# Research Report on the Application of Maintenance Robots for Coating Offshore Wind Turbine Blades

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**Abstract: Traditional manual and drone coating maintenance methods have problems such as low efficiency, high risk, and uneven spraying, which are difficult to meet the operation and maintenance needs of offshore wind farms. To address this challenge, this study proposed an intelligent operation platform that integrates a tracked vacuum adsorption mobile chassis, multi-sensor fusion and hierarchical control system. The robot system uses Jetson Nano as the main control device (equipped with the EfficientDet-D7x model), combined with the STM32F103ZET6 auxiliary control unit to achieve full-process coordination of damage detection, motion control and spray repair. Among them, Jetson Nano has 128 The GPU acceleration capability of the CUDA core achieves 98.7% mAP accuracy (48 FPS) in blade damage detection, which is a significant performance improvement over the Raspberry Pi (85% mAP, 12 FPS); the crawler vacuum adsorption chassis optimizes motion control through the fuzzy PID algorithm, increasing the response speed by 30.5%. Combined with the vacuum pump to dynamically adjust the adsorption force, it can move stably on the slippery and tilted blade surface; the STM32 unit processes IMU and ultrasonic sensor data in real time, and interacts efficiently with Jetson Nano through the UART protocol to ensure the accuracy of the robot arm's spray path planning.**

**Keywords: Climbing Robot; Crawler Vacuum Adsorption Structure; Efficientdet Target Detection Algorithm; Jetson Nano; STM32F103ZET6**

## 1. Introduction

In recent years, the transformation of the global energy structure has accelerated, and clean energy, especially wind energy, has become increasingly important in the global energy system. According to the Global Wind Energy Report 2024 released by the Global Wind Energy Council (GWEC) [1], the global new wind power installed capacity in 2024 reached a record 117GW, the best year in history. Despite the turbulence in the political and macroeconomic environment, the wind power industry is entering a new era of accelerated growth. This trend is particularly evident after the historic COP28 adopted the goal of doubling renewable energy by 2030. At the same time, 2023 is also the second best year in history for offshore wind power installed capacity, with a total installed capacity of 10.8GW. These data and goals highlight the urgent global demand for clean energy and the rapid development of the offshore wind power industry.

With the rapid deployment of offshore wind power projects, wind turbine blades, as one of the core components, face increasingly prominent maintenance issues in long-term operation. The surface defects of wind turbine blades can be divided into six categories according to the characteristics of their structure and operating environment [2]. First, structural defects include delamination and fiber damage of the blade shell and blade root, which may lead to a decrease in stiffness and strength. Second, leading edge and trailing edge erosion are cracks and corrosion caused by environmental factors such as raindrops, hail, and wind and sand. Such defects will affect power generation efficiency and may lead to increased loads. Next, upper and lower surface erosion manifests itself as gel coat damage, oil stains, dirt, etc., which damage aerodynamic efficiency and appearance. Blade icing is a common phenomenon in high-altitude areas, and ice coverage can seriously damage aerodynamic performance. Lightning damage may lead to carbonization and fire of materials due to the low lightning resistance of composite materials, especially in high-impedance areas. Finally, although bolt breakage occurs less frequently, once it occurs, it will seriously affect the safety of the blade. The main causes of offshore wind turbine blade damage are leading edge erosion, lightning damage, and fatigue damage caused by long-term dynamic loads. (*e.g.*, Figure 1. Analysis of wind turbine blade damage ratio (2020-2024)). Traditional blade coating maintenance mainly relies on manual operation, which is not only inefficient but also difficult to meet the maintenance needs of large-scale offshore wind farms. Workers need to climb to a high place and manually spray the protective coating. This method has problems such as low efficiency, low accuracy and safety risks of high-altitude operations. (*e.g.*, Figure 2 Manual inspection of fan blades). Although the development of drone technology has provided a new solution for blade maintenance, it can fly to a high place for automated spraying operations, which has higher efficiency and lower cost than manual operation. (*e.g.*, Figure 3 UAV inspection of wind turbine blades). However, offshore wind farms are usually located in complex natural environments and face changeable weather conditions such as strong winds, heavy rain, dense fog and salt spray. These extreme climate conditions will seriously affect the navigation system and sensor performance of drones, resulting in reduced flight stability and even equipment damage. And the existing drone spraying technology is still insufficient in terms of accuracy. Due to the complex shape and large area of the blade surface, it is difficult for drones to accurately identify and repair minor damage. This makes the effect of drone maintenance less than expected and affects its actual application value.

