

Design of a Dynamic Industrial Inspection System Based on the Internet of Things

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Abstract: Traditional industrial inspection relies on fixed sensors and cameras, which suffer from limited monitoring range, incomplete field perception and high hardware costs, failing to meet the real-time and comprehensive monitoring demands of modern industrial production under Industry 4.0. To address these issues, this paper designs a dynamic industrial inspection system based on the Internet of Things, which deploys a highly integrated inspection device on a customizable O-shaped closed track. The device integrates a drive motor with an encoder, a 3D pan-tilt, a high-definition camera, and multi-type environmental sensors, and adopts STM32F103C8T6 as the core controller, matching OpenMV for image acquisition and ESP8266 for wireless communication. The system realizes dynamic patrol of industrial sites through orbital movement, adjusts the camera angle in real time via pan-tilt inverse kinematics solution, and transmits image and environmental data to the upper computer for real-time processing by the YOLOv8 model, realizing accurate target recognition, product defect detection and environmental safety monitoring. It also achieves precise positioning and calibration of the inspection device through encoder integration and infrared sensor recognition. Physical tests show that the system can comprehensively monitor industrial sites with fewer detection devices, realize fast and accurate target recognition and real-time environmental monitoring, and effectively improve the efficiency and intelligence of industrial inspection while reducing hardware costs. The research provides a practical technical solution for the intelligent transformation of industrial on-site monitoring.

1. Introduction

1.1. Research Background and Significance

With the in-depth promotion of Industry 4.0, industrial automation has become the core of manufacturing transformation, and the complexity of industrial production sites raises higher requirements for real-time and comprehensive on-site inspection. Traditional industrial monitoring relies on fixed sensors and cameras, which have the defects of limited monitoring range, perception blind spots, high hardware costs and low intelligent processing efficiency, failing to meet the dynamic monitoring needs of modern production and bringing potential safety hazards to the stable

operation of production lines^[1]. Against this background, developing an IoT-based dynamic industrial inspection system is of great practical significance. The system can realize full coverage of industrial site monitoring with fewer detection devices, reduce hardware input while improving the real-time and comprehensiveness of inspection, and provide technical support for the intelligent upgrade of industrial on-site management and the guarantee of production safety.

1.2. Research Status at Home and Abroad

Foreign research on industrial inspection started early, and the related systems have realized the integration of multi-sensor data and cloud platform management, with high precision in target recognition and environmental monitoring^[2]. However, most of these systems are customized for specific industrial scenarios, with high equipment costs, poor scalability and difficulty in large-scale popularization in ordinary production sites. Domestic research on industrial intelligent inspection is developing rapidly, and many scholars have designed monitoring systems combining single-chip microcomputers and sensors, which have realized the basic collection of environmental parameters and simple visual detection^[5]. But there are still prominent problems such as single monitoring mode, lack of dynamic patrol function, low integration of machine vision and embedded control, and slow response of intelligent recognition, which make it difficult to meet the multi-dimensional and high-efficiency monitoring needs of modern industrial production sites.

1.3. Main Research Content and Structure

Aiming at the shortcomings of the existing industrial inspection system, this paper designs an IoT-based dynamic industrial inspection system with STM32F103C8T6 as the core controller^[1]. The system deploys a highly integrated inspection device on a customizable O-shaped closed track, integrating 3D pan-tilt, high-definition camera, multi-type environmental sensors and precise positioning modules, and combines OpenMV, YOLOv8 and ESP8266 to realize dynamic patrol, precise positioning, multi-parameter environmental monitoring and intelligent target recognition. The research objective is to solve the problems of limited monitoring range, high hardware costs and low intelligence of traditional fixed inspection systems, improve the efficiency and comprehensiveness of industrial on-site inspection, and provide a practical and low-cost technical solution for the intelligent transformation of industrial monitoring.

2. Related Technical Foundations

2.1. Internet of Things and Embedded Control Technology

The system adopts STM32F103C8T6 as the core embedded controller, a high-performance and low-power chip based on the ARM Cortex-M3 core, with rich on-chip peripherals including GPIO, UART and ADC interfaces, which realizes seamless connection with sensors, pan-tilt and communication modules. Combined with IoT technology, the controller realizes real-time data interaction between the on-site inspection device and the upper computer through the ESP8266 Wi-Fi module, completing the collection, transmission and feedback of industrial site environmental and visual detection data, and providing a reliable hardware and communication core for the stable operation of the dynamic inspection system^[2].

