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Design and Simulation Analysis of an Intelligent Deck Paint Removal Robot for Ships

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Abstract: To address the long-standing challenges of low efficiency, severe pollution, and high costs in the ship deck paint removal industry, this study proposes a design for an intelligent paint removal robot tailored to ship deck applications, based on an analysis of paint layer types and their properties. The robot integrates a locomotion unit, recognition unit, paint removal unit, and waste paint recovery unit, enabling integrated operations for deck paint removal and recycling. Additionally, a spring-based flexible structure is designed to control the height between the electromagnetic heating module and the paint surface, ensuring adaptability to ship decks with varying curvatures while maintaining an optimal removal distance. The system's reliability is validated through computational modeling and simulation analysis. This research contributes to reducing labor intensity in paint removal processes and advancing the development of the ship deck paint removal industry.

1. Introduction

Periodic maintenance of ship deck paint coatings is a critical process for ensuring maritime safety and extending service life. Traditional deck paint removal methods primarily rely on manual grinding or chemical solvent cleaning. The former suffers from issues such as low efficiency, high labor intensity, and severe dust pollution, while the latter poses risks of deck corrosion due to chemical residue and incurs high costs for waste liquid treatment, failing to meet green environmental standards. Although existing mechanical paint removal equipment can partially replace manual labor, it generally exhibits defects such as poor adaptability to curved surfaces, high risk of substrate damage, and low waste paint recovery rates, making it inadequate for the large-scale and eco-friendly upgrading requirements of the maritime industry.[1][2].

Relevant studies have identified the following challenges in paint removal machinery: (1) Variations in deck curvature across different ship types render single-type paint removal equipment inadequate for universal adaptation; (2) Segregated operations for paint removal and waste treatment compromise overall efficiency; (3) Current static port-based paint removal processes result in prolonged operational cycles. To address these issues, this study proposes an intelligent paint removal robot integrating flexible adhesion, paint removal, and waste recovery functionalities. Through modular structural design and intelligent control technologies, the system achieves efficient, clean, and cost-effective deck paint removal operations.[3][4].

2. Overall Design Scheme for an Intelligent Paint Removal Robot for Ship Decks

The robot consists of five integrated modules: locomotion, recognition, paint removal, waste paint recovery, and control. The locomotion units are positioned at all four sides of the chassis, while the recognition system is mounted on the upper section. The paint removal module is installed at the lower section, with the waste paint recovery unit located at the rear of the operational direction. The central control system coordinates all submodules through a hierarchical architecture.

The robot achieves full functionality by coordinating all modules through an STM32F407 microcontroller. As illustrated in Figure 1, the 3D model of this paint removal robot comprehensively incorporates key factors such as inter-module connectivity, waste paint recovery mechanisms, and environmental adaptability. The operational workflow follows a structured sequence:"the recognition module detects paint layer distribution → the locomotion module positions itself at the target area → the paint removal mechanism executes ablation → the waste recovery system synchronously collects residues → operational data is fed back to the control system for parameter optimization". This design features simple operation, clear procedural steps, convenient component fabrication, and low production costs. Its flexible structural design enables adaptation to ship decks with varying curvatures, ensuring consistent paint removal efficiency.[5][6].