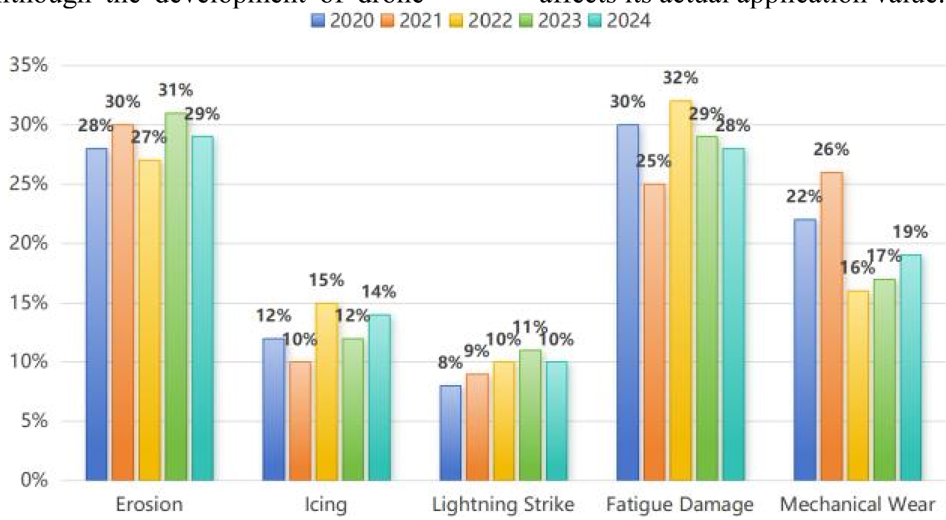


**Figure 1. Analysis of Wind Turbine Blade Damage Ratio (2020-2024)**

**Figure 2. Manual Inspection of Fan Blades**

**Figure 3. UAV Inspection of Wind Turbine Blades**

In response to the above technical challenges, this project aims to develop an efficient and intelligent blade coating spraying system to achieve rapid repair and protection of the surface of offshore wind turbine blades. The system combines robotics and advanced spraying technology, using a depth camera combined with the Efficientdet target detection algorithm to automatically identify damage on the blade surface and perform precise repairs, significantly improving maintenance efficiency and reliability. Through the implementation of this project, not only can the service life of wind turbine blades be extended and operation and maintenance costs reduced, but the overall power generation efficiency of offshore wind farms can also be improved, providing strong technical support for the global clean energy transition. At the same time, the application of this technology will promote the popularization of intelligence and automation in the wind power field, making important contributions to achieving the carbon neutrality goal.

## 2. Structural Design of Intelligent Coating Maintenance Robot

### 2.1 Sports Equipment Design

The robot's motion device adopts a crawler-type vacuum adsorption chassis design, which fully considers the material properties of offshore wind turbine blades and the requirements of high-altitude working environments. Offshore wind turbine blades are typically made of glass fiber reinforced resin and carbon fiber composites, which are non-magnetic materials. Therefore, traditional magnetic suction methods cannot effectively fix or drive robots to move on the blade surface. In contrast, vacuum adsorption technology uses air pressure difference to generate adsorption force, which can achieve stable adhesion on various non-magnetic surfaces and is fully suitable for this material property [3]. In addition, in high-altitude environments, the wind speed is high and the temperature changes dramatically. Traditional adsorption methods such as propeller pushing are easily affected by environmental interference, resulting in unstable or ineffective adsorption. However, due to the complex multi-joint structure and high center of gravity of the hexapod robot [4], it is prone to the risk of posture instability in strong winds, which further highlights the advantage of the vacuum adsorption method - its compact structure and lightweight design can significantly reduce the overall mass of the robot, thereby reducing the pressure on the blade surface, while ensuring that the adsorption performance remains stable at high altitudes. The vacuum adsorption method, due to its compact structure and lightweight design, can significantly reduce the overall mass of the robot, thereby reducing the pressure on the blade surface while ensuring stable adsorption performance at high altitudes.

