Design of an Adaptive Stair-Climbing Robot Based on Heterogeneous Dual-Core Intelligent Control Technology

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Abstract. With the deepening trend of societal aging, the demand for mobile robots in scenarios such as elderly assistance, disability aid, logistics, and rescue is growing. Navigating stairs in complex, unstructured environments has become a key challenge in robotics. Traditional wheeled, tracked, or legged robots suffer from weak adaptability, insufficient stability, or high cost. This paper designs an adaptive stair-climbing robot utilizing a heterogeneous dual-core control architecture built with an STM32H743 microcontroller and a Raspberry Pi 4B. It integrates multiple sensors including an RGB-D camera, an Inertial Measurement Unit (IMU), and encoders. The Raspberry Pi 4B serves as the upper-layer intelligent decision-making core, performing planning and decision-making through fuzzy logic and Model Predictive Control (MPC). The STM32H743 acts as the lower-layer real-time control core, achieving precise execution via PID control. The robot can adapt to stairs with slopes of 30°–45° and step heights of 150–200 mm made of different materials, maintaining a stability margin of no less than 20 mm during climbing. Compared to traditional tracked robots, the stability margin is improved by over 35%. The robot demonstrates good stability and robustness in various stair environments, providing an innovative technical approach for mobile robots in complex terrains.

Keywords: *Adaptive Stair-climbing Robot; Heterogeneous Dual-core Control; Multi-Sensor Fusion; PID Control*

1. Introduction

To address stair terrain, related research domestically and internationally has primarily focused on three categories of robots: wheeled, tracked, and legged. Wheeled mechanisms offer high efficiency but poor obstacle-crossing capability. Tracked mechanisms improve possibility to some extent but often lack stability during stair ascent, being prone to posture instability. Legged robots have the best environmental adaptability but are limited by complex control logic and high manufacturing costs [1]. The core performance differences among different types of mobile mechanisms are shown in Table 1. In recent years, the use of hybrid mobile mechanisms has become a research focus for such compromise solutions [3]. Although existing hybrid mechanisms balance movement efficiency and obstacle-crossing ability, most rely on pre-programmed gaits. In unknown stair environments, they exhibit algorithmic lag in dynamic center-of-gravity adjustment, with response delays commonly exceeding 80 ms. In contrast, a heterogeneous dual-core architecture can compress decision-making delays to within 50 ms. The multi-wheel-group mechanism combines the efficiency of wheeled systems with the obstacle-crossing capability of tracked systems, allowing flexible switching between wheeled and tracked modes, providing a solid mechanical foundation for adapting to stair terrain.

Most existing research focuses on mechanical structure improvements or relies on fixed gaits preset with stair parameters. When dealing with unknown or variable-parameter stair environments, the "perception-decision-adaptation" intelligent control capability of such solutions remains insufficient. Embedding an intelligent system into a multi-wheel-group mobile platform to endow it with autonomous adaptation capability is key to solving the problem.

Table 1. Performance comparison of different mobile mechanisms for stair climbing.

Mobile Mechanism Type	**Movement Efficiency**	**Obstacle-Crossing Capability**	**Stair-Climbing Stability**
Wheeled Mechanism	High	Weak	Poor (Prone to Slipping)
Tracked Mechanism	Medium	Medium	Fairly Poor (Prone to Instability)
Legged Mechanism	Low	Strong	Good
Hybrid Mechanism	Medium	Medium	Average
Adaptive Multi-Wheel-Group Mechanism	Medium-High	Strong	Excellent

This paper proposes an innovative "heterogeneous dual-core intelligent control + multi-sensor fusion" solution, developing an adaptive stair-climbing robot. The heterogeneous dual-core architecture balances real-time control and intelligent decision-making. The upper layer uses a fuzzy control algorithm, which does not rely on an accurate mathematical model, to achieve dynamic decision-making. The lower layer uses PID control for accurate execution. The aim is to endow the robot with autonomous adaptation capability in unknown stair environments, overcoming the limitations of traditional solutions, and providing a new approach for autonomous robot navigation in unstructured environments.

2. Overall Design of the Adaptive Stair-Climbing Robot

The adaptive stair-climbing robot system is a complex system integrating mechanics, electronics, control, and information processing. Its overall design follows the principles of modularity, intelligence, and high reliability. The entire system consists of three core modules: the mechanical body module, the sensing and actuation module, and the heterogeneous dual-core intelligent control module. The overall framework diagram is shown in Figure 1, illustrating the information and control flow from environmental perception to motion execution.

