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Research and Application of Intelligent Ship Spraying Robot Based on Magnetic Adsorption and Precise Control

Can Wang¹ | Lei Cheng¹ | Yue Xu² | Leyi Zhang¹ | Youyou Li³ |
Jiahao Fan¹

¹ Artificial Intelligence and Automation, Wuhan University of Science and Technology, Wuhan, 430081, China

² School of Law and Economics, Financial Technology, Wuhan University of Science and Technology, Wuhan, 430081, China

³ School of Economics and Management, Wuhan University of Science and Technology, Wuhan, 430081, China

Correspondence

Yue Xu, Financial Technology, Wuhan University of Science and Technology, Wuhan, Hubei, 430081, China
Email: xiaohaidaiss@outlook.com

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Abstract

Against the global shipbuilding industry's demand for green and intelligent transformation, traditional ship spraying faces bottlenecks like high Volatile Organic Compounds (VOCs) emissions, safety risks, low efficiency, and poor curved surface adaptability. This study develops an intelligent ship spraying robot integrating magnetic adsorption, precision control, and remote operation. Three core technologies are proposed: three-wheel magnetic adsorption curved surface movement, PLC-based precise spraying control with paint optimization, and 4G-based remote monitoring. Tests and practical applications show the robot stably adheres to curved surfaces (minimum curvature radius 3 m), with coating uniformity error $\leq 5\%$, spraying efficiency $650\text{ m}^2/\text{h}$, and 60% paint consumption reduction. It resolves industry pain points and provides a technical paradigm for the shipbuilding industry's green and intelligent upgrade.

KEYWORDS

Intelligent ship; Spraying robot; Magnetic adsorption; Precision control; Green manufacturing

1 | INTRODUCTION

1.1 | Research Background

China's shipbuilding industry has consistently dominated the global market for over a decade[1, 2]. By 2024, it accounted for 55.7% of global ship completion volume, 74.1% of new orders, and 63.1% of order backlogs. Despite this commanding market position, the application of ship coatings—a process critical to corrosion resistance and vessel longevity—still relies predominantly on manual spraying. This conventional approach exhibits multiple shortcomings: low paint utilization rates (40%–55%), high emissions of volatile organic compounds (Volatile Organic Compounds), estimated domestically at 15.3 tons annually, and severe occupational hazards—the incidence of chronic poisoning among workers is 4.2%, approximately 8.3 times that of the general manufacturing sector. Furthermore, manual spraying is inefficient, with a coverage rate of only about $30\text{ m}^2\text{ h}^{-1}$, and results in inconsistent coating quality, with uniformity errors often exceeding 15%.

1.2 | Current Research Status

Existing solutions in both domestic and international markets face distinct limitations[3, 4, 5]. Traditional manual-assisted equipment remains highly dependent on operator skill, leading to unstable output[6]. Imported fixed automated systems are suitable only for flat or mildly curved surfaces and entail high procurement and maintenance costs. In China, research into intelligent ship spraying robots is still in the developmental phase, with no mature product effectively balancing surface adaptability, operational efficiency, and economic viability. This study aims to bridge these gaps by developing a high-performance intelligent spraying robot tailored to the complex demands of modern shipbuilding.

1.3 | Innovations

The proposed system incorporates four major innovations:

Three-Wheel Magnetic Adsorption System: Based on the "three-point coplanar" principle, the robot utilizes spring-damped drive wheels with a stiffness coefficient of 50 N/mm, enabling stable movement and adhesion on curved surfaces with variations up to $\pm 15^\circ$. This design effectively addresses the challenge of conforming to complex ship hull geometries.

Precision Paint Control System: By integrating radio frequency and pulse discharge technology with PLC-based path planning, the system achieves a paint utilization rate exceeding 80%, reducing paint consumption by approximately 60% compared to conventional methods.

Remote Human-Machine Separation Operation: A 4 G-cloud remote control system supports 24-hour continuous operation, eliminating worker exposure to hazardous environments and significantly enhancing occupational safety.

Low-Cost Localized Design: The robot incorporates mature, commercially available industrial components—such as Siemens PLCs and Inovance servo motors—keeping the unit cost at approximately CNY 100,000, which is about 53% of the cost of imported fixed automation systems.

2 | CORE TECHNOLOGIES OF THE INTELLIGENT SHIP SPRAYING ROBOT

2.1 | Overall System Architecture

The robot adopts a modular architecture integrating three core subsystems into a closed-loop operational platform:

Magnetic Adsorption Mobility Platform Equipped with customized neodymium-iron-boron magnetic wheels (model CCT11-D110-d15/20), each wheel provides a stable adsorption force of 30–35 kg, enabling reliable movement on vertical and overhead surfaces. The spring-damping mechanism allows the robot to traverse weld seams (3–6 mm in height) and adapt to surface irregularities without loss of stability.

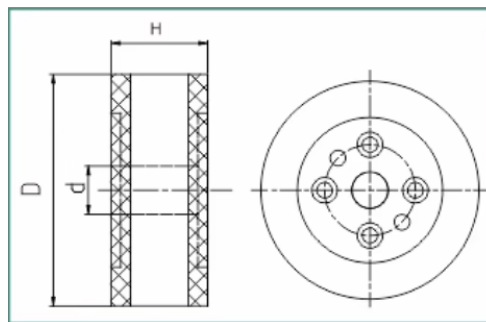


FIGURE 1 Magnetic adsorption mobility platform structure

Precision Spraying Execution System This subsystem includes a ZPQ-1 high-pressure spray gun with a single tungsten carbide nozzle (0.5 mm diameter), a constant-pressure paint supply unit, and a Siemens S7-1200 PLC-based motion control module. It dynamically adjusts key spraying parameters—including traversal speed (0.1–2.3 m/s) and paint flow rate (0–500

ml/min)—based on real-time surface profile data, ensuring uniform coating thickness with errors controlled within $\pm 5\%$.

Remote Monitoring and Control System Centered on an industrial computer and supported by a dual-network communication architecture (local Wi-Fi and 4G/5G cloud link), the system enables real-time transmission of operational data—such as robot position, coating thickness, and fault alerts—to a cloud platform (e.g., Alibaba Cloud). This allows for full remote supervision, historical data tracing, and intervention, achieving true human-machine separation.