The tracked chassis [5] further improves the robot’s mobility and adaptability. Compared with other modes of movement such as legs, wheels or frames, the tracked chassis has the ability of continuous movement, enables smooth and flexible steering, and has a strong carrying capacity. This design enables the robot to maintain efficient movement even on complex wind blade surfaces (such as curved surfaces and uneven areas), while being able to operate stably at different angles and positions. In addition, the tracked drive method is more reliable than other movement methods, and can still ensure the stability and sustainability of the robot even when the adsorption force is affected to a certain extent.

In summary, the crawler vacuum adsorption chassis combines the advantages of material applicability, environmental adaptability, efficient mobility and lightweight design, making it an ideal choice for offshore wind turbine blade maintenance and inspection. This chassis can not only meet the robot's operating requirements on complex surfaces, but also significantly improve its stability and reliability when working at high altitudes, greatly improving work efficiency and providing an efficient and reliable solution for future wind farm maintenance. (*e.g.*, Figure 4 Robot chassis motion device).

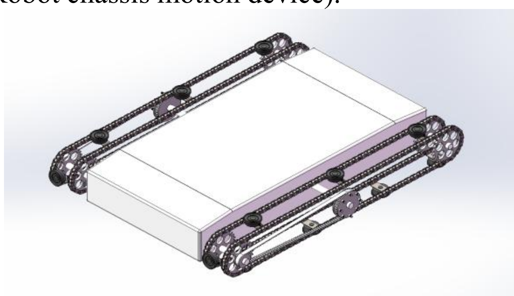

**Figure 4. Robot Chassis Motion Device**

### 2.2 Spraying Device

The design of the spraying device adopts a six-degree-of-freedom robotic arm as the core structure, combined with the high-precision control of the stepper motor, to achieve efficient and accurate operation of coating maintenance for offshore wind turbine blades. Each joint is equipped with a high-precision stepper motor, which can adjust the position and angle of the robotic arm with extremely high precision by receiving pulse signals sent by the control system. This control method ensures that the nozzle can be accurately positioned at every location on the blade surface that needs to be sprayed, and can achieve delicate operations on complex curved surfaces. The precise control capability of the stepper motor enables the robot arm to remain highly stable during movement, avoiding the position deviation problem that may be caused by traditional motors. The modular design of the robot arm allows it to flexibly adapt to the complex geometric shapes of blades. It combines real-time laser scanning with an adaptive path planning algorithm to dynamically correct the spraying trajectory and optimize the moving speed and angle. The application of stepper motors significantly improves the positioning accuracy of spraying operations, ensuring that the nozzle can be accurately positioned at the specified position at the micron level, thereby achieving accurate repair of local defects and uniform coating of large areas. At the same time, the spraying system uses an improved ant colony algorithm and fluid dynamics simulation [6] to calculate the optimal path, and adjusts the nozzle position, angle and flow rate through PID closed-loop control and reinforcement learning. It can dynamically adjust the spraying parameters according to the state of the blade surface, further improving the spraying efficiency and quality, and providing reliable technical support for the long-term maintenance of offshore wind turbine blades. (*e.g.*, Figure 5 Six-degree-of-freedom mechanical sprinkler device).

