaning decision module adjusts the cleaning path and parameters dynamically: the robot will intensify cleaning by repeating passes or increasing suction/mop action for heavily soiled zones while keeping standard parameters for regular areas, balancing cleaning efficacy and energy consumption.

V. Human–Machine Interaction and Smart Home Integration

Users of housekeeping robots are not limited to tech-savvy individuals. Interaction design must accommodate the elderly, children, and low-digital-literacy users. Our design blends offline voice control, LED status indicators, and a smartphone app so users can edit maps, schedule cleanings, and monitor tasks via the app, or invoke simple voice commands for start, pause, return-to-dock, and spot cleaning.

Offline voice recognition reduces dependence on cloud services and enables operation under unstable network conditions. LED-based emotional feedback improves intuitive understanding of the robot's status; for instance, steady lighting during normal cleaning, a distinct low-battery indicator, and flashing or voice prompts when the robot is stuck or requires maintenance. Such direct cues are especially useful in shared household spaces and are easier for elders and children to comprehend than app-only notifications. LED, voice, and app feedback should be designed around task states to give a coherent representation of whether the robot is cleaning, idle, returning to dock, faulted, or finished.

Smart home integration elevates the robot beyond a standalone cleaning device. With onboard environmental sensors (temperature–humidity, PM2.5, formaldehyde, VOC), the robot can collect spatially distributed environmental data while roaming and interact with other smart devices such as air purifiers, humidifiers, and HVAC systems. For example, when poor air quality is detected, the robot can issue a control command to a home automation platform to turn on an air purifier; low humidity can trigger a linked humidifier. In critical events such as smoke, gas leak, or extreme temperature, the robot can notify the user via the app and voice alarm. This mobile sensing capability transforms the robot into a spatially aware node of the smart home, improving overall environmental coverage.

VI. System Testing and Results Analysis

To validate feasibility, testing should evaluate mobility, obstacle avoidance, cleaning effectiveness, interaction responsiveness, and sensing stability. Test environments include typical living rooms, student dormitories, small offices, and pet activity zones, simulating open floors, narrow corridors, furniture-dense layouts, scattered cables, carpet edges, hair clumping, and water/oil stains. Evaluation metrics include cleaning coverage rate, obstacle avoidance success rate, entrapment frequency, average path length, noise level, runtime (battery endurance), voice recognition rate, and app command response latency. Multi-scenario testing yields more objective assessments of real-world readiness.

From expected performance, the Mecanum chassis improves maneuverability in tight areas; multi-sensor fusion reduces single-sensor induced misjudgments; the ROS2 architecture eases future algorithmic and functional extensions; and lightweight vision models make dirt detection feasible within limited compute constraints. Nonetheless, limitations persist in low-cost hardware contexts: limited compute power, sensor resolution, and mechanical robustness can hinder detection accuracy under complex lighting, transparent obstacle recognition, long-term hair entanglement, carpet climbability, and heterogenous smart-home protocol compatibility. These areas require iterative refinement and hardware–software co-design.

VII. Conclusion

This paper proposed a low-cost intelligent housekeeping robot design that integrates omnidirectional mobility, ROS2-based control, multi-sensor fusion, machine-vision cleaning decisions, age-friendly voice interaction, and smart-home linkage. The proposed system addresses routine household cleaning while offering environmental monitoring and simplified interaction, aiming to reduce operational complexity for diverse users. Although prototype validation and long-term field testing remain necessary, the architecture and integration strategies presented here are feasible for prototyping and provide a practical reference for subsequent product development and application research in household service robotics.

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