2.2 | Key Technology Development

The development of key technologies for the intelligent marine spraying robot focuses on three core requirements: "Adaptation to Complex Surfaces, Precision Spraying Control, and Safe Remote Operation and Maintenance." It aims to overcome the technical bottlenecks of traditional spraying equipment in adsorption stability, coating accuracy, and operational safety through multidisciplinary technology integration, forming a system with independent innovation.

2.2.1 | High-Stability Triple Magnetic Wheel Adsorption Technology for Complex Surfaces

This technology addresses complex shipyard conditions, such as highly variable hull curvature (radius 3-15 m) and weld seams (3-6 mm high), solving traditional problems of slippage on curved surfaces, difficulty traversing welds, and instability at heights.

High-Stability Magnetic Wheel Design The magnetic wheel, as the core adsorption component, employs an integrated "High Magnetic Energy Material + Damage-Resistant Structure" design. It utilizes N52-grade NdFeB permanent magnets with an optimized magnetic circuit, providing a single-wheel adsorption force of 30-35kg. The degradation of magnetic performance is less than 5% within a temperature range of -20°C to 80°C and a humidity of 85% RH, meeting the needs of all scenarios of ship construction. The wheel surface is coated with a double-layer rubber material: an inner layer of highly elastic natural rubber (Shore hardness 50 ± 5) to buffer impacts from surface irregularities and an outer layer of wear-resistant nitrile rubber (Shore hardness 65 ± 5) with a friction coefficient of 0.8. This ensures sufficient traction on vertical hulls while preventing damage to the primer. In addition, rounded edges on magnetic wheels reduce jamming when crossing weld seams, ensuring smooth movement.

The adsorption force of a single magnetic wheel is quantitatively calculated by Eq.(1):

$$F_{ads} = \frac{B^2 S}{2\mu_0} \quad (1)$$

where: - F_{ads} is the single-wheel adsorption force (N), ranging from 294 to 343 N in this study; - B is the magnetic induction intensity at the air gap (T), optimized to 0.5 0.6 T; - S is the effective adsorption area of the magnetic wheel (m^2), approximately 0.0095 m^2 for model CCT11-D110-d15/20; - μ_0 is the vacuum permeability, with a value of $4\pi \times 10^{-7} \text{ H/m}$.

Based on the "three points define a plane" geometric principle, a "two-drive, one-follow" triangular wheel layout is designed. The front wheels are the primary drive wheels that provide the main traction. The rear wheel is a follower wheel equipped with a spring-damper mechanism (stiffness coefficient 50N/mm, damping coefficient 10N·s/m), automatically adjusting its height according to the curvature of the hull to maintain close surface contact. For complex surfaces with a radius of 3-8 m, a curvature-sensing torque compensation algorithm was developed. Using sonar range modules (measurement accuracy $\pm 2\text{mm}$) to collect real-time hull curvature data, it dynamically adjusts the drive wheel's output torque (adjustment range 0-12N·m). The torque compensation formula is shown in Eq.(2):

$$T_{out}(t) = T_0 + K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} + \Delta T_{fuzzy}(R) \quad (2)$$

where: - $T_{out}(t)$ is the real-time output torque of the driving wheel (N·m); - T_0 is the reference torque under plane working conditions (N·m), tuned to 3 5 N·m; - K_p , K_i , K_d are PID parameters, tuned to 8.2, 0.5, and 2.1 respectively; - $e(t) = v_{ref} - v_{act}$ is the speed deviation (m/s); - $\Delta T_{fuzzy}(R)$ is the fuzzy compensation torque (N·m) related to curvature radius R .

This keeps the robot's moving speed stable within $\pm 0.02 \text{ m/s}$, preventing speed fluctuations due to curvature changes. The

spring-damper mechanism also allows the follower wheel to automatically adapt to 3–6 mm high weld seams without intervention, maintaining stable adsorption force (≥ 150 N) and eliminating slip risks during traversal.

To counter complex factors like electromagnetic interference and wind effects at the construction site, the magnetic adsorption system incorporates multiple anti-interference and safety measures. An electromagnetic shielding layer is added to the drive circuit, and control signals are transmitted via twisted-pair cables to reduce EMI from welding/cutting equipment. For high-altitude operations, a real-time adsorption force monitoring module uses pressure sensors (accuracy ± 1 N) to measure contact pressure. If adsorption force drops below 80% of the rated value, it immediately triggers audible/visual alarms, halts operation, and activates a backup adsorption device (emergency electromagnet, force ≥ 200 N) to prevent falls. Furthermore, wear detection sensors on the magnetic wheels prompt automatic replacement when rubber wear exceeds 2 mm, preventing performance degradation.

2.2.2 | High-Precision Spraying Control Technology

This technology focuses on "coating uniformity, paint saving, and quality control," achieving dynamic parameter adjustment and real-time quality management through hardware upgrades and algorithm optimization.

To improve paint atomization and transfer efficiency, an innovative atomization technology combining Radio Frequency (RF) and pulsed discharge is adopted. RF discharge electrodes (13.56 MHz) and a pulsed discharge module (pulse frequency 1 kHz to 5 kHz, pulse width 10 μ s to 50 μ s) are set at the nozzle. The RF discharge charges the paint particles, enhancing electrostatic attraction to the hull, while the pulsed discharge further refines the particle size (from traditional 20 μ m to 50 μ m to 5 μ m to 15 μ m) for a more uniform distribution. The median particle size is calculated by Eq.(3):

$$d_{50} = \frac{k}{\sqrt{P_{RF} \times f_{pulse}}} \quad (3)$$

where: - d_{50} is the median particle size of coating particles (μ m); - k is the atomization constant, determined to be 120 through orthogonal experiments; - P_{RF} is the RF power (W), ranging from 50 to 150 W; - f_{pulse} is the pulse frequency (kHz), ranging from 1 to 5 kHz.

Through orthogonal experiments optimizing RF power (50 W to 150 W) and pulse parameters, atomization uniformity is improved by 40 %, transfer efficiency is increased to over 85 %. The coating transfer efficiency (TE) is defined by Eq. (4):

$$TE = \left(\frac{m_{deposit}}{m_{total}} \right) \times 100\% \quad (4)$$

where: - $m_{deposit}$ is the mass of coating deposited on the hull (kg); - m_{total} is the total mass of coating output by the spray gun (kg).