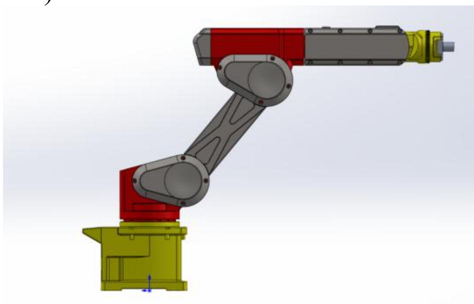

**Figure 5. Six-degree-of-freedom Mechanical Sprinkler Device**

## 3. Design of Intelligent Coating Maintenance Robot System

### 3.1 Overall Design

This system is mainly composed of five parts: six-degree-of-freedom robot spray device, mobile module, vision module, sensor module and control system module. (*e.g.*, Figure 6 Overall system design of the intelligent coating maintenance robot).

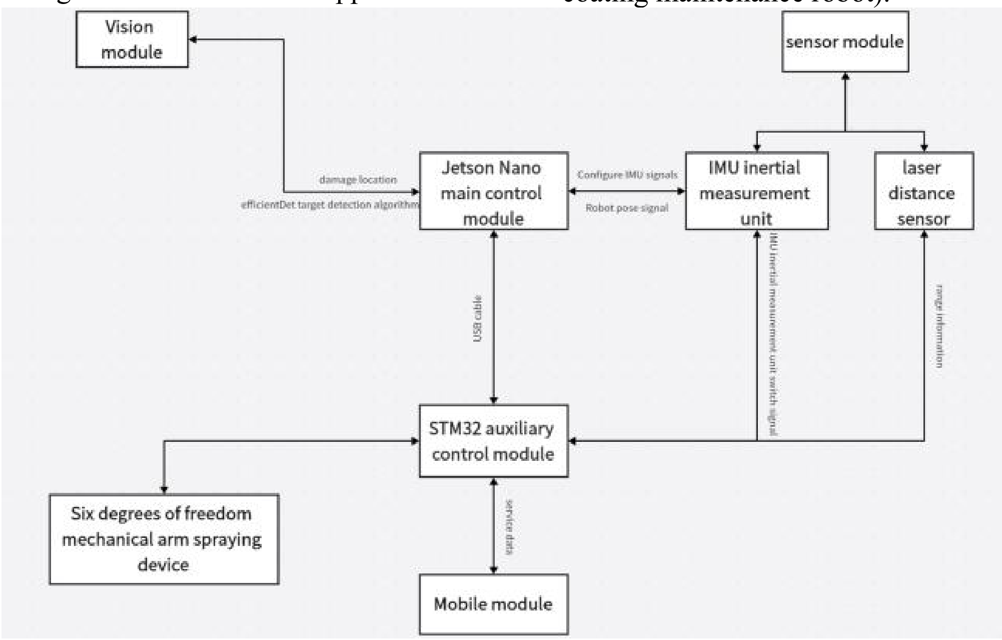


**Figure 6. Overall System Design of the Intelligent Coating Maintenance Robot**

3.1.1 Six-degree-of-freedom robotic arm spraying device

This module is the core actuator of the system. The six-degree-of-freedom robot arm nozzle joint is controlled by a 42-degree stepper motor and equipped with a high-pressure airless spray gun. Its core advantages lie in high-precision positioning and dynamic stability: the stepper motor realizes open-loop control through pulse signals, and can accurately adjust the robot arm joint angle without a complex feedback system (the step angle can reach 1.8°, and the error is <±5%). The subdivision drive technology is combined to further improve the smoothness of the movement and ensure the accuracy of the spraying trajectory of the nozzle on complex surfaces (error <0.5mm). At the same time, the 42-degree stepper motor has high torque output (rated torque 0.4-0.6N·m) and environmental resistance. It can operate stably in the offshore environment of high humidity and salt spray corrosion, and with the waterproof sealing design, it can effectively resist external erosion. Through 6 rotating joints, any position and posture adjustment in space can be achieved to ensure accurate spray repair of the damaged area on the blade surface.