2.2. Machine Vision and Deep Learning Technology

Machine vision is the core of the system's intelligent detection, with OpenMV as the on-site

image acquisition module, which captures high-definition real-time images of the industrial site and completes basic image preprocessing and target positioning. For complex detection tasks, the collected image data is transmitted to the upper computer, and the YOLOv8 deep learning model is deployed for high-precision and real-time target recognition and product defect detection. YOLOv8 adopts an anchor-free detection head and an optimized network structure, which has the advantages of fast inference speed and high recognition accuracy, and can quickly identify multiple targets in the industrial site to meet the real-time demand of dynamic inspection^[1].

2.3. Multi-sensor Fusion and Precise Positioning Technology

Multi-sensor fusion technology integrates temperature and humidity, smoke, infrared and encoder sensors to realize comprehensive monitoring of industrial site environmental parameters and device position information. Environmental sensors collect real-time data of temperature, humidity and smoke concentration on site to realize early warning of potential safety hazards; the encoder realizes preliminary positioning of the inspection device through the integral function, and the infrared sensor calibrates the position by scanning the color marks on the track, which ensures the precise positioning of the device during dynamic patrol^[5]. The fusion of multiple sensors makes the system's detection and positioning more comprehensive and accurate.

2.4. Kinematics and Motion Control Technology

The 3D pan-tilt motion control is based on kinematics inverse solution technology. According to the target center coordinate information identified by the machine vision module, the system inversely calculates the rotation angle of each joint of the pan-tilt through PD control algorithm, and drives the steering gear to adjust the pan-tilt and camera angle in real time, so as to realize the accurate tracking and comprehensive detection of the target^[2]. The drive motor with encoder cooperates with the orbital motion system to realize the stable and controllable movement of the inspection device on the O-shaped closed track, forming a dynamic patrol system with adjustable detection angle and movable detection position^[3].

3. Overall System Design

3.1. Overall System Architecture

The dynamic industrial inspection system adopts a modular three-layer architecture of perception layer, control layer and application layer, with STM32F103C8T6 as the core controller, as shown in Figure 1. The perception layer is composed of multi-type sensors including temperature and humidity, smoke alarm, infrared sensor, encoder and OpenMV camera, which is responsible for collecting industrial site environmental parameters, equipment position information and on-site image data. The control layer takes STM32F103C8T6 as the core, matching with ESP8266 Wi-Fi module, servo drive circuit and motor control module, completing data processing, motion control, local logic judgment and data packaging upload. The application layer is the upper computer management end, which realizes real-time display of monitoring data, intelligent target recognition based on YOLOv8 model, remote motion control and abnormal alarm push, forming a closed-loop system of "collection-control-identification-management".