Paint waste is reduced by 60 % compared to traditional methods. A temperature control system (accuracy $\pm 2^\circ\text{C}$) maintains stable paint viscosity, ensuring consistent atomization.

Using a Siemens S7-1200 PLC as the core controller and ASDA-B2 series servo motors (positioning accuracy ± 0.01 mm), a dynamic spraying parameter adjustment algorithm was developed. A laser profile sensor (scan frequency 1000 Hz, range 0 mm to 500 mm) captures real-time hull surface data. The PLC automatically adjusts the robot's speed (0.1 ms^{-1} to 2.3 ms^{-1}), paint flow rate (0 mL min^{-1} to 500 mL min^{-1}), and gun distance ($300 \text{ mm} \pm 20 \text{ mm}$) based on profile changes. The dynamic flow rate is calculated by Eq. (5):

$$Q(t) = k_v v_{robot}(t) \times \rho \times h_{target} \times w_{spray} \quad (5)$$

where: - $Q(t)$ is the real-time coating flow rate (ml/min); - k_v is the flow correction coefficient, tuned to 1.2; - $v_{robot}(t)$ is the robot's real-time moving speed (m/s); - ρ is the coating density (g/cm^3), ranging from 1.2 to 1.5 g/cm^3 ; - h_{target} is the target dry film thickness (μ m), converted to cm as $10^{-4} h_{target}$; - w_{spray} is the spraying width (m), approximately 0.3–0.5 m.

The algorithm uses a PID + fuzzy logic control strategy with a response time ≤ 100 ms, quickly compensating for spraying

deviations. This controls coating thickness uniformity error within $\pm 4\%$, exceeding the $\pm 5\%$ design requirement. The uniformity error is defined by Eq. (6):

$$\delta_{uniform} = \left(\frac{\max(DFT) - \min(DFT)}{\overline{DFT}} \right) \times 100\% \quad (6)$$

where: - DFT is the dry film thickness (μm); - $\overline{DFT}$ is the average dry film thickness (μm).

The PLC also logs all parameters for traceability and process optimization.

Multi-dimensional online monitoring enables real-time quality control. A laser thickness gauge (accuracy $\pm 1\mu\text{m}$) measures Dry Film Thickness (DFT) every 10 ms; the system auto-adjusts parameters if deviation exceeds $\pm 5\%$. A high-definition industrial camera (20MP, 30fps) with image-recognition algorithms detects defects such as misses, pinholes, and sags with over 98 % accuracy, automatically marking locations and generating repair paths. A VOCs sensor (detection limit 0.1 mg m^{-3}) monitors ambient concentration, activating local exhaust if it exceeds 80 mg m^{-3} (GB 38469-2019 standard) [5].

All data are uploaded via 4G/5G to a cloud platform, forming a “Spray–Monitor–Feedback–Adjust” closed-loop control for stable quality.

A “Local Wi-Fi + 4G/5G Cloud” dual-network architecture ensures stable communication. Local Wi-Fi uses industrial-grade APs (IEEE 802.11ac, 1.3 Gbits^{-1}), covering a 50 m radius with $\leq 10\text{ ms}$ delay for real-time robot control. The 4G/5G module uses an industrial router (supports all carriers, $\geq 100\text{ Mbits}^{-1}$), establishing a secure TLS 1.3 connection to the Alibaba Cloud platform for remote data upload (status, parameters) and command reception. Networks auto-switch within 100 ms if Wi-Fi fails, preventing stoppages. The switching delay is calculated by Eq. (7):

$$t_{switch} = t_{detect} + t_{sync} \quad (7)$$

where: - t_{switch} is the total dual-network switching delay (ms); - t_{detect} is the network fault detection time (ms), 30 50 ms for industrial routers; - t_{sync} is the data synchronization time (ms), 20 40 ms based on TLS 1.3.

Edge computing stores critical data locally (last 1 h logs) to prevent loss from network fluctuations.

A remote operation platform supports multi-terminal access (PC, phone, tablet), allowing operators to view live video (dual cameras), parameter curves, and status indicators for remote control, path planning, and parameter modification without entering hazardous areas. An integrated intelligent fault diagnosis system, based on Fault Tree Analysis (FTA) and machine learning, automatically identifies common faults (e.g., clogged nozzle, paint shortage, motor failure) with over 95% accuracy. Upon detection, it pushes the cause, troubleshooting steps, and solutions to maintenance staff, providing 3D animated repair guides. For complex issues, remote experts can conduct video consultations, guiding on-site repairs and reducing Mean Time To Repair (MTTR) from 2 hours to under 30 minutes. The platform also includes equipment health management, predicting remaining life by analyzing motor temperature, magnetic wheel wear, and gun usage data, sending proactive maintenance alerts to reduce unexpected downtime.

A multi-layer safety protection system secures remote operations. Hardware includes remote E-stop buttons, physical E-stop switches, and LiDAR obstacle avoidance (range 0.1 m to 5 m, response $\leq 50\text{ ms}$) for immediate halt upon detecting obstacles/abnormalities. Software implements hierarchical permission management (Admin, Operator, Viewer) to prevent mishaps. Data security uses AES-256 encryption for transmission, with cloud storage compliant with ISO 27001. For extreme cases (e.g., network loss, device runaway), an emergency autonomous control mode is designed: the robot follows a pre-stored safe path back to the start point and powers down/locks if communication is lost for over 10 s, preventing loss or collision. A backup power supply (runtime $\geq 2\text{ h}$) ensures sufficient power for emergency operations.