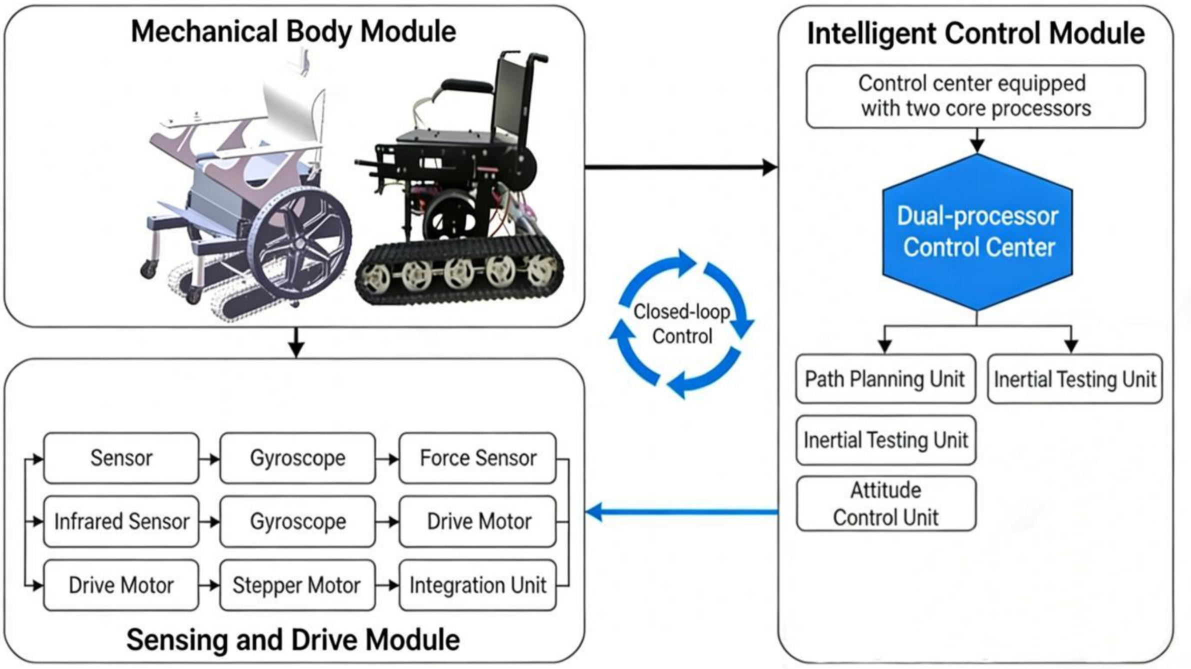

Figure 1. Overall system framework diagram.

2.1. Mechanical Body Module

The mechanical body is the physical carrier of the robot, as shown in Figure 2.

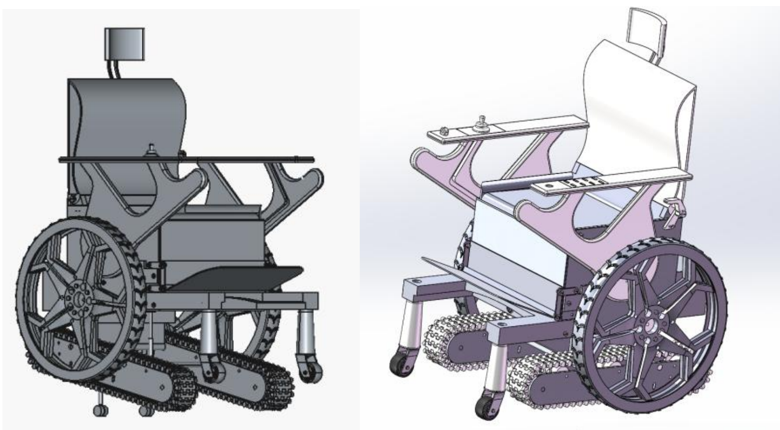

Figure 2. Rendering of the adaptive stair-climbing robot.

It adopts a multi-wheel-group mobile mechanism that combines the efficiency of wheeled systems with the obstacle-crossing ability of tracked systems. The mechanism consists of 4 symmetrically distributed wheel groups. Each wheel group integrates a driving wheel, auxiliary support wheels, and an elastic tensioning component. Based on feedback from step contact, it can automatically adjust the support angle and tension of the wheel groups, ensuring multiple support points provide stable support force during climbing. This retains the high movement efficiency of wheeled mechanisms while possessing the strong obstacle-crossing capability of tracked mechanisms, effectively preventing tipping over [4].

2.2. Sensing and Actuation Module

The sensing and actuation module is the "nerves" and "muscles" for the robot to perceive the environment and execute actions. It includes a depth vision sensor (e.g., RGB-D camera) for detecting the distance, angle, and step height of stairs ahead; an Inertial Measurement Unit (IMU) for measuring changes in the robot's own posture; encoders for feeding back the actual positions of joints; and DC servo motors or steering gears as power outputs. The core perception task, undertaken by the RGB-D camera for stair environment detection, requires accurate identification and parameter extraction of stair targets. The complete logical flow for stair target detection is shown in Figure 3. This process takes color images and depth point cloud data as input, achieves stair contour segmentation and key parameter fitting through multi-stage processing, and obtains reliable environmental perception data. Based on this, the robot makes adaptive stair-climbing decisions [5].

