

moving average to suppress high-frequency noise; then setting threshold constraints to judge sensor state, and dividing into Normal, Warning and Error levels; finally, updating visual interface and triggering early warning prompts.

The system adopts multi-threaded architecture to separate MQTT background message receiving and UI main thread rendering, which avoids interface stalling caused by network delay and data processing block. The time series visualization algorithm constructs dynamic curve charts through circular buffer and adaptive axis range, with timestamp log recording function, realizing traceable display of monitoring data.

Research Results

1. A multi-sensor edge acquisition platform based on ESP32 is developed successfully. It supports synchronous access to temperature, torque moment, viscosity and light sensor signals, with stable data collection, low power consumption and flexible scalability, which can meet the deployment requirements of industrial oil condition monitoring nodes.

2. The MQTT-based wireless telemetry transmission link is verified to be stable. It maintains low-latency and high-reliability data transmission in complex wireless environment, and JSON format simplifies subsequent data parsing and secondary development.

3. The server-side data processing and early warning system operates reliably. The moving average filtering algorithm can effectively suppress environmental noise; the configurable threshold parameters can be adjusted without recompiling the code. The multi-threaded design ensures smooth response of the visual interface and real-time performance of abnormal alarm.

4. The combined detection scheme of four sensors can comprehensively characterize the degradation, pollution and lubrication performance changes of lubricating oil, which replaces the traditional manual sampling detection mode and has good practical application value.

The constructed intelligent oil condition prediction system realizes low-cost, real-time and reliable whole-process monitoring of lubricating oil state. It has the advantages of open architecture, strong customizability and easy expansion, which can provide technical support for industrial equipment predictive maintenance and subsequent intelligent oil state prediction research.

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ARCHITECTURE OF INTELLIGENT WEAR PREDICTION SYSTEM

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To address the shortcomings of traditional offline monitoring for rotating machinery friction pairs, such as strong lag, high deployment costs, and dependency on external networks, a friction condition intelligent prediction system based on a three-layer IoT architecture using the ESP32 controller was designed. The system adopts a local offline deployment model, capable of real-time acquisition of multi-source parameters of friction pairs, wear feature extraction, and remaining life prediction. It features lightweight design, easy scalability, and high reliability, meeting the online monitoring requirements of industrial friction pairs.

Keywords: friction prediction, three-layer IoT architecture, ESP32, Intelligent identification; real-time monitoring; machine learning.

System Architecture Design

The system adopts a layered modular design approach, divided from top to bottom into three core layers: the Presentation Layer, the Business Logic Layer, and the Device Layer (fig. 1). It follows the design principles of high cohesion and low coupling. All components are interconnected via a local WiFi LAN, with all data traffic confined within the local network, enabling the complete business loop of “collection – analysis – prediction – control” without requiring access to external networks, thereby ensuring data security and operational autonomy. Specifically, the Presentation Layer serves as the tablet-based web interaction interface, shouldering the core human-computer interaction functions; the Business Logic Layer, centered on the Raspberry Pi 4B, acts as the system’s communication hub and intelligent decision-making unit; and the Device Layer, built on the ESP32 microcontroller, establishes terminal nodes that directly interface with the friction testing rig to perform physical signal acquisition and drive the actuators. This architecture allows for the flexible addition or removal of terminal nodes according to monitoring requirements without modifying the core system framework.

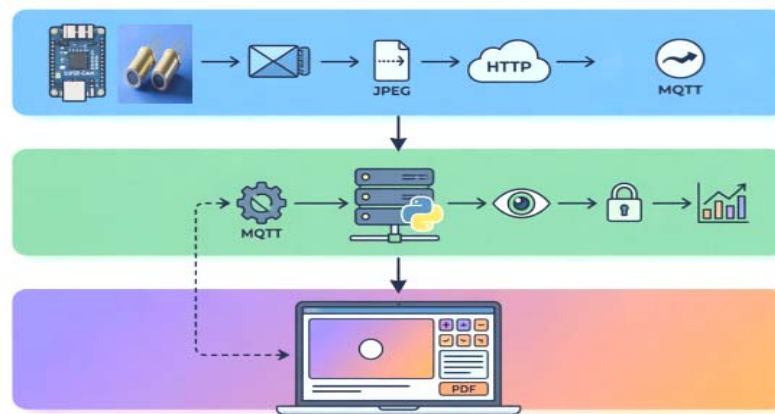


Fig. 1. Architecture of the system

Presentation Layer (Tablet Web Interface)