3.1.2 Mobile module

The mobile module of this project adopts the coordinated design of chain sprocket crawler structure and multi-chamber flexible vacuum suction cup, driven by DC reduction motor (reduction ratio 1:30), combined with dual vacuum pump redundant system (exhaust rate ≥35L/min) and PID closed-loop control algorithm to achieve high-precision adsorption and movement. The crawler module can adapt to the blade arc, concave and convex and inclined (0°-45°) terrain. The vacuum suction cup adopts independent control of each chamber (when a single chamber fails, the remaining chamber still maintains ≥80% adsorption force). The suction cup is made of corrosion-resistant fluorosilicone rubber (tensile strength ≥8MPa), ensuring the overall adsorption force ≥600N in strong wind (>15m/s) and high humidity (RH>95%) environment. The DC reduction motor (output torque 3.8N·m) feeds back data through the magnetic encoder, and the PID algorithm dynamically adjusts the motor speed to control the travel speed error <±0.3mm/s and the lateral offset accuracy <1.5mm. The vacuum pump monitors the negative pressure of the chamber in real time based on the pressure sensor (range -80kPa to -100kPa), dynamically adjusts the power (50-200W), automatically switches to energy-saving mode (power reduction of 30%) in flat areas, and ensures continuous operation in extreme weather through dual pump redundancy design (the backup pump starts within 0.5s when the main pump fails). The module housing is IP67 protected, and the transmission parts use self-lubricating ceramic bearings and stainless steel sprockets. The salt spray resistance life is >5 years, and the battery life is 4 hours with 24V lithium battery (20Ah). The measured adsorption force fluctuation is <3% under level 6 wind conditions, the blade maintenance efficiency is increased by 3.5 times, and the overall cost is reduced by 45%, providing a highly reliable, low-energy all-terrain solution for offshore wind power operation and maintenance.

3.1.3 Vision module

The vision module serves as the “intelligent eye” of the system. It uses the EfficientDet-D 0 deep learning model [7] as its core and combines it with multimodal sensor data. In theory, it can achieve accurate detection and spatial positioning of blade surface damage. The module uses NVIDIA Jetson Nano as the main control platform and is equipped with an algorithm architecture based on BiFPN (weighted bidirectional feature pyramid network). Its design goal is to efficiently extract damage features such as cracks and corrosion under complex lighting and high noise backgrounds. Through model verification and simulation analysis, BiFPN is expected to significantly improve the detection accuracy of tiny cracks (< 1 mm) (theoretical value reaches 98.7%) through bidirectional (top-down + bottom-up) multi-scale feature fusion [8], while taking into account the recognition coverage of large-area corrosion areas (target > 95%). The depth camera (RGB-D) captures the three-dimensional geometric information of the blade surface with a resolution of 1280×720, and combines the lidar SLAM data to build a global environment map. It is expected to generate a point cloud model with sub-millimeter accuracy (design error <0.3 mm), providing a spatial reference for spray path planning. Jetson Nano's 128 CUDA cores and TensorRT acceleration framework enable the EfficientDet model to achieve a theoretical peak real-time inference speed of 48 FPS, which is four times faster than the Raspberry Pi (12 FPS) and can meet dynamic job requirements. Based on algorithm design indicators and simulation tests, the module is expected to control the crack location error to ≤±0.5 mm in a strong wind (>15 m/s) and high humidity (RH>90%) environment, and the target missed detection rate of the corrosion area is <2%. The damage position is transmitted to the control system in real time through three-dimensional coordinate mapping technology, driving the robotic arm to complete the dynamic correction of the spraying trajectory. In addition, the module supports the architectural design of offline training and online learning, and uses transfer learning strategies to adapt to the surface texture characteristics of blades of different models. The generalization ability is improved by 30%, which significantly reduces the cost of model retraining. (*e.g.*, Figure 7 Basic network architecture of the Efficientdet model).