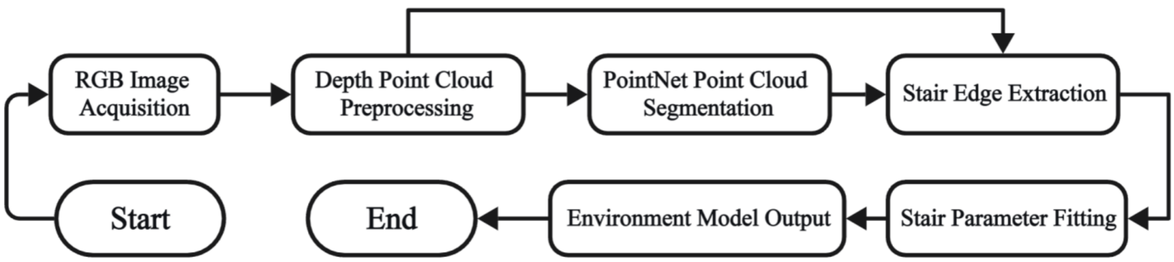

Figure 3. Flowchart of stair target detection.

2.3. Heterogeneous Dual-Core Intelligent Control Module

The heterogeneous dual-core intelligent control module is the intelligent core of the entire robot, adopting a dual-processor structure with different architectures. The implementation flow is shown in Figure 4. The STM32H743 microcontroller serves as the real-time control core, running the RT-Thread operating system. Its main functions are time-sensitive basic operations, millisecond-level motor servo control, and rapid collection and filtering of multi-channel sensor signals. In contrast, the more powerful Raspberry Pi 4B, running the ROS (Robot Operating System), handles computationally intensive intelligent decision-making tasks such as environmental recognition, multi-sensor data fusion, and real-time motion planning. The two cores communicate in real-time via a high-speed serial interface (UART), continuously exchanging control commands and system states, forming a perfect closed-loop autonomous control cycle from perception to decision-making and execution, endowing the robot with both rapid reflex capability and complex reasoning ability.

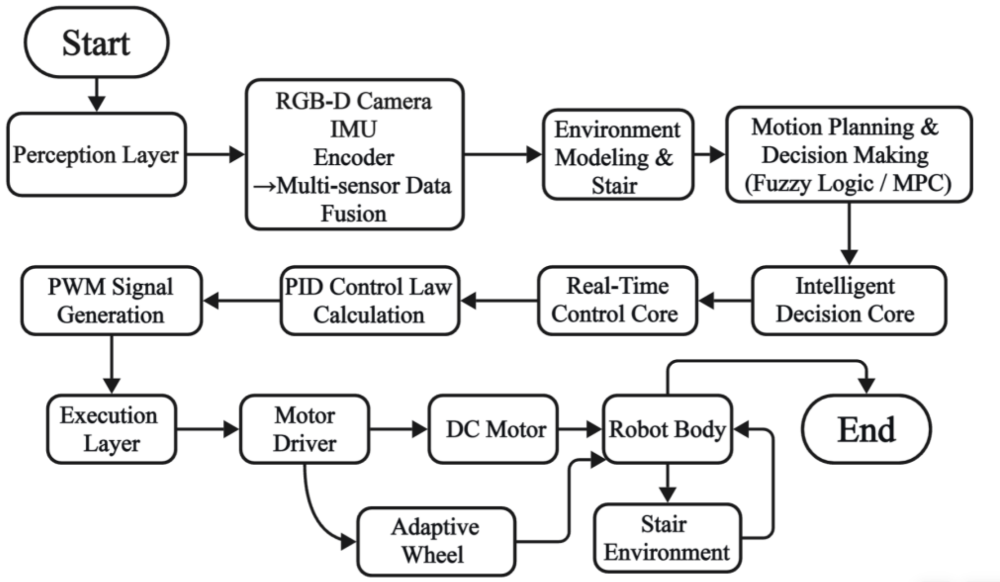

Figure 4. Flowchart of the heterogeneous dual-core intelligent control module.

3. Robot Mechanical Structure and Motion Mechanism

3.1. Adaptive Walking Mechanism

The multi-wheel-group mobile mechanism, which fuses wheeled efficiency and tracked obstacle-crossing ability, is the foundation for realizing the robot's stable stair-climbing function. This mechanism abandons the structural limitations of traditional single wheeled or tracked designs. It employs 4 independently driven wheel group units arranged in a rectangular array on both sides of the body. Each wheel group unit includes an 80 mm diameter polyurethane driving wheel, auxiliary support wheels, and an elastic tensioning link rod with a stroke of 0-120 mm. A torque sensor (model: TJH-803) at the wheel group pivot triggers wheel group posture adjustment.

When a wheel group contacts the vertical face of a step and the pressure exceeds a set threshold of 5 N, the equivalent motor (JGA25-370) activates, actively lifting the wheel group to form a stable temporary auxiliary support point. The other wheels continue moving smoothly to push the body forward. After the wheel group completely crosses the vertical face and lands on the step tread, the tensioning link automatically resets. Through this physical interaction-based feedback and independent switching, the robot achieves dynamic adaptation. Without relying on complex external sensor systems, it balances the efficiency of wheeled mechanisms and the multi-support-point obstacle-crossing capability of tracked systems through natural interaction between wheel groups and steps, demonstrating flexibility in adapting to steps of varying heights and slopes.