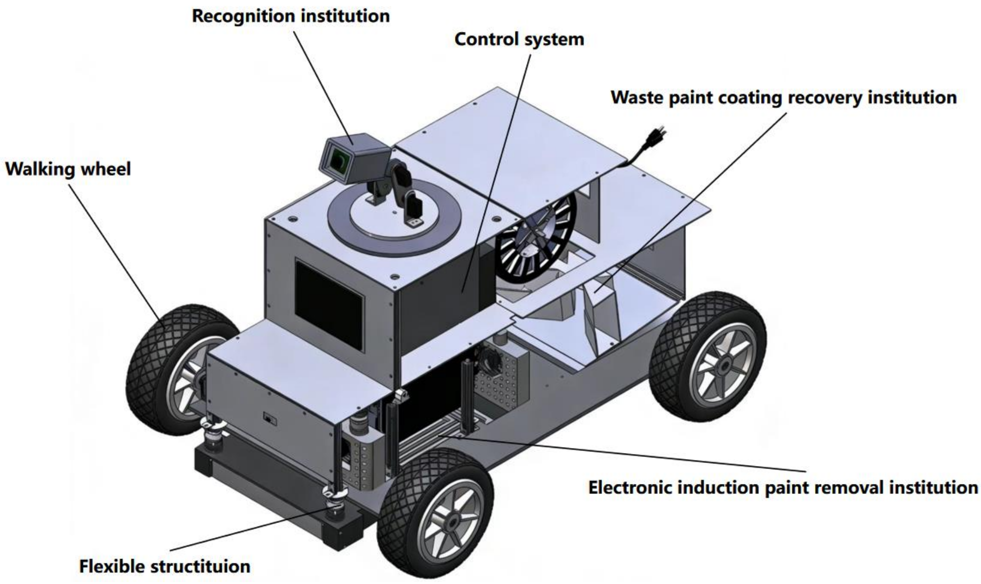

Figure 1. Three-Dimensional Model of an Intelligent Paint Removal Robot for Ship Decks

3. Structural design

3.1. Height-fixed structure for electromagnetic induction heating modules

The height-fixed structure of the electromagnetic induction heating module consists of vibration damping units and limit-position rolling optical shafts. The structure is composed of a sleeve with a base disc, vibration damping springs, and limit copper columns. The vibration damping springs are nested on the outer side of the sleeve, which is secured to the assembly by a limit sleeve. As illustrated in Figure 2, there are six vibration damping units in total, including two pairs of large-scale units and one pair of small-scale units. The preload force of the vibration damping springs is determined by the overall weight of the equipment. The limit-position rolling optical shafts consist of two pairs, each with a diameter of 10 mm and a length of 45 mm

When the robot moves to a raised area on the deck, the optical shaft slides upward under force, compressing the spring to avoid rigid collisions; conversely, in recessed areas, the spring extends, allowing the optical shaft to slide downward and ensuring a 2 mm gap between the baseplate and the deck. Due to the optical shaft's presence, the electromagnetic induction heating module remains consistently aligned within a single plane, maintaining a 2 mm distance from the deck—the optimal spacing for ship deck paint removal at equivalent power levels. During the design of the flexible structure, key considerations must include: the relationship between the diameter of the limit-position rolling optical shaft and the curvature of the ship deck, the relationship between the diameter of the limit-position rolling optical shaft and the paint removal power, and the preload force of the vibration-damping short springs. This mechanism innovatively addresses adaptability challenges for paint removal equipment across different ship decks, significantly enhancing the efficiency of electromagnetic induction-based paint removal[7][8].

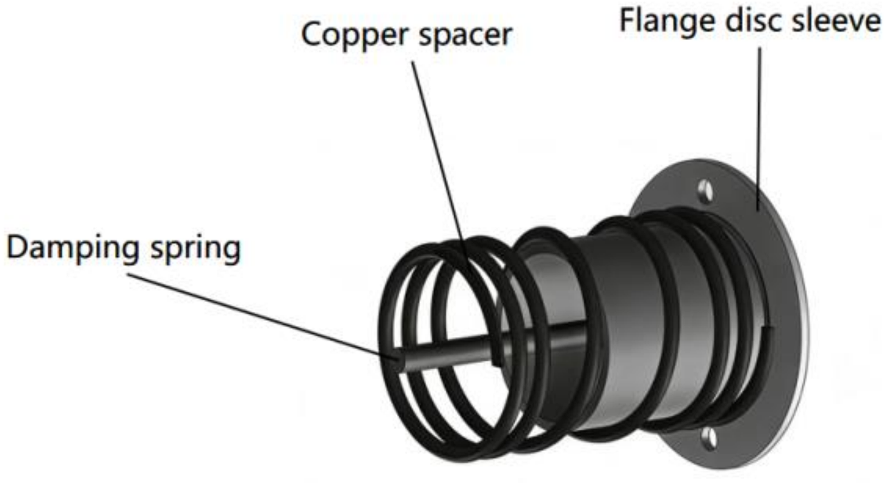

Figure 2. Flexible structural connector

The permissible heights of the spring in its free state are 81.007 mm (primary) and 70 mm (secondary), with inner diameters of 30 mm (primary) and 37 mm (secondary). The maximum calculated allowable load of the spring:

$$F_{\text{allowance}} \leq \frac{\tau \cdot \pi \cdot d^3}{8 \cdot K_s \cdot C}$$

In the formula, τ represents the allowable shear stress of the material, K is the curvature correction factor, and C is the spring index. Under identical conditions: (primary) > (secondary). Therefore, it is sufficient to ensure compliance with the maximum allowable load of the secondary spring.