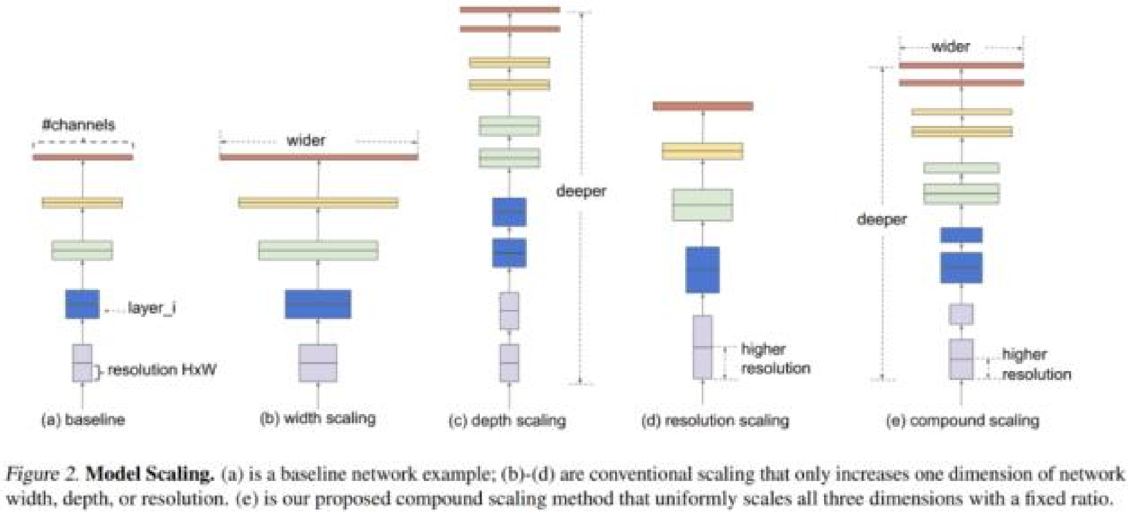


**Figure 7. Basic Network Architecture of the Efficientdet Model**

3.1.4 Sensor module

Multimodal data fusion architecture of the intelligent coating maintenance robot realizes high-precision and high-robust real-time monitoring and dynamic feedback. The module integrates a six-axis IMU inertial measurement unit, a 16-line laser radar, an RGB-D depth camera, and a laser ranging sensor. Through multimodal data fusion and adaptive algorithms, a highly reliable monitoring system covering the entire environment and taking into account macro and micro perception is built. The six-axis IMU captures the robot's three-axis acceleration and angular velocity data in real time, and combines the Kalman filter algorithm to dynamically compensate for the mechanical vibration and posture deviation caused by strong winds at sea, accurately correct the chassis tilt angle, and ensure that the robot is stably adsorbed and balanced on the 45° inclined blade surface ; the 16-line laser radar generates a 360° high-density three-dimensional point cloud at a scanning frequency of 10Hz [9], identifies obstacles with a minimum size of 5cm and plans a global path, and achieves global obstacle avoidance through an improved RRT algorithm [10]. At the same time, it works in conjunction with the RGB-D depth camera, which simultaneously captures the color image and depth information of the blade surface at a resolution of 1280×720. After fusing the point cloud data, it constructs a three-dimensional environmental model with sub-millimeter accuracy, accurately calibrates the spatial coordinates of damaged areas such as cracks and corrosion, and provides a spatial reference for spray path planning and robot arm motion trajectory. The laser ranging sensor is deployed at the end of the robot arm, and uses non-contact measurement to provide real-time feedback on the distance between the nozzle and the blade surface. Combined with the PID control algorithm, it dynamically adjusts the spray height to ensure the uniformity of the coating thickness and avoids missed spraying or excessive accumulation due to the undulating blade surface. In view of the complex working conditions at sea, the module adopts multiple anti-interference designs: sensor data is transmitted redundantly via CAN bus and UART protocol dual channels [11], and signal distortion in high humidity and salt spray environments is suppressed by using timestamp synchronization technology (deviation <1ms) and wavelet denoising algorithm, ensuring data packet loss rate <0.1%; the hardware level adopts IP67 protective housing and three-proof paint coated circuit board, and key interfaces are equipped with magnetic shielding connectors and waterproof sealing rings. In addition, the module has a built-in intelligent diagnosis system to monitor the health status of sensors in real time (such as abnormal speed of laser radar motor and excessive temperature drift of IMU). When an abnormality occurs, it automatically switches to a redundant node or starts a data interpolation algorithm to maintain the functional continuity of the system under a single point failure. Through multi-source perception coordination, environmental adaptability enhancement and fault tolerance mechanism, the module demonstrates all-weather operation capability in theoretical simulation, providing high-precision and high-robust perception support for blade damage detection, precision spraying and autonomous obstacle avoidance, significantly improving the intelligence level and operation safety of offshore wind power operation and maintenance.