3.2. Kinematics and Stability Analysis

To quantitatively analyze the robot's motion, a simplified kinematic model was established. Let the projection of the robot's center of gravity on the horizontal plane be $G(x_g, y_g)$, and the contact points of each wheel group with the ground be $P_i(x_i, y_i),\ i = 1,2,3,4$. During stair climbing, the robot's static stability margin SM can be defined as the minimum value of the shortest distances from the center of gravity G to each side of the current support polygon.

$$SM = imindistance\big(G, edge\ i(Polygon)\big)$$

The robot is statically stable only when $SM > 0$. In dynamic processes, dynamic stability must be evaluated by calculating the Zero Moment Point (ZMP) or the rate of tilt angle change, combined with IMU data. The wheel group alternating support strategy designed in this paper aims to actively maintain a large support polygon, keeping SM above a safe threshold throughout the climbing process.

To achieve precise tracking of the preset trajectory and accurate control of the motor driving torque, it is necessary to establish the system's kinematic and dynamic models. In kinematics, the D-H parameter method is used to establish coordinate systems, with the base at the body center and links at each wheel group joint. Deriving the forward kinematics equation relates joint variables such as wheel group speed and tensioning angle to the robot's overall pose (position, orientation), providing the basis for the inverse solution in multi-wheel-group coordinated trajectory planning. In dynamics, a system dynamic model is constructed based on the Lagrange equation, focusing on analyzing the force balance relationships during different phases such as wheel group contact with steps and lifting for obstacle crossing. This includes the robot's own gravity, inertial forces generated by motion, ground contact reaction forces, and motor driving torques, estimating the peak torque requirements for each joint. This provides theoretical support for motor selection and parameter tuning of the underlying PID controller.

In actual control, simplified forms of these models are used for real-time prediction and planning by the upper-layer Raspberry Pi decision core.

3.3. Obstacle-Crossing Stability and Posture Adjustment

During stair climbing, stability is the primary condition for ensuring task success and the robot's own safety. The special stair environment causes the robot's center of gravity position to continuously change with climbing height, which can easily lead to forward/backward or lateral tipping. Therefore, obstacle-crossing stability analysis and active posture adjustment strategies are key links in the overall design. The robot's posture adjustment strategy is shown in Figure 5, achieving stable climbing by dynamically adjusting support point positions. The robot's stability is quantitatively assessed by calculating the position of the center of gravity within the support polygon; this assessment metric is the static stability margin. For dynamic processes like climbing, professional concepts such as the Zero Moment Point (ZMP) must also be considered [8]. The core feature of the adaptive walking mechanism designed in this paper is multi-point alternating support, which actively maintains a large stable support area. Cooperating with the heterogeneous dual-core control system, the intelligent decision core solves relevant data in real-time, including body tilt angle and angular velocity information from the IMU, and support leg position information from joint encoders. Based on this data, it dynamically calculates the robot's real-time center of gravity and stability margin. The Raspberry Pi 4B then generates motion trajectories and posture compensation commands according to the calculation results and sends them to the real-time control core via the UART asynchronous serial port. The real-time control core communicates with peripherals like the IMU and encoders using the SPI interface, effectively ensuring high-speed acquisition of underlying sensor data. The real-time control core utilizes its high timer resolution to execute high-speed PID control algorithms, converting received commands into precise PWM driving signals for each joint motor, ultimately achieving motion tracking and dynamic stability.

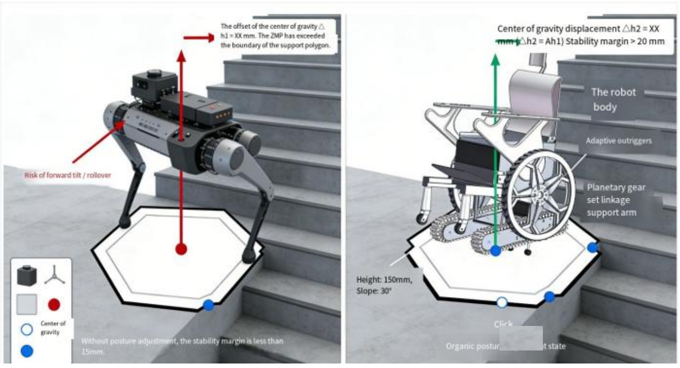

Figure 5. Posture adjustment strategy comparison diagram.

4. Design of the Heterogeneous Dual-Core Intelligent Control System

4.1. Heterogeneous Dual-Core Hardware Architecture and Task Allocation

The hardware architecture of the dual-core intelligent control system is the foundational platform for achieving high-performance control. The specific hardware configuration, task division, and key performance parameters are shown in Table 2.

Table 2. Hardware task division of the heterogeneous dual-core control system.