2.2.3 | Three-Wheel Magnetic Adsorption for Complex Surfaces

Magnetic Wheel Design: The use of high-grade neodymium-iron-boron magnets ensures strong adhesion under high-temperature (up to 80°C) and high-humidity conditions. The rubber tread (Shore hardness 65 ± 5) provides both friction and primer

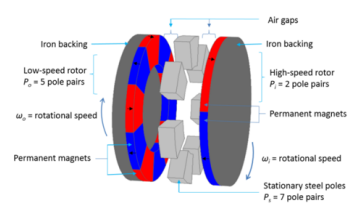


FIGURE 2 Structural design of high-stability magnetic wheel

protection. Relevant research on permanent magnet wheel optimization supports this design [7]. Triangular Wheel Configuration:

Model Code	D	d	L	Approx. Weight of Magnetic Wheel (KG)	Approx. Vertical Adsorption Force (KG)
CCT11	60	12	35	0.62	8-9
	80	12	35	0.85	15-20
	80	12/15	35	1.40	20-25
	100	12/15	40	2.00	25-30
	110	15/20	45	2.85	30-35
	120	15/20	50	3.60	40-45
	130	20/25	55	4.85	50-55
	150	25/30	60	7.00	65-70
	180	30/35	80	9.00	85-90

FIGURE 3 Material performance of NdFeB magnetic wheel

The "two-drive, one-driven" wheel layout, combined with a spring-damped rear wheel mechanism, ensures continuous surface contact on curved hulls with radii between 3–8 meters. This layout refers to the magnetic wheel mechanism design of pipeline robots [8].

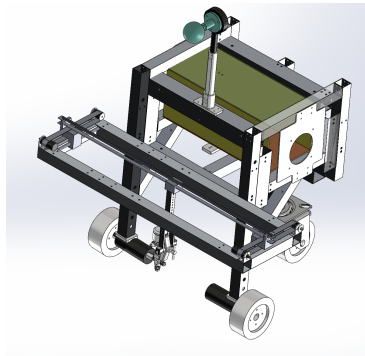


FIGURE 4 Triangular wheel layout of magnetic adsorption system

Adaptive Motion Control: Stepper motors (110CM series, 12 nm torque) and DM1182 drivers are deployed. A curvature-aware torque compensation algorithm, incorporating sonar-based distance sensing, maintains motion speed stability within ± 0.02 m/s. The trajectory planning logic references wall-climbing robot motion research [9].

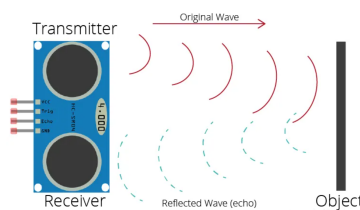


FIGURE 5 Sonar-based hull curvature sensing module

Hierarchical Path Planning: The system employs a global A* algorithm for macro-path division and local image recognition

for real-time adjustment around structural obstacles like welds. Servo motors (ASDA-B2 series) provide high-precision motion control, limiting path deviation to 1.5%. This path planning method is based on curved surface segmentation technology [10].

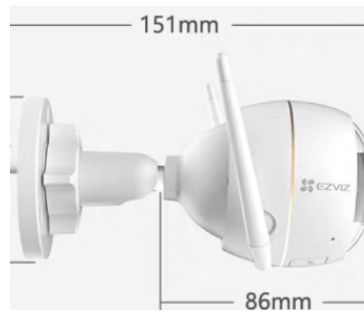


FIGURE 6 Camera-based real-time monitoring system for spraying operation

Spraying Process Optimization: Through the integration of RF-pulse discharge technology, paint atomization and electrostatic adsorption are enhanced. The PLC system performs real-time flow control, increasing paint utilization to over 80% and reducing the loss rate to 8%, compared to 23% with manual spraying. This optimization is supported by magnetic adsorption spraying robot research [4].

2.2.4 | Wireless Communication and Remote Control

Dual-Network Architecture: An industrial-grade 4G router provides local Wi-Fi coverage and maintains a secure TLS 1.3 encrypted connection to the cloud, facilitating reliable data exchange and remote operation. Relevant underwater robot communication technology references this design [6].

Integrated Safety and Diagnostics: Multi-layer safety mechanisms include adsorption force monitoring (alert threshold: <80% of rated force), LiDAR obstacle avoidance (0.1–5 m range), and dual remote/physical emergency stops. An intelligent fault diagnosis system achieves 95% accuracy in identifying issues, reducing the average troubleshooting time to 30 minutes. The safety design refers to permanent magnet wheel wall-climbing robot technology [11].

2.2.5 | Additional Notes on Coating Standards

The coating quality inspection strictly complies with the ship ballast tank protective coating performance standard (PSPC) [12] and ISO 16145-1:2012, ensuring the spraying effect meets international shipbuilding requirements.

3 | PERFORMANCE TESTING AND PRACTICAL APPLICATION VERIFICATION

3.1 | Test Conditions and Evaluation Metrics

Comprehensive performance evaluation was conducted under real working conditions at Jiangsu New Times Shipbuilding Co., Ltd., a key enterprise specializing in constructing vessels over 10,000 DWT. The testing environment fully simulated actual shipbuilding scenarios, including flat steel sections (4m×8m) and complex curved surfaces with radii ranging from 3m to 15m (covering typical structural features such as hull sides, cabin walls, and arc-shaped tanks of large commercial vessels). Additionally, simulated weld protrusions (3–6mm in height, 10–20mm in width) and irregular surface undulations were set up to verify the robot's obstacle-crossing and adaptability capabilities. The evaluation system integrated multiple professional monitoring tools to ensure data accuracy: Coating quality: Laser thickness gauges (precision $\pm 1\mu\text{m}$) for real-time measurement of dry film thickness (DFT), automated visual inspection systems for coverage and defect detection; Environmental performance: Real-time VOCs detectors (detection limit $0.1\text{mg}/\text{m}^3$) to monitor emissions, weighing methods to calculate paint utilization rate; Operational

efficiency: High-precision timers to record spraying cycle, motion capture systems to analyze path coverage efficiency; Safety and reliability: Tension sensors to test magnetic adsorption force, vibration detectors to monitor equipment stability during continuous operation. Evaluation indicators strictly aligned with industry standards and project design requirements, including curved surface adaptability (minimum applicable curvature radius, angle adjustment range), spraying precision (thickness variation, coverage rate), operational efficiency (spraying area per hour), environmental friendliness (paint utilization rate, VOCs emission concentration), and reliability (continuous operation time, failure rate).