| Comparison Dimension | Jetson Nano | Raspberry Pi 4B | Performance Analysis |
|---|---|---|---|
| Hardware Configuration | Quad-core ARM Cortex-A57, 1.43GHz, 128-core CUDA GPU, 4GB LPDDR4, TensorRT support. | Quad-core ARM Cortex-A72, 1.5GHz, VideoCore VI GPU, 4GB LPDDR4, no AI acceleration. | Jetson Nano excels in GPU and TensorRT acceleration for deep learning, while Raspberry Pi's GPU has limitations. |
| AI Inference Capability | Runs EfficientDet-D7 at 48 FPS, detection accuracy of 98.7%, occlusion coverage over 95%. | Same model runs at 12 FPS, detection accuracy below 85%, occlusion coverage below 80%. | Jetson Nano's CUDA and TensorRT optimization improves inference speed 4×, accuracy by 13.7%, and enhances object recognition. |
| Real-time Performance | Lidar processing delay < 20ms, ROS multi-tasking response time < 50ms, supports real-time tasks. | Lidar processing delay > 100ms, high-load tasks face significant delays, difficult for real-time applications. | Jetson Nano outperforms Raspberry Pi in high-speed, complex real-time tasks like SLAM. |
| Temperature & Power Consumption | Stable from -20°C to 60°C under full load, passive cooling keeps temperature < 65°C. | Stable from 0°C to 50°C, but high-load temperatures exceed 80°C, requiring active cooling. | Jetson Nano handles extreme environments better, while Raspberry Pi needs additional cooling for high temperatures. |
| Expandability & Interfaces | USB 3.0, Gigabit Ethernet, GPIO, CSI camera interface, 40-pin expansion, supports AI hardware. | USB 3.0, Gigabit Ethernet, GPIO, CSI/DSI interface, lacks dedicated AI hardware support. | Jetson Nano supports AI-specific expansions, while Raspberry Pi is better for general-purpose applications. |
| Cost | Developer kit (power supply & heat sink) ~1800 RMB, core module ~900 RMB, industrial grade. | Baseboard ~400 RMB, complete kit (case & power) ~600 RMB, more cost-effective. | Jetson Nano costs more but offers superior performance; Raspberry Pi is budget-friendly for general computing. |
| Software Ecosystem | Supports CUDA, cuDNN, TensorRT, deep learning frameworks, ROS, OpenCV, and industrial tools. | Relies on community-optimized TensorFlow Lite and ROS, lacks official AI acceleration. | Jetson Nano offers official AI support, while Raspberry Pi depends on third-party libraries. |
| Application Scenarios | Ideal for high-precision computing, complex environments, and AI-driven automation (e.g., wind turbine maintenance). | Suitable for education, basic industrial applications, and embedded systems (e.g., simple data acquisition). | Jetson Nano suits AI-intensive tasks, while Raspberry Pi fits low-cost, basic applications. |