Core Type	Processor Model	Operating System	Response Time	Interface Connected To
Real-Time Control Core	STM32H743 (ARM Cortex-M7)	RT-Thread	Microsecond level (≤10 μs)	Motor drivers, joint encoders, IMU
Intelligent Decision Core	Raspberry Pi 4B (ARM Cortex-A72)	Linux + ROS Noetic	Millisecond level (≤50 ms)	RGB-D camera, Real-Time Control Core

This design adopts a heterogeneous dual-processor solution, with the real-time control core focusing on "fast response and precise execution" and the intelligent decision core focusing on "complex data processing and dynamic decision-making." Figure 6 visually presents the collaborative hardware foundation of the heterogeneous dual cores.

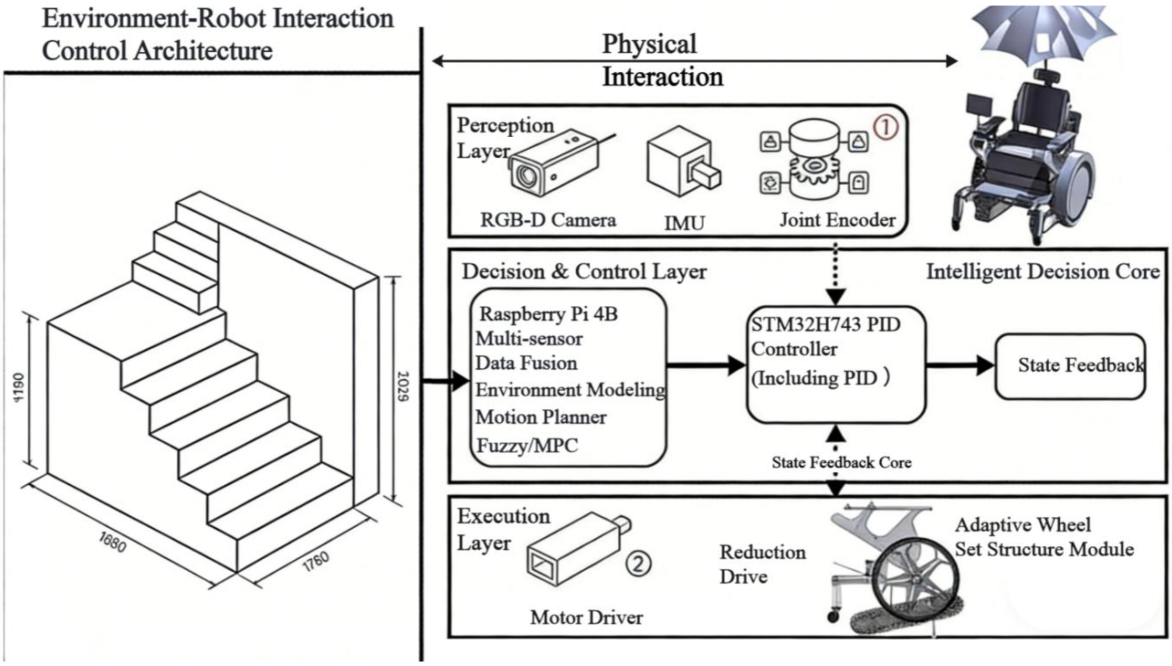

Figure 6. Hardware architecture and task allocation diagram.

The real-time control core uses an STM32H7 series microcontroller with an ARM Cortex-M7 core. Its specific pin assignment and hardware connection design are shown in Figure 7. Its maximum main frequency can reach 480 MHz, and it possesses abundant timer/PWM output channels and nanosecond-level interrupt response capability, fully meeting the stringent "low latency, high precision" requirements of underlying control. The core connects directly to hardware devices such as hub motor drivers, wheel pair encoders, and the IMU via high-speed General Purpose Input/Output (GPIO) and Serial Peripheral Interface (SPI). It runs underlying programs on the lightweight real-time operating system (RT-Thread) to receive speed/position feedback signals from wheel pair encoders, complete the closed-loop PID control of hub motors ensuring precise tracking of multi-wheel-group motion trajectories; and perform filtering preprocessing on the raw three-axis acceleration and angular velocity data collected by the IMU to reduce noise interference. It parses target posture commands and wheel group power distribution commands issued by the intelligent decision core, converting them into specific driving PWM signals to achieve coordinated motion control of each wheel group motor.

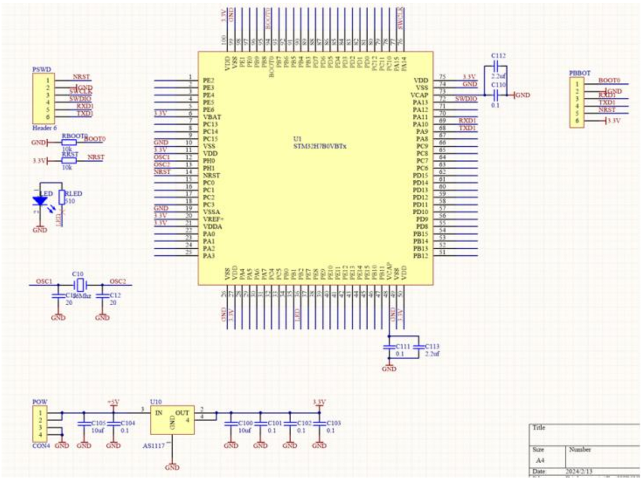

Figure 7. Hardware diagram of STM32H743 core pins.