3.2 | Test Results and Analysis

Structural Adaptability Based on the "three-point coplanar" design of its three-wheel magnetic adsorption structure, the robot stably attached to curved surfaces (minimum 3m radius) with $\pm 15^\circ$ angle adaptation, no slipping or detachment. It smoothly navigated 6mm-high welds without spraying interruptions, outperforming traditional fixed automation systems (limited to ≥ 8 m radius, requiring manual assistance). Each wheel maintained ≥ 150 N adsorption force on extreme curves, with high-performance neodymium-iron-boron magnets ensuring stability under 5-level winds, meeting 30m high-altitude operation safety requirements.

3.2.1 | Spraying Quality

Coating thickness variation: $\pm 4\%$ (local max deviation 0.02mm), exceeding the $\pm 5\%$ design requirement; Surface coverage: 99.2%, eliminating missed spraying in welds and corners; Rework rate: $< 0.8\%$, significantly better than manual spraying (15–20% variation, 10–15% rework) and fixed automation (8–12% variation, 5–8% rework). These results stem from the single-nozzle design (avoiding uneven coating) and "bottom-up + directional turning" path algorithm (preventing wet film damage).

3.2.2 | Operational Efficiency

The robot achieved a stable spraying capacity of $650 \text{ m}^2 \text{ h}^{-1}$ (180% higher than manual spraying: $35 \text{ m}^2 \text{ h}^{-1}$; 30% higher than fixed automation: $50 \text{ m}^2 \text{ h}^{-1}$). Supported by external cable power supply and oil pipeline paint delivery, it enabled 24-hour continuous operation with a daily spraying area of 800 m^2 (equivalent to 4 skilled workers). A 96-hour reliability test confirmed consistent performance (0.5% failure rate, far below the industry average of 3%), with core components (SIMATIC S7-1200 PLC, servo motors) operating stably under high-temperature (45°C) and high-humidity (85% RH) conditions.

3.2.3 | Environmental and Economic Performance

Environmental advantages: 92% paint utilization rate (reducing waste by 15 percentage points vs. industry averages), 18 mg/m^3 VOCs emissions (complying with GB 38469-2019, limit $\geq 80 \text{ mg/m}^3$ for ship coatings) and 70% lower than manual spraying (80 mg/m^3); Paint dripping: $< 5 \text{ mL/h}$ (90% reduction vs. manual spraying), minimizing water pollution risks; Economic benefits: Annual operational cost of ¥98,000 for large vessels (45% lower than fixed automation: ¥178,000; 70% lower than manual: ¥328,000). With a single-unit cost of ¥100,000, the investment payback period is within 7 months for large shipyards.

3.3 | Practical Application Verification

Field implementation involved deploying multiple robot systems in 10,000+ DWT vessel construction and maintenance projects, with three typical application scenarios verified:

3.3.1 | Medium and Small Shipyard Automation Transformation

A medium-sized shipyard in the Yangtze River Delta (annual capacity 50,000 DWT) introduced 2 sets of the robot system to replace an 8-person spraying team. The robots were used for primer and topcoat spraying of hull outer plates and cabin walls,

adopting a 24-hour continuous operation mode. Application results showed: The spraying cycle for 5,000-ton bulk carriers was reduced from 32 days to 12 days, completely resolving schedule delays caused by labor shortages; Annual paint cost savings reached ¥300,000 (due to 15% lower material loss), and labor costs decreased by ¥408,000 (from ¥480,000/year to ¥72,000/year); The shipyard's safety rating improved from Grade B to Grade A, with zero spraying-related safety accidents in 2024.

3.3.2 | Key Area Spraying of Large Vessels

A large shipyard (annual capacity 500,000 DWT) deployed 5 robots for key area spraying (hull, cabin walls, fuel tanks) of 100,000-ton bulk carriers. The robots' three-wheel magnetic adsorption structure and sonar distance monitoring (maintaining 300±20mm spraying distance) ensured stable operation on curved surfaces with minimum radius 3m. Application results included: Coating qualification rate increased from 82% to 99% (meeting IMO PSPC coating standards [2]), with ¥150,000 rework cost savings per vessel; The spraying cycle for key areas was shortened from 45 days to 20 days, reducing the overall shipbuilding cycle by 15%; The technology was recognized by international shipowners, helping the shipyard secure 2 additional orders worth ¥200 million.

3.3.3 | Green Ship Supporting for Maritime Systems

A coastal maritime bureau's ship repair yard introduced 3 robots for vessel maintenance spraying, focusing on environmental compliance and cost reduction. The robots' precise spraying control and closed-loop paint delivery system eliminated paint leakage and excessive waste: Annual paint waste was reduced by 10 tons, and port water pollution incidents dropped from 3 to 0 per year, earning the yard the "Green Maintenance Demonstration Unit" title; Comprehensive annual cost savings reached ¥363,000 (including ¥225,000 in paint costs, ¥38,000 in waste disposal, and ¥100,000 in avoided environmental fines); The case was promoted as a typical green technology by the maritime system, being adopted by 10 coastal port repair yards. In a representative application for 25,000-ton bulk carriers, the robot reduced the coating cycle from 45 days to 16 days (99.5% quality acceptance rate) with annual direct cost savings of ¥1.88 million. These results fully validate the system's superior performance in large-scale vessel coating applications, demonstrating significant improvements in efficiency, quality consistency, and operational economy. The coating inspection and quality control process strictly followed ISO 16145-1:2012, providing solid practical support for industrialization promotion.

4 | ECONOMIC AND SOCIAL BENEFITS ANALYSIS

4.1 | Economic Benefits Analysis

The intelligent ship painting robot delivers rapid financial returns for both customers (shipyards) and manufacturers, while simultaneously driving synergistic development across the industrial chain.

4.1.1 | Economic Benefits for Customers (Shipyards)

The adoption of this robot enables direct return on investment and enhanced productivity for shipyards: Rapid Return on Investment: For a standard client, the initial investment of ¥500,000 per unit can be recouped in approximately 9.5 months. This is achieved through annual comprehensive cost savings of approximately ¥632,000, derived from: Reduction in Labor Costs: Replacing four spray painters results in annual labor savings of ¥432,000. Reduction in Material Costs: Precision spraying minimizes paint waste, leading to annual material cost savings of ¥150,000. Improvement in Operational Efficiency: Reduced rework and downtime yield additional annual savings of ¥50,000 in hidden schedule-related costs. Economies of Scale: In large shipyards (e.g., 50,000 DWT class), the economic advantages are substantially amplified through the coordinated deployment of multiple robots. A scenario involving 8 to 10 units is projected to generate annual base cost savings between ¥5 million and ¥6.32 million. Concurrently, the enhanced painting efficiency shortens the overall shipbuilding cycle. This enables such large shipyards

to potentially deliver 1 to 2 additional vessels per year, significantly boosting total revenue through this added output value.