Meanwhile, another critical factor for springs is their stiffness, and the stiffness calculation is conducted under identical conditions.

$$\text{have: } K = \frac{G \cdot d^4}{8 \cdot D^3 \cdot N}$$

Substitute the following data for calculation: primary height = 81.007 mm, secondary height = 70 mm; primary inner diameter = 30 mm, secondary inner diameter = 37 mm: $K_{primary}=8788$, $K_{secondary}=8984.25$, due to Given that there are 4 primary springs and 2 secondary springs,

Therefore, since the stiffness of the primary springs (4 units) exceeds that of the secondary springs

(2 units), meeting the stiffness requirement of the secondary springs is sufficient.

Through relevant methodologies, we conducted an independent force analysis on the secondary spring, examining its stress conditions under full-load conditions and assessing risks of fracture or severe deformation. A SolidWorks finite element analysis model was employed to evaluate stress distribution and displacement during operation. The computational results are illustrated in Figures 3 and 4. The force analysis under a 500 N load reveals a maximum equivalent stress of 67.2 MPa and a maximum displacement of 4.3966 mm. These values remain below the allowable stress threshold for 316 stainless steel, with minimal deformation, thereby satisfying operational strength requirements

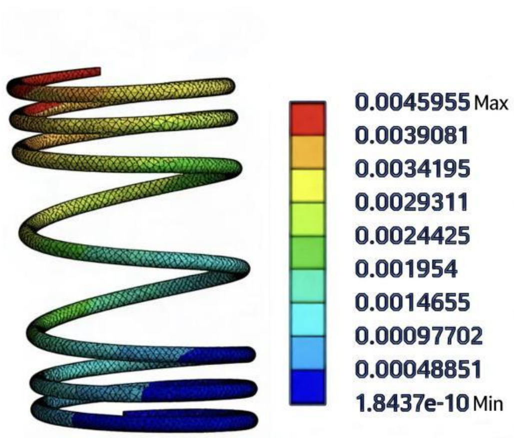

Figure 3 Stress Analysis Diagram

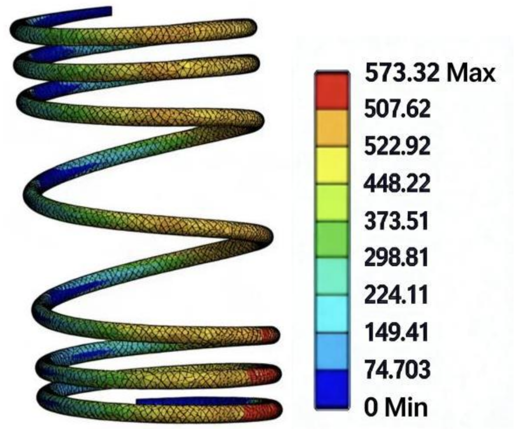

Figure 4 Deformation Analysis Diagram

3.2. Paint Removal and Recycling Institution

The institution integrates a high-frequency induction paint removal module and a mechanical scraping recovery module. The core of the electromagnetic induction paint removal module consists of a high-frequency induction coil driven by a high-frequency power supply to generate an alternating magnetic field. When the coil approaches the deck, eddy currents are induced in the metallic deck due to electromagnetic induction. These eddy currents are converted into thermal energy through the metal's electrical resistance, causing the adhered paint film to separate from the substrate via thermal expansion stress and carbonize, achieving non-contact paint removal. The mechanical scraping recovery module employs a coordinated design of an elastic scraper and a collection trough. An elastic metal scraper is positioned behind the induction coil (in the operational direction) to physically scrape the carbonized paint layer from the deck surface, leveraging the reduced adhesion between the carbonized paint and the deck. The scraped paint debris is continuously recovered through a bottom collection trough, as illustrated in Figure 5.