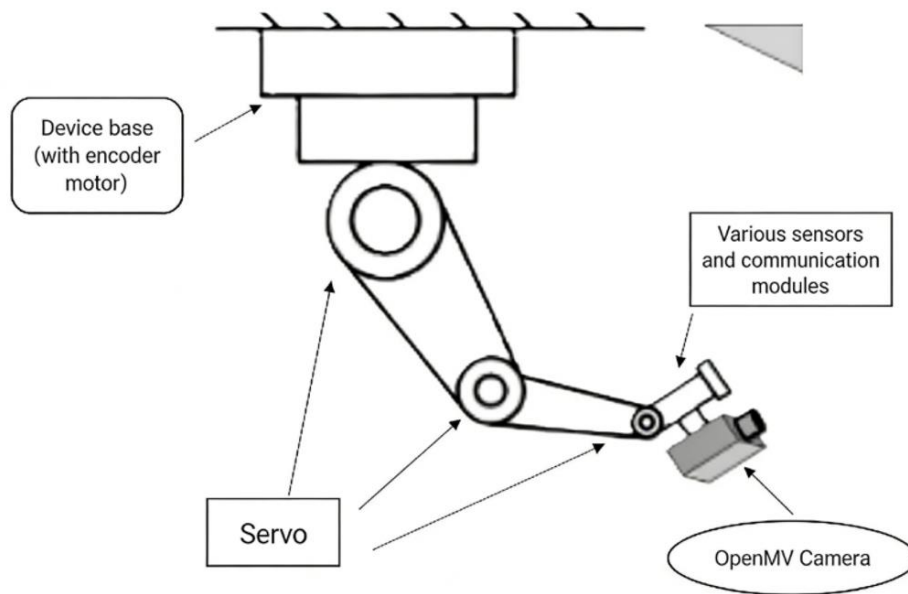


Figure 1 Overall System Architecture of the Dynamic Industrial Inspection System

3.2. Hardware Structure of Inspection Device

The mobile inspection device is the core execution unit of the system, with a mechanical structure shown in Figure 2. The device is installed on a customizable O-shaped closed track, with a device base equipped with an encoder motor as the power source to drive the whole device to move along the track, realizing dynamic patrol of the industrial site. A three-degree-of-freedom servo linkage mechanism is connected below the base, which can adjust the pitch, yaw and rotation angle of the end camera in real time through inverse kinematics solution. The end of the mechanism is equipped with an OpenMV camera, various environmental sensors and communication modules, which can adjust the detection angle flexibly during the movement process to achieve full coverage of the industrial site. The mechanical structure design ensures the stability of the device during movement and the flexibility of angle adjustment, meeting the multi-angle detection needs of dynamic inspection.

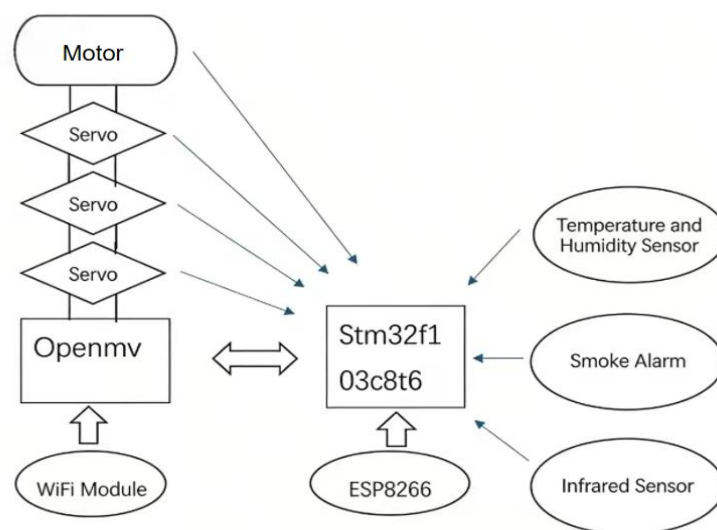


Figure 2 Mechanical Structure of the Mobile Inspection Device

3.3. Core Functional Modules

The system is divided into six core functional modules with clear division of labor and collaborative work. The multi-sensor data acquisition module completes real-time collection of environmental parameters and position signals; the STM32 main control module undertakes data processing, motion control and logic judgment; the servo and motor drive module realizes the orbital movement of the device and the angle adjustment of the pan-tilt; the OpenMV image acquisition module is responsible for on-site image capture and preprocessing; the ESP8266 wireless communication module realizes data transmission between the local device and the upper computer; the upper computer intelligent recognition module deploys the YOLOv8 model to complete target recognition and defect detection. Each module interacts with data through the main controller, ensuring the efficient and stable operation of the whole system.

3.4. Data Transmission and Control Logic

The system follows the logic of "local real-time control + remote intelligent processing". The perception layer transmits collected sensor data and image signals to the STM32 main controller in real time, which processes the data and sends control signals to the motor and servo modules to adjust the device's position and camera angle. At the same time, the main controller packages the environmental data and image information and uploads them to the upper computer through the ESP8266 module. The upper computer runs the YOLOv8 model for intelligent recognition, feeds back the recognition results and control commands to the main controller, and the main controller adjusts the detection strategy according to the commands, realizing the two-way interaction of data and the closed-loop control of the system.

4. Hardware Design of the System

4.1. Overall Hardware Framework

The hardware design of the dynamic industrial inspection system adopts a modular and hierarchical architecture with STM32F103C8T6 as the core control unit, which is functionally divided into four interconnected sub-modules: main control and communication unit, multi-sensor perception unit, motion execution unit, and visual acquisition unit. The whole hardware circuit is laid out in a centralized and compact manner, with the main controller as the center, and each functional module is connected through standard interfaces such as UART, I2C, ADC, and PWM, realizing efficient transmission of data and control signals while reducing signal interference between modules. The design adheres to industrial-grade reliability standards, selects anti-interference electronic components, and optimizes circuit grounding and wiring design to ensure the stable operation of the system in the complex electromagnetic environment of industrial sites. The modular framework not only facilitates independent debugging and maintenance of each module but also provides scalability for subsequent function expansion, such as adding more types of sensors or expanding the number of motion control axes^[4].