The intelligent decision core is selected from the ARM Cortex-A series application processors, specifically the Raspberry Pi 4B. Its quad-core Cortex-A72 processor offers strong computing performance, capable of running the Linux operating system and ROS Noetic (Robot Operating System) smoothly, providing hardware support for deploying complex algorithms. The core is responsible for non-real-time but highly complex intelligent processing tasks. It receives color images and depth data from the RGB-D camera via a USB 3.0 interface, then fuses preprocessed IMU data and encoder feedback on actuator status information. Using multi-sensor data fusion algorithms, it constructs a "robot-environment" combined state model. The system can identify key environmental parameters such as stair slope, step height/depth, generate adaptive multi-wheel-group coordinated motion trajectories for the current environment, and immediately generate compensation commands if posture deviation risks are detected, sending them to the real-time control core.

The two cores achieve bidirectional communication via a high-speed asynchronous serial port (UART) at a data transmission rate of 115200 bps. This communication method forms a classic closed-loop solution for heterogeneous dual-core robots, enabling a 10 μs state data upload and a 50 ms command issuance response [4]. The real-time control core uploads state information such as motor speed, body tilt angle, and trajectory position collected by sensors every 10 μs, providing a dynamic data foundation for intelligent decision-making. The intelligent decision core issues updated motion and posture correction commands every 50 ms, which the real-time control core quickly responds to and executes.

This separation of responsibilities avoids potential performance conflicts between real-time control and complex decision-making tasks within a single processor. Efficient communication achieves overall coordinated control, providing stable hardware support for the robot's stair climbing and environmental adaptation.

4.2. Sensor Data Fusion and Environmental Modeling

Accurate perception of the environment is a prerequisite for the robot's autonomous adaptive climbing. The multi-modal sensors on the robot provide complementary environmental information. The RGB-D camera acquires color images and depth information from the environment in front of the robot [10]. With the help of point cloud processing algorithms, stair surfaces can be segmented, and stair step heights and depths can be extracted to build a geometric model of the stairs ahead. The IMU provides the robot's body three-axis acceleration and three-axis angular velocity. Through attitude calculation algorithms (such as complementary filtering or Kalman filtering), the robot's pitch and roll angles relative to the direction of gravity can be estimated in real-time, which are key parameters for assessing body posture stability. In complementary filtering, the low-pass filter cutoff frequency for IMU accelerometer data is set to 5 Hz, and the high-pass filter cutoff frequency for gyroscope data is set to 0.5 Hz. By fusing attitude data with a weighting coefficient k=0.98, noise interference on tilt detection is effectively reduced. Joint encoders accurately feedback the rotation angle or extension length of each adaptive leg. Combined with the robot's kinematic model, the pose of the robot chassis relative to support points can be derived.

The data fusion center on the Raspberry Pi 4B (intelligent decision core) deeply fuses visual data collected from the local RGB-D camera with the IMU attitude data and detailed encoder information preprocessed and acquired in real-time by the real-time control core (STM32H743) via the SPI bus [5], constructing an integrated robot-environment state model. The model flowchart is shown in Figure 8.

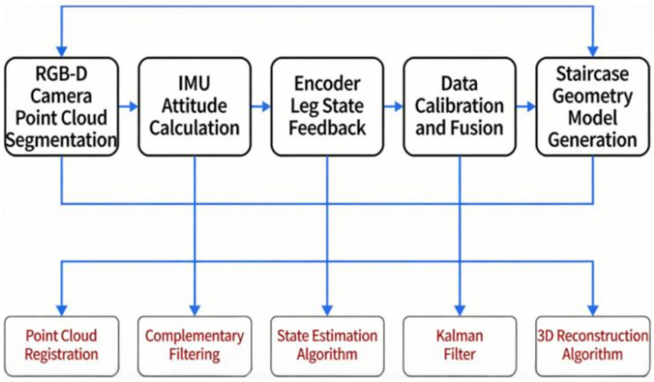

Figure 8. Flowchart of multi-sensor data fusion.

4.3. Adaptive Motion Planning and Stability Control Algorithm

Based on the integrated environmental state model, the core algorithms for adaptive motion planning and stability control operate. Motion planning generates a reference path for safely traversing all steps from the current position according to identified stair parameters (slope, step height/depth) and the robot's kinetic constraints, planning differentiated motion sequences for multiple wheel groups. As shown in Figure 9, to accurately convert the reference trajectory into motor operation commands, the system adopts a dual closed-loop control strategy.