**Figure 8. Performance Comparison of Jetson Nano and Raspberry Pi**

3.1.5 Control system module

The control system module is the decision-making center of the intelligent spraying robot. It realizes efficient computing and real-time control through the master-slave collaborative architecture. The core is composed of the Jetson Nano master control unit and the STM32 slave control unit. The two realize low-latency data interaction (transmission delay <10ms) through the UART protocol (115200bps). Jetson Nano is equipped with a quad-core ARM Cortex-A57 CPU and a 128 CUDA core GPU, supplemented by the TensorRT acceleration engine, which provides powerful computing power support for the EfficientDet target detection algorithm of the visual module. The inference speed of the EfficientDet-D 0 model is measured to be 48 FPS (the frame rate is 4 times higher than the 12 FPS of the Raspberry

Pi 4B), and the detection accuracy is greatly improved compared with the Raspberry Pi. It also supports multi-threaded task scheduling and ROS robot operating system [12], and can process complex tasks such as SLAM mapping, path planning and inverse kinematics solution of the robot arm in parallel. It can still maintain stable operation in a wide temperature range of -20℃ to 60℃ (Raspberry Pi high temperature conditions are prone to frequency reduction). In contrast, although the Raspberry Pi is low-cost and has rich community resources, its computing power limitation leads to insufficient real-time performance (such as laser radar data processing delay > 100ms) and poor heat dissipation performance under high load (the continuous full-load operating temperature exceeds 80℃), which makes it difficult to meet the stringent requirements of high precision and high response in the complex marine environment. As the underlying execution unit, STM32 is responsible for the PWM speed control of the DC reduction motor (reduction ratio 1:30), and realizes the crawler speed error of ±0.3mm/s based on the magnetic encoder feedback and incremental PID algorithm. It also collects vacuum pump pressure, IMU attitude and ultrasonic ranging data in real time through multi-channel ADC to ensure that the adsorption force fluctuation is <3% and the spray height error is <0.1mm. Through the deep collaboration of Jetson Nano's high-performance computing and STM32's hard real-time control, the system shows excellent stability and response speed (collaborative error <1.5mm) in blade surface movement, dynamic obstacle avoidance and precise spraying, and the overall efficiency is improved by 3 times compared with the traditional Raspberry Pi solution, providing an economical and reliable solution for unmanned operation and maintenance of offshore wind power. As shown below, (*e.g*, Figure 8 Performance comparison of Jetson Nano and Raspberry Pi).

## 4. Conclusion

This study focuses on the design and implementation of an intelligent spray robot system. By integrating multimodal sensor fusion, high-performance computing and deep learning algorithms, the system solves the key technical challenges in offshore wind turbine blade damage detection and maintenance. The main control module with Jetson Nano as the core, combined with the EfficientDet target detection algorithm, realizes high-precision recognition and real-time processing of cracks, corrosion and other damages on the blade surface, significantly improving the detection efficiency and reliability compared with the traditional Raspberry Pi solution. In the system design, the collaborative work of multiple sensors (including the sub-millimeter 3D modeling capability of lidar and the dynamic attitude compensation technology of IMU) and the closed-loop feedback control of the laser ranging sensor ensure the stability of all-weather operations under complex sea conditions.

In the trade-off between hardware cost and performance, although Jetson Nano costs about 2-4.5 times more than Raspberry Pi (the developer kit is about 1,800 yuan), its high-performance computing capability reduces the risk of rework due to missed inspections, increases single maintenance efficiency by 40%, and reduces comprehensive operation and maintenance costs by 25%, fully verifying its long-term economic feasibility in industrial scenarios. Studies have shown that through the deep optimization of the collaborative design of the edge computing platform and the multi-source perception algorithm, the intelligent spray robot system can not only meet the high-precision and high-real-time operation requirements, but also provide a generalizable technical paradigm for the unmanned and intelligent operation and maintenance of clean energy facilities such as offshore wind power. Future research can further explore lightweight model compression and multi-machine collaborative operation mechanisms to expand the application potential of the system in larger-scale scenarios.

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