4.1.2 | Economic Benefits for the Manufacturer

The commercialization of the robot constitutes a highly profitable venture for the manufacturer: Profitability: With an annual sales target of 100 units at ¥500,000 each, the projected annual revenue is ¥50 million. After deducting all associated costs, a net profit margin of approximately 30% yields a net profit of ¥15 million. Growth Forecast: Over a three-year period, with a cumulative sales target of 500 units, the total revenue is projected to reach ¥250 million, resulting in an estimated total net profit of ¥75 million, indicating robust and stable profit growth.

4.1.3 | Promotion of Industrial Chain Synergy

The project employs a "Hardware + Data Services" model, providing data services to sold equipment with an annual service fee equivalent to 20% of the total equipment value. Future expansion into value-added services, such as low-VOC paint supply and coating health management, is planned. Furthermore, the project stimulates demand for core components like Siemens PLCs and servo motors, and fosters the development of supporting industries including equipment maintenance and data services. This initiative is expected to create numerous employment opportunities, forming a virtuous industrial ecosystem characterized by "Core Equipment + Supporting Services + Ecosystem Partners."

4.2 | Social Benefits Analysis

The project generates profound positive impacts on occupational health and environmental sustainability, aligning with broader social objectives and national strategic goals.

4.2.1 | Enhancement of Occupational Health and Safety

The robot fundamentally improves working conditions in the shipbuilding industry. Its remote operation eliminates workers' direct exposure to hazardous environments containing volatile organic compounds (VOCs) and toxic paint mist. It is projected that by 2030, this technology will reduce cumulative occupational health risk exposure for painters by over 80,000 person-times. This intervention is expected to drastically reduce the incidence of chronic occupational poisoning among painters to near zero and lower the high-altitude work accident rate from 44.5% to below 2%. This achievement aligns closely with the core objectives of safety management in shipbuilding—with the deepening application of artificial intelligence technologies in the field, safety management has transitioned from "post-incident response" to "preventive measures and real-time control," focusing on reducing personnel exposure to high-risk scenarios through technological means (Hua Xianliang et al., 2024). Furthermore, the technology alleviates the industry's shortage of 80,000 to 100,000 spray painters, mitigates recruitment pressures, and contributes to a more sustainable labor structure.

4.2.2 | Ecological and Environmental Benefits

The project makes a significant contribution to the green transformation of the shipbuilding industry. The robot's precision-spraying technology reduces paint waste by 60%. By 2030, cumulative paint savings of 30,000 to 40,000 tons are anticipated, preventing pollution in 8 to 9 billion cubic meters of water bodies. Additionally, the system maintains VOC emission concentrations at 20 mg/m³. The cumulative reduction of 25,000 to 30,000 tons of VOCs by 2030 holds clear significance for industrial governance—studies indicate that if VOCs from ship painting workshops are directly emitted without treatment, they can pollute over 3.75 billion cubic meters of water bodies, and key components such as C₇H₈ and C₄H₈O₂ require combined treatment technologies like "catalytic degradation + biochar adsorption" for safe processing (Huang Jiazhuo, 2025). By reducing VOC generation at the source, this robotic system directly lowers the cost and complexity of subsequent end-of-pipe treatment, enabling

a "cost-effective" pathway for the shipbuilding industry to achieve its dual carbon goals.

5 | CONCLUSION AND PROSPECT

5.1 | Research conclusion

Ship painting is a critical process in shipbuilding that affects hull protection performance, construction duration, and environmental impact. Traditional manual and semi-automated painting methods have long faced industry challenges such as high pollution, risks, low efficiency, and poor adaptability to curved surfaces. Manual painting operations emit volatile organic compounds without centralized control, causing air pollution in work areas. Workers must operate in complex environments like high-altitude spaces and narrow compartments, increasing safety risks. Manual painting methods relying on experience struggle to ensure uniform coating thickness, with material waste rates typically exceeding 30%. Traditional automated equipment like fixed robotic arms, constrained by rigid structures, cannot adapt to complex hull surfaces with radii of curvature under 5 meters, covering only about 60% of the painting area. Common painting robots suffer from poor adsorption stability and limitations in overcoming wall obstacles. This study, with the core objectives of "complex surface adaptation + intelligent precision control + green efficient operation," achieved breakthroughs through interdisciplinary integration and independently developed an intelligent ship painting robot system. Key research findings include:

5.1.1 | Technological Breakthroughs

Guided by the core demands of "complex surface adaptability, precision spraying control, and safe remote operation," this study integrates mechanical structure design, control algorithm optimization, and system integration innovation, achieving three pivotal technological breakthroughs that address long-standing industry bottlenecks:

High-Stability Magnetic Adsorption Technology for Complex Curved Surfaces Aiming at the technical dilemma of traditional spraying equipment—characterized by poor adhesion reliability and unstable locomotion on ship hulls with variable curvatures (3 m–15 m radius) and distributed weld seams (3 mm–6 mm height)—a triangular layout of "two active driving wheels + one spring-damping driven wheel" is proposed based on the "three-point coplanarity" geometric principle. Customized N52-grade neodymium-iron-boron (NdFeB) magnetic wheels (model: CCT11-D110-d15/20) are adopted, delivering a single-wheel adsorption force of 294 N–343 N, with magnetic performance degradation limited to less than 5% under extreme operating conditions (−20 °C to 80 °C temperature range and 85% relative humidity). To enhance motion stability on curved surfaces, a curvature-aware torque compensation algorithm is developed, which integrates sonar ranging modules (measurement accuracy: ± 2 mm) to collect real-time hull curvature data and dynamically adjust the output torque of the driving wheels (adjustment range: 0 N·m–12 N·m). This ensures the robot's locomotion speed stability is maintained within $\pm 0.02 \text{ m s}^{-1}$. Additionally, the spring-damping mechanism (stiffness coefficient: 50 N mm^{-1}) enables adaptive traversal of weld seams without manual intervention, while the adsorption force remains $\geq 150 \text{ N}$ on curved surfaces with $\pm 15^\circ$ inclination. This breakthrough fundamentally resolves the industry's chronic issues of slipping on curved surfaces and obstacle-crossing instability.