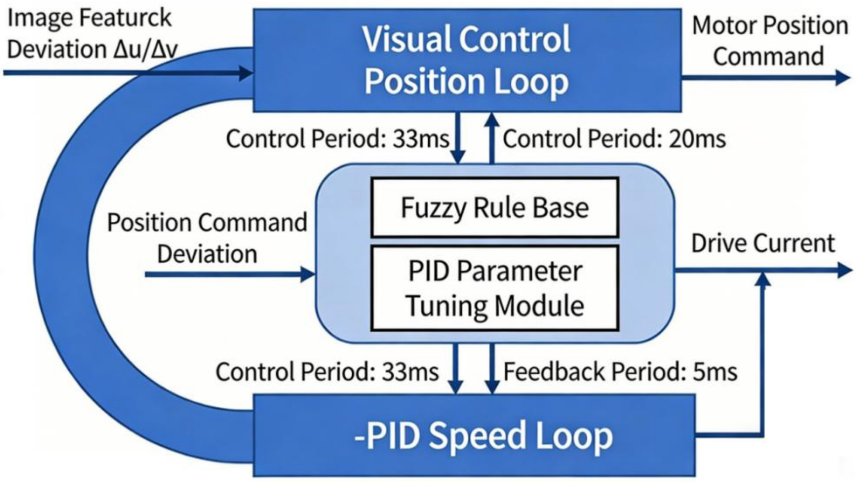

Figure 9. Flowchart of the dual closed-loop control.

The trajectory planner determines the movement path (position and orientation) of the robot base and the motion sequence for adjusting each leg (when to lift, lower, and anticipate) based on the area [11]. Because the stair environment may have uncertainties, the planner needs online re-planning capability to cope with updated situations or emergencies. The stability control algorithm works closely with the planner, operating as a supervisory and compensation layer. It continuously monitors the real-time stability margin calculated from IMU data and the kinematic model, specifically as shown in Figure 10. The logic between the upper and lower layers of the algorithm is annotated, indicating command interaction and compensation mechanisms between the two layers, reflecting the layered collaboration of the algorithm.

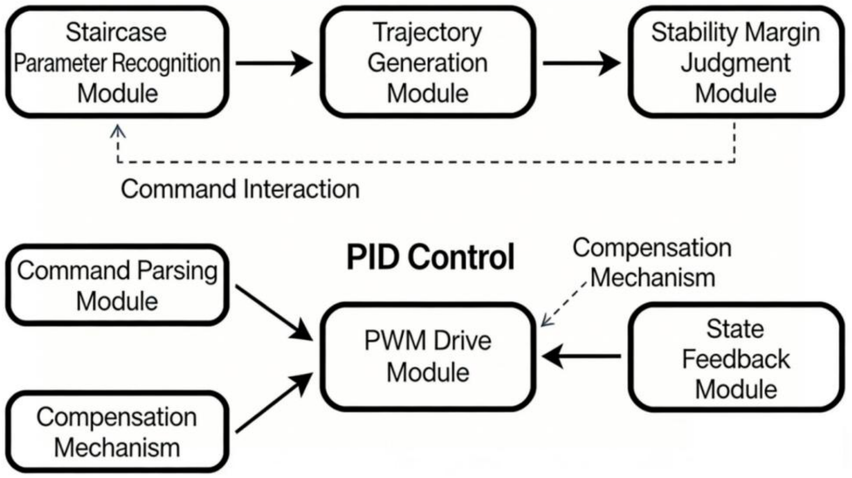

Figure 10. Closed-loop diagram of adaptive motion planning and stability control algorithm.

4.4. Experimental Verification

To verify the performance of the adaptive stair-climbing robot designed in this paper in complex stair environments, a multi-scenario test platform was built. Tests selected common stair types in civil buildings and simulated extreme scenarios such as wet, slippery, and irregular steps. Test indicators included average climbing speed, stability margin, and continuous stair-climbing success rate. Each group of tests was repeated 3 times, with the final result being the average value. The selection of test scenarios referenced the application requirements for elderly and disabled assistive robots. Specific test parameters and results are shown in Table 3.

In the standard stair scenario, the robot achieved a 100% success rate, maintaining a stability margin above 20 mm. Through coordinated adjustment of multiple wheel groups, fluctuations in body tilt angle were controlled within ±3°, demonstrating good stability performance. In complex scenarios such as irregular and slippery stairs, the robot's average ascent speed decreased, but the stability margin still met safety requirements, with a continuous climbing success rate of no less than 90%. Experimental results indicate that the mechanical structure and heterogeneous dual-core intelligent control strategy designed in this paper can effectively adapt to different types of stair environments, verifying the effectiveness and practicality of the proposed solution.

Table 3. Stair-climbing performance test results.

Test Stair Type	Step Height (mm)	Step Slope (°)	Surface Material	Average Climbing Speed (m/s)	Stability Margin (mm)	Climbing Success Rate (%)
Residential Standard Stairs	150	30	Concrete	0.22	28	100
Public Building Wide Stairs	180	35	Ceramic Tile	0.18	25	100
Worn Irregular Stairs	160 (±15)	32	Marble	0.15	22	97
Simulated Slippery Stairs	170	38	Floor Tile	0.13	20	95

5. Conclusion

This paper presents an adaptive stair-climbing robot based on heterogeneous dual-core intelligent control technology. It integrates a multi-wheel-group mechanical structure combining wheeled efficiency and tracked obstacle-crossing ability with a layered control system, addressing the pain point of poor adaptability of traditional robots in complex stair environments. The dual-core architecture balances real-time control and intelligent decision-making, ensuring environmental perception accuracy. Experiments have verified the stability and practicality of the solution, providing an innovative solution for the development of mobile robots in complex terrains.

