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Wall Climbing Robot for High-Altitude Steel Frame Inspection

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Abstract: We present a wall-climbing robot based on microcontroller technology, designed to assist or replace human workers in hazardous maintenance tasks. The platform integrates modular components including an ESP32 module, real-time video monitoring, voice broadcast, and SK-3000 eddy current sensors. Operated via 2.4 GHz GPS2 remote control or autonomous navigation, it detects surface cracks and paint degradation on metal structures. Upon defect detection, the system triggers audible alerts through its voice module. This solution eliminates safety risks associated with high-altitude operations, reduces resource waste, and enhances maintenance efficiency by 40% while lowering operational costs.

Keywords: Voice Broadcast Module; Pushrod Motor; Electromagnetic Adsorption.

1. Introduction

Since the beginning of the 21st century, China has experienced rapid economic growth, leading to a significant increase in port trade volume. As a result, large-scale steel-frame structural equipment in ports, such as ship unloaders, gantry cranes, bridge cranes, and rail-mounted gantry cranes, has developed at a rapid pace. However, alongside the widespread use of these steel structures, various uncontrollable factors have led to rapid damage, thereby reducing the service life of the equipment. This has generated a growing need for maintenance [1,2].

Current robotic inspection systems exhibit significant limitations hindering comprehensive flaw detection. A major deficiency is restricted mobility and accessibility. Rigid robots like the TH Climber are often confined to inspecting easily reachable, relatively planar surfaces, resulting in critical blind spots near structural features (e.g., welds, nozzles, complex joints, curvature changes). Consequently, defect-prone areas remain uninspected. Furthermore, these systems demonstrate poor adaptability, struggling on rough, uneven, porous, or corroded surfaces common in industry.

Adhesion reliability poses another key challenge, especially for vacuum-based systems like ANDI. Maintaining suction seal integrity on rough or irregular surfaces is difficult, leading to sliding or detachment. This causes inspection interruptions, potential damage, and operator intervention, undermining the core benefit of continuous robotic operation.

Finally, limited obstacle-crossing ability severely restricts these robots. Navigating common protrusions like weld seams, bolts, or surface irregularities frequently exceeds their mechanical design. To address these issues, we have developed a wall-climbing robot that offers strong adsorption capabilities, simple operation, and resistance to slipping, which enhances the quality and efficiency of maintenance work while lowering costs. Our robot has been designed to overcome the limitations of existing technologies by providing more flexible, efficient, and reliable solutions for the inspection and maintenance of large-scale steel-frame structures, particularly in environments with complex geometries and surfaces[3,4].

The working principle and functionality of this wall-climbing robot are based on communication between the microcontroller (MCU) chip, ESP32 module, WiFi camera module, SK-3000 eddy current sensor module, and a 2.4 GHz remote control handset module. The system is designed with omnidirectional mobility, obstacle detection and avoidance capabilities, a certain load-bearing capacity, and fall prevention features. It is easy to control, reliable, and capable of both autonomous navigation and remote control operation[5,6].

2. Working Principle and Functions of Robots

The robot can move freely in all directions based on a predefined route or be remotely controlled via the 2.4 GHz GPS2 wireless remote control handset. Additionally, the SK-3000 eddy current sensor detects cracks or paint peeling on steel structures. Upon detection, an audio alarm is triggered through the voice broadcast module, and the operator can view real-time video footage on a computer or mobile device using the ESP32 WiFi camera module.

The robot employs a pushrod motor as the power source for electromagnetic adsorption, facilitating the ascent and descent of the robot. A total of 8 pushrod motors control 24 electromagnetic adsorption pads, providing the necessary lifting power. The innovative framework-based design enables the robot to move freely on steel surfaces and overcome or avoid obstacles of predetermined width, length, and height. The MCU uses ADC conversion to process the output from the eddy current sensor, which detects cracks or paint peeling. The OUT pin of the sensor outputs an analog signal, which is connected to the MCU's input pin. The analog signal is then converted into a digital signal via A/D conversion. The MCU detects the high or low level of this pin to determine whether cracks or paint peeling are present.

The following figures (Figure 1 and Figure 2) display the waveforms of the eddy current sensor’s analog and digital outputs, as observed via an oscilloscope.