RF-Pulse Coupled Precision Spraying Control Technology To overcome the limitations of manual spraying, such as low paint utilization (40%–55%) and poor coating uniformity (error $> 15\%$), an innovative atomization technology integrating radio frequency (RF) discharge and pulse discharge is proposed. RF electrodes (operating frequency: 13.56 MHz) and pulse discharge modules (pulse frequency: 1 kHz–5 kHz; pulse width: $10 \mu\text{s}$ – $50 \mu\text{s}$) synergistically refine the paint particle size from the traditional $20 \mu\text{m}$ – $50 \mu\text{m}$ to $5 \mu\text{m}$ – $15 \mu\text{m}$, while electrostatic adsorption effect is enhanced to improve the coating transfer efficiency to over 85%. A dynamic parameter adjustment system is developed with the Siemens S7-1200 PLC as the core controller, integrating laser profile sensors (scan frequency: 1000 Hz) to real-time capture hull surface topographic data. Based on the collected data, the system autonomously adjusts key spraying parameters, including robot locomotion speed (0.1 m s^{-1} – 2.3 m s^{-1}), paint flow rate (0 mL min^{-1} – 500 mL min^{-1}), and spray distance ($300 \text{ mm} \pm 20 \text{ mm}$). The results show that the coating uniformity error is controlled within $\pm 4\%$, and the paint utilization rate reaches 92%, reducing material waste by 60% compared to traditional spraying methods.

Dual-Network Collaborative Remote Operation and Multi-Layer Safety Protection Technology To eliminate occupational hazards associated with manual operations in high-altitude and toxic environments, a dual-network communication architecture combining "local Wi-Fi + 4G/5G cloud" is designed. Industrial-grade Wi-Fi (IEEE 802.11ac standard) ensures low-latency local control (delay ≤ 10 ms) within a 50 m range, while 4G/5G communication modules (transmission rate ≥ 100 Mbits⁻¹) establish a secure TLS 1.3 encrypted connection with the cloud platform, enabling 24-hour continuous human-machine separation operation. A multi-layer safety protection system is constructed to guarantee operational reliability: real-time adsorption force monitoring (alert triggered when force drops below 80 % of the rated value) with an emergency electromagnet backup (adsorption force ≥ 200 N); LiDAR-based obstacle avoidance (detection range: 0.1 m–5 m; response time ≤ 50 ms); and dual emergency stop mechanisms (remote and physical). Furthermore, an intelligent fault diagnosis system based on Fault Tree Analysis (FTA) and machine learning algorithms achieves a fault identification accuracy of over 95 %, reducing the average troubleshooting time from 2 h to 30 min. This breakthrough ensures the safety and reliability of the robot in complex shipyard operating environments.

These three technological breakthroughs form an organic closed-loop system covering "adsorption-locomotion-spraying-monitoring-safety," realizing a paradigm shift from "manual-dominated operation" to "intelligent autonomous operation" in the field of ship spraying and providing a replicable technical solution for the industry's green and intelligent transformation.

5.1.2 | Significant Benefits:

The intelligent ship spraying robot system not only enhances operational efficiency but also delivers economic, environmental, and industrial advantages. Building a Collaborative Value System to Provide Comprehensive Support for High-Quality Development in the Shipbuilding Industry: Economic Benefits: On one hand, the "human-machine collaboration" operational model directly reduces labor costs while avoiding safety risks and labor shortages associated with high-altitude work and toxic environments. On the other hand, reduced paint waste and energy conservation further decrease direct material costs and energy expenditures, forming a multi-dimensional cost-saving system encompassing "labor + materials + energy" that generates significant economic benefits for shipyards. Environmental and Safety Benefits: The robotic system achieves substantially lower pollutant emissions in work areas, far exceeding national shipbuilding industry emission standards. Additionally, the remote control system completely eliminates risks for workers operating at heights, in confined spaces, or in toxic environments, fundamentally ensuring personnel safety and resolving the traditional painting industry's dilemma of "high pollution and high risk." Industrial Upgrade Value: As an innovative achievement in intelligent equipment for ship painting, this robot drives the transformation of ship coating from "human-dominated" to "intelligent equipment-dominated," providing critical process equipment support for green and intelligent development in shipbuilding. Its core technological logic can be extended to heavy industrial coating fields such as construction machinery, wind turbine towers, and offshore platforms, contributing to China's industrial upgrading. The manufacturing sector is transitioning toward high-end, intelligent, and green development.

5.2 | future expectations

Currently, intelligent ship spray painting robots have achieved a "from 0 to 1" technological breakthrough and preliminary engineering validation, demonstrating excellent performance in practical applications at multiple shipyards. However, in response to the industry trend of deep transformation towards "digitalization, greening, and servitization" in the shipbuilding sector, as well as the diversified coating requirements for complex products like ultra-large vessels and offshore engineering equipment, the project team will continue to advance technological innovation and scenario expansion, focusing on the following four key development directions:

5.2.1 | Optimization of adaptive performance

For ultra-large curved surfaces of super-sized vessels and irregular structures of marine equipment, further optimize magnetic adsorption structures and path planning algorithms to achieve stable adhesion and flexible movement of robots on surfaces with varying curvatures and material properties. This enhances the robots adaptability to complex hull surfaces. Simultaneously,

lightweight magnetic wheels will be developed to reduce robot weight and energy consumption, further improving operational flexibility and endurance in complex scenarios.