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References

[1] Luo, W., Zhang, C., et al. (2025). 移动机器人路径规划算法体系综述与展望 [A Review and Future Outlook of Path Planning Algorithm Systems for Mobile Robots]. *Computer Engineering and Applications*, 1-18. https://link.cnki.net/urlid/11.2127.TP.20251230.1853.014.[in Chinese]

[2] Song, X., Zhang, Y., Dong, T., & Li, F. (2025). DHRN: A robot autonomous navigation

method in crowds based on heterogeneous framework. *Neurocomputing*, 132375.

[3] Shen, Z., Wang, R., Wang, L., Lu, W., & Wang, W. (2025). Application Research on General Technology for Safety Appraisal of Existing Buildings Based on Unmanned Aerial Vehicles and Stair-Climbing Robots. *Buildings*, 15(22), 4145.

[4] Shao, C. (2025). 基于 STM32H743 的无刷直流电机 FOC 自动化控制系统设计 [Design of an FOC Automatic Control System for Brushless DC Motors Based on STM32H743]. *Automation & Instrumentation*. (09), 73-77. https://doi.org/10.14016/j.cnki.1001-9227.2025.09.073.[in Chinese]

[5] Yang, D. (2024). 消防爬楼运输机器人研究与设计 [Research and Design of a Fire-Fighting Stair-Climbing Transport Robot]. *Modern Manufacturing Technology and Equipment*, 60(12), 84-86. https://doi.org/10.16107/j.cnki.mmte.2024.0840.[in Chinese]

[6] Zhao, J. (2024). 基于多传感器融合的地面移动机器人定位方法研究 [Research on Positioning Methods for Ground Mobile Robots Based on Multi-Sensor Fusion]. Chongqing University. https://doi.org/10.27670/d.cnki.gcqdu.2024.001574.[in Chinese]

[7] Zheng, P. (2023). 基于多传感器融合的移动机器人定位和路径规划方法研究 [Research on Positioning and Path Planning Methods for Mobile Robots Based on Multi-Sensor Fusion]. *Southeast University*. https://doi.org/10.27014/d.cnki.gdnau.2023.004282.[in Chinese]

[8] Xiao, Y. (2023). 可重构移动机器人多模态运动控制关键技术研究 [Research on Key Technologies of Multi-Modal Motion Control for Reconfigurable Mobile Robots]. *Chongqing University.* https://doi.org/10.27670/d.cnki.gcqdu.2023.002758.[in Chinese]

[9] Su, L., Zhang, L., Shao, J., et al. (2023). 楼梯清洁机器人的爬楼规划研究[Research on Stair-Climbing Path Planning for Stair-Cleaning Robots]. Journal of Jiangxi Normal University (Natural Science Edition), 47(1), 77-81. https://doi.org/10.16357/j.cnki.issn1000-5862.2023.01.10. [in Chinese]

[10] Zhang, J., Wang, Z., Zhang, Y. (2022). ADAMS 的电梯载荷测试机器人稳定性仿真 [Stability Simulation of Elevator Load Testing Robots Based on ADAMS]. *Mechanical Management and Development.* 37(07), 11-14. https://doi.org/10.16525/j.cnki.cn14-1134/th.2022.07.004.[in Chinese]

[11] Chen, Y., Li, Y. (2022). 驱动式多功能助老爬楼机设计 [Design of a Driven Multi-Functional Stair-Climbing Machine for Elderly Assistance]. Development & Innovation of Machinery & Electrical Products. 35(04), 54-56.

[12] Li, R., Xiao, Z., Chen, G. 基于曲柄摇杆机构的多足爬楼机器人设计 [Design of a Multi-Legged Stair-Climbing Robot Based on a Crank-Rocker Mechanism]. *Modern Manufacturing Technology and Equipment*. 58(07), 70-72. https://doi.org/10.16107/j.cnki.mmte.2022.0468.[in Chinese]

[13] Sun, S., Zhai, Z., Chen, L., et al. (2026). 基于 Arduino 的老人和儿童家庭服务机器人 [A Home Service Robot for the Elderly and Children Based on Arduino]. *Mechanical & Electrical Engineering Technology*. 1-8. https://link.cnki.net/urlid/44.1522.TH.20251217.1623.003.

[14] He, L., Chen, Y., Qi, J. (2025). 基于激光雷达-IMU 双层耦合的移动机器人位姿估计 [Mobile Robot Pose Estimation Based on LiDAR-IMU Double-Layer Coupling]. Computer Applications and Software. 42(12), 65-70.

[15] Duan, H. (2025). 基于多传感器数据融合的工业机器人运动路径规划研究 [Motion Path Planning for Industrial Robots Based on Multi-Sensor Data Fusion]. *Die & Mould Manufacture*. 25(12), 198-200. https://doi.org/10.13596/j.cnki.44-1542/th.2025.12.067.[in Chinese]