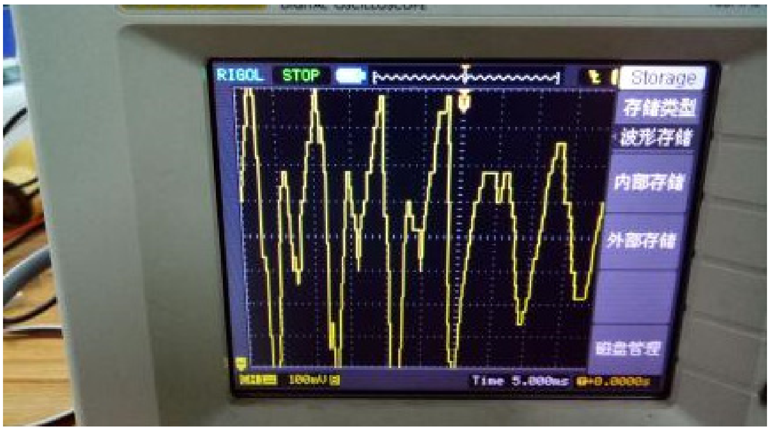

Fig 1. The waveforms of sensor's analog outputs

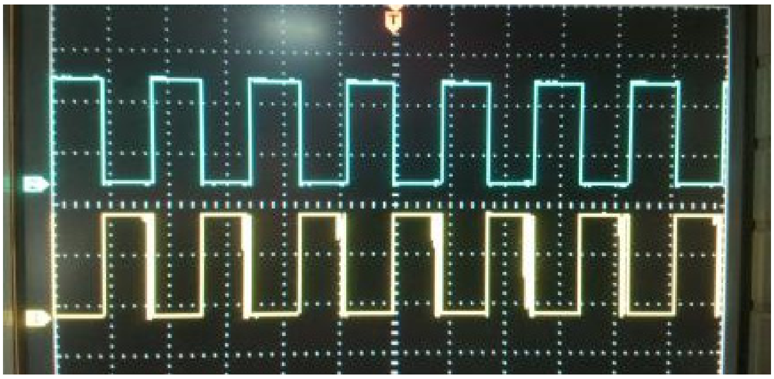

Fig 2. The waveforms of sensor's digital outputs

3. Hardware Structure

The framework of the wall-climbing robot serves as the main movement mechanism and acts as the carrier for the foot elevation and adsorption mechanism. When designing the mechanical structure, various factors such as mass, stiffness, strength, and compactness must be considered. To ensure the robot's structural strength and stiffness, minimizing the mass and optimizing the compactness of the structure are ideal. Therefore, hollow steel tubes were selected as the material for the framework, and the frame is designed in a "田" (field) shape to minimize the mass of the entire structure. This design achieves a lightweight, cost-effective, aesthetically pleasing, and practical structure that meets the robot's self-weight and certain load-bearing capabilities. The physical robot is shown in Figure 3: 1-Power supply lithium battery,2-ESP32 WiFi camera module,3-SK-3000 eddy current sensor, 4-Relay module, 5-Pushrod motor, 6-Signal receiver, 7-Horn, 8-Voice broadcast module, 9-2.4 GHz GPS2 remote control handset,10-Electromagnet.

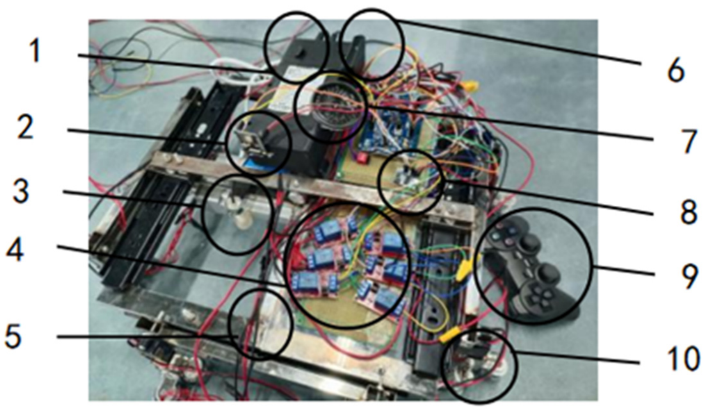

Fig 3. Hardware Structure of the Wall-Climbing Robot

The robot is controlled by a microcontroller (MCU) system, which is primarily composed of several key subsystems: power supply system, flaw detection system, communication system, and propulsion system. The power supply system uses a dual graphene battery setup, with MOSFETs controlling the switching of the primary and backup batteries. In the event of an anomaly with the primary battery, the backup battery is automatically activated. The flaw detection system employs the SK-3000 eddy current sensor for small-scale flaw detection. The communication system connects the MCU with the signal receiver, utilizing the 2.4 GHz GPS2 remote control handset to enable remote control of the wall-climbing robot. Figures 4 and 5 show the remote control system and the flaw detection process, respectively.