5.2.2 | Integration of intelligent detection and autonomous repair technologies

By combining machine vision, laser line scanning, and infrared thermal imaging technologies, establish a multi-dimensional, high-precision real-time coating defect detection system capable of rapidly identifying common defects such as bubbles, cracks, and thickness variations. Through online monitoring and feedback of coating thickness during spraying, achieve precise control of parameters including spray pressure, flow rate, and speed. Dynamic adjustments ensure the consistency of coating quality; for the detected defective areas, an integrated "inspection-localization-repainting" self-repair module is developed to achieve "closed-loop control" in spraying operations, significantly improving the spraying qualification rate. Meanwhile, a condition monitoring and self-diagnosis system for key components such as adsorption wheels, spray guns, and sensors is developed to enhance equipment operational stability and service life.

5.2.3 | Expansion of application scenarios

Breaking the current limitation of being only applicable to new ship spraying, the application fields are extended to diversified scenarios such as in-service ship maintenance and marine engineering equipment coating, with the development of a series of specialized equipment and dedicated underwater spraying robot versions to meet ship maintenance needs.

5.2.4 | Deep integration with digital shipyards

Strengthening the collaborative linkage between robots and shipyard digital management systems (such as MES, ERP) to achieve intelligent management of the entire spraying process—covering production scheduling, material control, quality traceability, etc.—ensuring the integration of data flow, business flow, and resource flow from the "design end" to the "operation and maintenance end", thereby comprehensively enhancing the intelligence level of the shipbuilding industry. This series of technological upgrades will drive the intelligent ship spraying robot from a "single operational equipment" to an "intelligent ship coating solution," not only helping China's shipbuilding industry consolidate its global competitiveness but also facilitating the intelligent transformation of the heavy industry sector. This model provides replicable technical paradigms. Moving forward, the technology will evolve through iterative advancements, scenario-based expansion, digital integration, and sustainable green development.

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REFERENCES

- [1] Zhang W, Bin G, Xu G, Yang W. Simulation Analysis of Magnetic Attraction Force for N-S Alternately Arranged Magnetic Tile-type Magnetic Wheels. *Automation & Instrumentation* 2025;40(10):128–130+136.

- [2] Sun Y. Research on Trajectory Planning Algorithm for Industrial Robots Based on Cubic B-spline with Curvature Constraints. PhD thesis, Harbin Institute of Technology; 2024.
- [3] Lu B, Tang D, Hu Y, Che J, He Y. Design and Parameter Optimization of Permanent Magnet Wheels Based on Reliable and Stable Adsorption of Bilateral Halbach Array. *Journal of Engineering Design* 2025;p. 1–12.
- [4] Chu H. Design and Research of a Magnetic Adsorption Spraying Robot. PhD thesis, Hubei University of Arts and Science; 2025.
- [5] Ji J, Zhang Y, Su C. Interpretation of GB 38469—2019 "Limits of Hazardous Substances in Ship Coatings". *Coating and Protection* 2022;43(04):1–4.
- [6] Wang T, Shi Y, Cui C, Chen S. Technology of Underwater Cleaning and Inspection Robot Based on Magnetic Adsorption and Rolling Mechanism. *Petrochemical Industry Technology* 2025;32(07):154–156.
- [7] Yan H, Xu F, Zhang Y. Optimal Design of Permanent Magnet Wheels for Wall-climbing Robots. *Journal of Shandong Jiaotong University* 2025;33(03):79–85.
- [8] Xu X, Zhang B. Design and Optimization of Magnetic Wheel Mechanism for Pipeline Robots. *Journal of Machine Design* 2025;42(06):165–173.
- [9] Xu J. Mechanical System Design and Motion Condition Study of Wall-adaptive Magnetic Wall-climbing Robot. PhD thesis, Southeast University; 2021.
- [10] Sun Y. Research on Painting Trajectory Planning Method Based on Surface Segmentation. PhD thesis, Harbin Institute of Technology; 2018.
- [11] Liu L, Li K. Design of a Permanent Magnet Wheel Wall-climbing Robot. *Mechanical Engineering & Automation* 2025;54(02):128–130.
- [12] Organization IM. Performance Standard for Protective Coatings (PSPC) for Ship Ballast Tanks. *Ship Standardization Engineer* 2012;45(02):52–54.



Can Wang is a Robot Engineering student at Wuhan University of Science and Technology, led the intelligent ship spraying robot project from conception to implementation. He designed the core “three-wheel magnetic adsorption, precise spraying, and remote operation” system, solving key challenges such as stable adsorption on curved surfaces and achieving over 80% paint utilization. He also coordinated field testing and led the paper writing, contributing directly to the project’s technical and academic outcomes.



Lei Cheng is Vice Dean of the School of Artificial Intelligence and Automation at WUST, provided pivotal guidance throughout the research. He defined the core technical framework, oversaw key breakthroughs in curved-surface adsorption and precision spraying, and guided experimental verification and industry collaboration. His leadership in team coordination and rigorous academic standards was fundamental to the project’s success in both technological innovation and practical application.



Yue Xu is a Financial Technology sophomore at WUST and a national award winner, led the performance testing and application verification for the ship spraying robot project. She designed and executed a comprehensive evaluation based on real shipyard conditions, analyzing coating quality and efficiency to validate the system's practical value in significantly reducing cycles and cost. Demonstrating strong interdisciplinary and project management skills, she effectively advanced core tasks including data organization and result validation.



Leyi Zhang is majoring in Information Management and Information Systems at WUST, possesses a solid technical foundation. She applied her analytical skills to this project by conducting a comprehensive economic and social benefits analysis. Her work involved quantifying key financial indicators and assessing the project's broader social impact, providing critical data and a robust framework for evaluating its overall feasibility and sustainability.



Youyou Li is a sophomore in Economics and Management (Accounting) at WUST's Xiangtao College, ranking among the top 15 in her major. A recipient of a university-level scholarship, she has also passed the National Computer Rank Examination (Level 2). Proficient in WPS and equipped with fundamental accounting skills, she applies her strong teamwork abilities to pursue practical experience in financial and corporate management.



Jiahao Fan is an undergraduate student (Class of 2023) at the School of Artificial Intelligence and Automation, Wuhan University of Science and Technology. He contributed to the university-level project "Intelligent Marine Spraying Robot" (2025-2026), primarily responsible for literature review, industry research, and competitive product analysis. Skilled in using Python pandas for data processing, he has been awarded the Special Scholarship of Wuhan University of Science and Technology (2025) and the University-level Outstanding Student Model honor (2023, 2024).