This design integrates the advantages of efficient thermal paint removal via electromagnetic induction and physical recovery through mechanical scraping, eliminating mechanical damage caused by conventional grinding while precisely removing carbonized paint layers with scrapers. It addresses both the pollution issues associated with chemical paint removal and the inefficiency defects of traditional recycling methods[9][10].

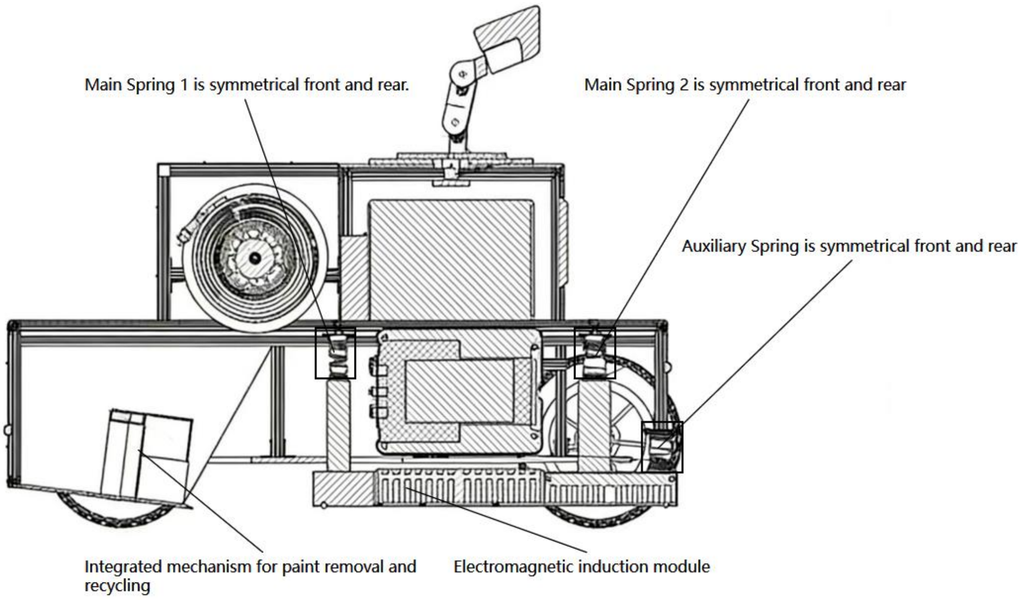

Figure 5. Paint Removal and Recycling Structure

4. Recognition and Control System

4.1. Visual Recognition and Control System

The visual recognition and control system employs a Raspberry Pi as the core for visual processing and an STM32 microcontroller as the core for execution control, following a processing sequence of recognition → data processing → execution, as illustrated in Figure 6: During the identification phase, an RGB-D camera captures images of the deck environment and transmits them to the Raspberry Pi, with the primary objective of identifying the distribution of ship deck coatings and the targeted areas for coating removal. Simultaneously, an ultrasonic module measures distances to the deck and obstacles to prevent collisions. In the data processing phase, the Raspberry Pi performs comparative analysis by referencing stored data on coating characteristics and deck environmental features. It identifies coated regions and obstacles, plans operational paths, integrates ultrasonic distance measurements for environmental assessment, and subsequently transmits control signals to the STM32 microcontroller. The STM32 decodes the signals, monitors the status of the coating removal unit, receives ultrasonic feedback, and regulates temperature via an electromagnetic induction heating module. All module feedback is relayed back to the Raspberry Pi and the database, establishing a closed-loop data control system. In the execution phase, the STM32 directs wheel motors to maneuver the coating removal device and initiates obstacle avoidance by driving motors upon detection of impediments. Once a target area is located, it activates the coating removal mechanism and waste recovery system. Sensor feedback continuously monitors operational status to ensure precision. Should a path prove unfeasible, the Raspberry Pi re-plans the route and orchestrates device adjustments to maintain progress in the coating removal task.