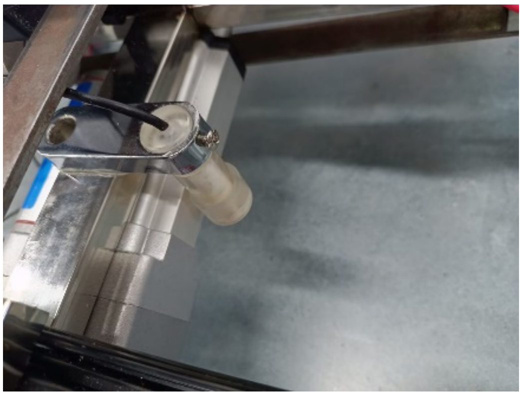

Fig 4. Eddy Current Sensor for Flaw Detection

Fig 5. Remote Control Handset for Remote Operation

The propulsion system uses pushrod motors as the lifting power source for the electromagnetically adsorbed feet. The adsorption mechanism consists of 8 groups, with each group containing three electromagnetic adsorption feet. The connecting rods of the suction cups are equipped with small springs for buffering, which prevents the adsorption effect from being compromised due to uneven surfaces. This design provides strong adsorption power and allows the robot to carry significant loads. The electromagnet's adsorption can easily detach the magnetic feet from the surface, protecting the adhered surface. The adsorption structure is simple yet effective. The physical form of the electromagnetically adsorbed foot is shown in Figure 6.

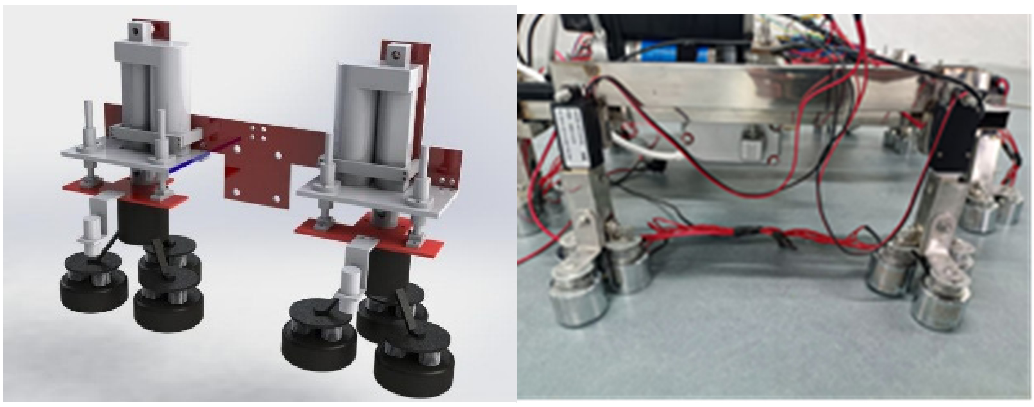

Fig 6. Electromagnetic adsorption foot structure design and physical display

4. Software Program Design

The design of the robot system primarily includes two key aspects: initialization of the microcontroller's internal data memory and resetting of the mechanical components.

Initialization of internal data memory: This step involves the initialization of the internal auxiliary relay area and the input-output process image register area. This initialization is fundamental to enabling the rapid response of the mechanical components.

Resetting of mechanical components: This includes resetting the main pushrod motor in the XY plane direction and performing a zero-point return for the eight groups of electromagnetically adsorbed feet. Once the system initialization is complete, the reset switch is turned off. According to the operational requirements, one of the four movement buttons (upward, downward, left, or right) is pressed to enable the wall-climbing robot to move autonomously along the steel frame surface.

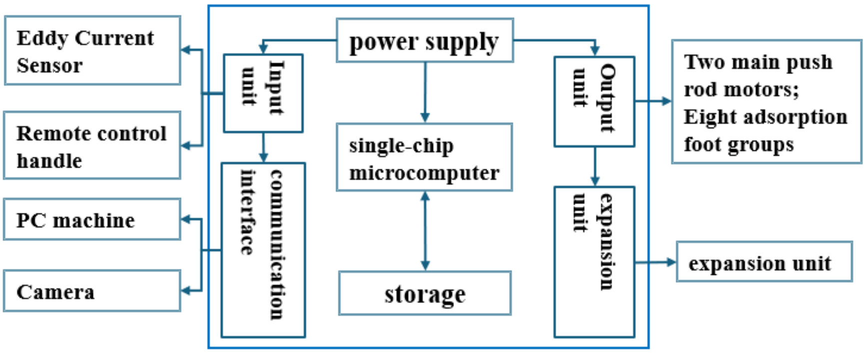

Fig 7. Overall scheme of control system

5. Directional Movement Program Design

The entire control program can be divided into six main components: the common program (including the sensor detection module), the reset program, the upward movement program, the downward movement program, the leftward movement program, and the rightward movement program.