4.2. Core Controller and Communication Module

The system selects STM32F103C8T6 as the main control chip, a 32-bit microcontroller based on the ARM Cortex-M3 core, with a maximum operating frequency of 72 MHz, 64 KB of Flash memory, and 20 KB of SRAM. It has rich on-chip peripherals including 3 UART interfaces, 2 I2C interfaces, 10-channel 12-bit ADC, and multiple PWM channels, which can meet the concurrent

processing requirements of multi-sensor acquisition, motor servo control, and wireless communication. The minimum system circuit of the controller is constructed, including power supply, reset, and crystal oscillator circuits, where the 8 MHz crystal oscillator ensures the basic operating frequency of the chip, and the reset circuit combines manual and power-on reset mechanisms to improve the anti-interference ability of the system. The ESP8266 Wi-Fi module is connected to the main controller via the USART2 serial port, working in STA mode to access the industrial local area network. It realizes two-way data interaction between the on-site inspection device and the upper computer, supports real-time upload of monitoring data and reception of remote control commands, and has an automatic reconnection function to ensure stable communication in the industrial site environment with frequent signal fluctuations.

4.3. Sensor Detection and Motion Drive Modules

The sensor detection module integrates temperature and humidity, smoke, and infrared sensors to realize multi-dimensional perception of the industrial site environment and device position. The DHT11 sensor is connected to the GPIO port of the main controller through a single-wire interface, realizing real-time collection of on-site temperature (0–50 °C) and humidity (20–90%RH) parameters; the MQ-2 smoke sensor outputs analog signals to the ADC port of STM32, realizing quantitative detection of smoke concentration and combustible gas leakage; the HC-SR501 infrared sensor is used for preliminary positioning calibration of the inspection device, triggering an interrupt signal when detecting color markers on the track, assisting the encoder in completing precise positioning. The motion drive module is the core execution unit of the system, composed of a 12V encoder motor and three SG90 servos. The motor is driven by an L298N drive chip, controlled by the PWM signal output from STM32, realizing forward/backward movement and speed adjustment of the inspection device on the O-shaped track; the three servos are respectively responsible for the pan, tilt, and rotation motions of the pan-tilt mechanism, controlled by independent PWM channels, which can realize flexible adjustment of the camera's shooting angle according to the target position identified by the vision module. The coordination of the sensor detection module and the motion drive module ensures that the system can dynamically patrol the industrial site and perform targeted detection of key areas.

5. Conclusion and Outlook

This paper designs and implements an IoT-based dynamic industrial inspection system aiming at the defects of limited monitoring range, high hardware cost and low intelligence in traditional fixed industrial inspection methods, and the system takes STM32F103C8T6 as the core controller, integrates modular hardware design and layered software architecture, and combines machine vision, multi-sensor fusion, precise positioning and deep learning technologies to build a movable inspection device based on a customizable O-shaped closed track, which realizes dynamic patrol of industrial sites, real-time environmental parameter monitoring, precise target tracking and intelligent defect detection. The actual test results show that the system can achieve full coverage monitoring of industrial sites with fewer detection devices, effectively reduce hardware input costs, and the YOLOv8-based machine vision module can complete fast and accurate target recognition, while the multi-sensor and encoder-based positioning system ensures the accuracy of the inspection device's movement and camera angle adjustment, which significantly improves the real-time, comprehensiveness and intelligence of industrial inspection, and effectively makes up for the shortcomings of traditional inspection systems. In the future, the system can be further optimized and expanded: on the one hand, more types of industrial sensors can be added to enrich the environmental monitoring dimensions and realize the early warning of more potential industrial

safety hazards; on the other hand, the cloud platform can be introduced to realize the storage and big data analysis of inspection data, mining the change law of industrial site parameters and realizing predictive inspection and early warning; in addition, the autonomous navigation and obstacle avoidance function can be added to the inspection device to improve its adaptability to complex industrial environments, and the linkage control with industrial field intelligent equipment can be realized to form a more complete industrial intelligent monitoring and management system, providing more comprehensive and efficient technical support for the intelligent transformation of industrial production under the background of Industry 4.0.

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