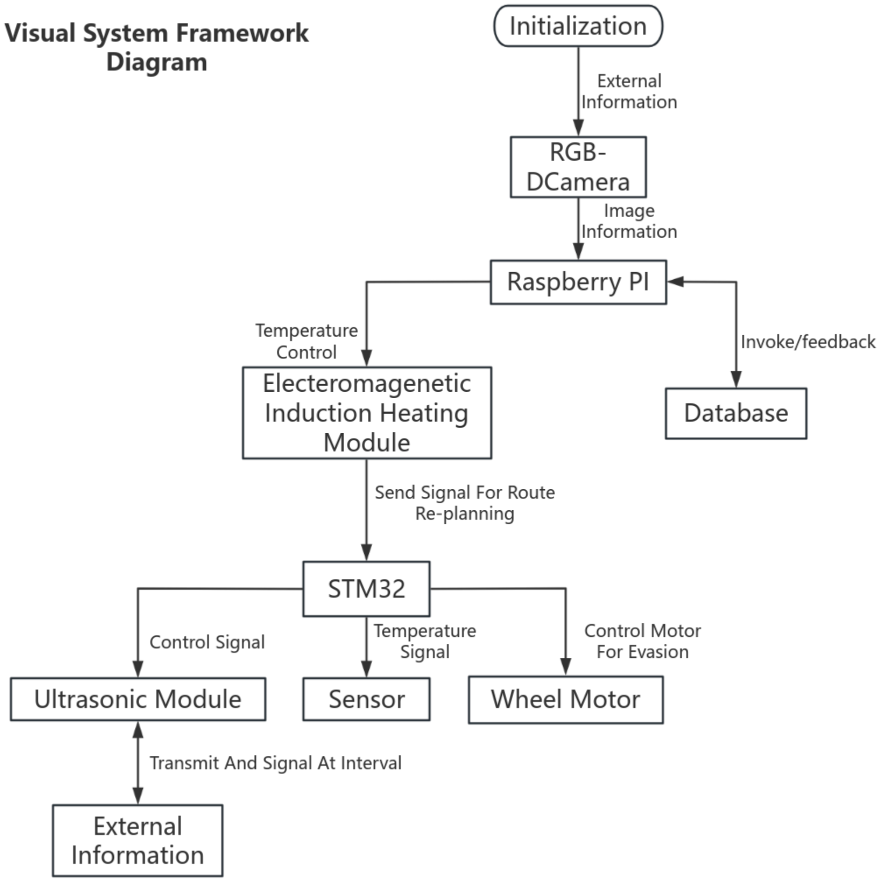

Figure 6. Framework of Visual Recognition Syste

4.2. Circuit control system design

The 24V lithium battery serves as the main power supply and is powered by a two-stage voltage reduction circuit for the control module. The 24V → 12V voltage reduction DCDC chip model is LM5164. The 12V → 5V voltage reduction uses the RY 8411 chip to output 5V/1A, which supplies power to the STM32F407VET6 main control chip. The MCU timer 1, timer 3, and timer 12 output 9 PWM control signals, respectively driving 1 steering mechanism and 4 stepper motors. By adjusting the duty cycle of the 6 square wave signals output by the controller, the rotation angle of the steering mechanism can be changed, thereby driving the transmission mechanism to complete recognition, paint removal, and recovery operations. The stepper motor controls the linear movement speed and displacement of the worm gear through the frequency and quantity of the output pulse signals. This system uses 4 servo motors (model MG996R, working voltage 4.8 - 7.2V) to control the key actions of the robot mechanism. Each servo motor is independently powered, and an optocoupler isolator (TLP280-4) is added between each servo motor signal and the microcontroller to avoid reverse interference.

5. Conclusion

The intelligent paint removal mechanism designed in this paper has achieved the removal and recycling of waste paint coatings through calculation, simulation and reasonable mechanical structure design. It not only solves the problems of paint removal efficiency, cost and labor intensity, but also due to its structural characteristics and diverse functions, can adapt to various ship decks, effectively solving the traditional problems of paint removal on ship decks. It has broad market prospects and provides reference and experience for the research and development of industrial intelligence.

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