The common program is responsible for controlling the actual output points. The reset, upward, downward, leftward, and rightward movement programs are responsible for controlling the auxiliary relay contacts within the microcontroller. The state of the actual output points in the common program is controlled by the status of the auxiliary relay contacts, which are set by the reset, upward, downward, leftward, and rightward movement programs.

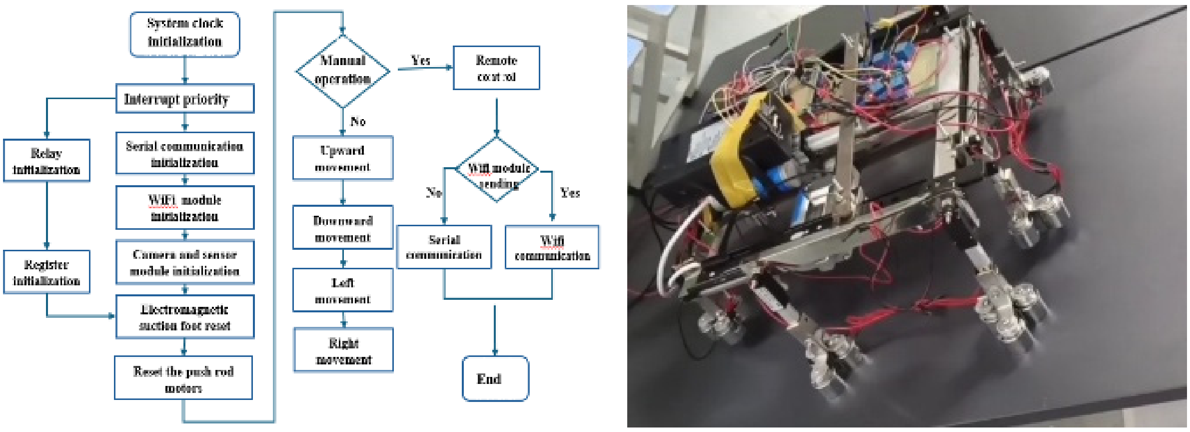

Fig 8. Process display and physical motion display

6. Conclusion

This study presents a wall-climbing robot for steel structure inspection. Its lightweight "田"-shaped frame and innovative electromagnetic adhesion system (24 pads controlled by 8 pushrod motors) enable robust omnidirectional movement and obstacle negotiation. The integrated SK-3000 eddy current sensor detects cracks and paint peeling; processed by the MCU's ADC, it triggers audio alarms, while an ESP32 camera provides real-time video. Remote control via a 2.4 GHz handset or autonomous operation is supported. An auto-switching dual battery system ensures power reliability. This design effectively combines mobility, precise flaw detection, and remote operation for practical structural inspection.

Acknowledgments

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References

[1] Schmidt, D., & Berns, K. Climbing robots for inspection and maintenance of large structures—A survey of design aspects and technologies. Robotics and Autonomous Systems, 2013, 61(12), 1288-1305.

[2] Yu W . Discussion on the Anti-Corrosion Treatment Technology of Port Machinery and Equipment[J]. Management & Technology of SME, 2019.

[3] Padrigalan K E .The Kinematic Analysis of a Wind Turbine Climbing Robot Mechanism[J].Applied Sciences, 2022, 12.

[4] Huynh T A , Vo K T , Nguyen H C ,et al. Design and simulation of a 3D-printed wall-climbing robot for high-risk construction tasks[J].Proceedings of the Institution of Mechanical Engineers, Part C. Journal of mechanical engineering science, 2024(8):238.

[5] Hong H, Sun X. Obstacle avoidance dynamic control of manipulator based on space operator algebra[J].Future Generation Computer Systems, 2021, 123.

[6] ZHANG Ming-lu, ZHANG Xuan, LI Man-hong, et al. Optimization Design and Flexible Detection Method of a Surface Adaptation Wall-Climbing Robot with Mul- tisensor Integration for Petrochemical Tanks[J]. Sensors, 2020, 20(22): 6651.