The presentation layer is a responsive web interface adapted for tablet devices, developed based on HTML5, CSS3, and the Vue.js framework. The layout is optimized for tablet touch screens, with three core functionalities: First, real-time visualization of parameters such as friction pair vibration, temperature, rotational speed, and wear prediction results, with automatic alarms for abnormal conditions; second, touch-based remote control of test conditions, supporting operations such as motor start/stop, speed adjustment, and load setting, with parameters that can be saved and recalled with one click; third, filtering, export, and trend analysis of historical test data. Technically, low-latency real-time data push is implemented using WebSocket, standardized command interaction is completed via REST API, and PWA technology is supported to achieve a native-like application experience.

Business Logic Layer (System Core)

The business logic layer, based on the Raspberry Pi 4B hardware platform, undertakes four core functions: First, communication scheduling, which handles concurrent front-end requests using the Python FastAPI asynchronous framework, and achieves stable communication with ESP32 nodes through the Mosquitto MQTT message broker, accomplishing routing and forwarding of control commands as well as multi-device command queue

management; Second, data processing and storage, filtering, normalizing, and extracting features from raw sensor data, with a focus on vibration signal features closely related to wear, storing high-frequency monitoring data in InfluxDB and system configurations and user information in SQLite [1]. Third, intelligent prediction, deploying a lightweight wear prediction model based on the LightGBM algorithm, with a test set recognition accuracy exceeding 89 %, suitable for local deployment on the Raspberry Pi edge without the need for cloud computing power. Fourth, system management and control, implementing user authentication, complete operation log recording, and device status polling.

Device Layer (ESP32 End Node)

The device layer is built on the ESP32-WROOM-32 microcontroller to create end nodes. This controller features ample GPIO interfaces and stable WiFi communication capabilities, while being cost-effective, making it suitable for large-scale deployment [2]. The node hardware integrates three main modules: a stepper/servo motor driving module to control the spindle speed and friction pair contact load of the test bench; a multi-source sensor acquisition module that collects vibration signals via the MPU6050, friction zone temperature via the DS18B20, and spindle speed via a photoelectric encoder; and a power and communication module that provides stable power supply and local WiFi communication.

The end node firmware is developed in C++ based on the Arduino framework. Its core logic is as follows: upon power-up, the node automatically connects to the local WiFi and MQTT message broker and subscribes to its dedicated control command topics; it performs sensor data acquisition, preprocessing, and publishing at a set frequency; upon receiving control commands, it drives the actuator to perform the corresponding actions and simultaneously reports the execution results and device status. The firmware includes an automatic network reconnection mechanism and a watchdog timer, and supports OTA (Over-The-Air) firmware upgrades, ensuring reliable node operation.

Inter-Layer Communication Protocol Design

The system adopts a hybrid protocol stack architecture, with all communications operating within a locally WPA3-encrypted WiFi LAN, eliminating the need for external network access. The presentation layer and business logic layer utilize a dual-protocol architecture of WebSocket + HTTP/REST API, with WebSocket enabling real-time bidirectional push for high-frequency data, achieving an end-to-end latency of ≤ 500 ms; HTTP/REST API is used for issuing control commands, querying historical data, and user authentication [3].

The business logic layer and device layer are centered on the Mqtt 3.1.1 protocol, adopting a publish/subscribe architecture. Each ESP32 node is assigned independent command, data, and status topics, enabling precise directional transmission of data and commands, featuring low overhead, high scalability, and self-healing upon disconnection; HTTP protocol is additionally used to facilitate OTA firmware upgrade package transmission. MQTT client authentication, web interface user authentication, and control command legitimacy verification are implemented to prevent unauthorized access and operational errors.

The intelligent prediction system for friction states established in this study has completed the entire local closed-loop process from data acquisition, feature extraction, and intelligent prediction to human-machine interaction. Compared with traditional monitoring systems, this system has lower hardware costs, convenient deployment, no dependence on external networks, and strong scalability, providing a lightweight technical solution for the condition monitoring and fault warning of friction pairs in industrial rotating machinery. In future work, the prediction model will be further optimized to improve prediction accuracy under complex operating conditions and to expand the system's multi-node parallel monitoring capability.

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АВТОМАТИЗИРОВАННЫЙ МОНИТОРИНГ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ПОЛЕЙ С ПОМОЩЬЮ ДРОНОВ И ИСКУССТВЕННОГО ИНТЕЛЛЕКТА

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Рассмотрен программно-аппаратный комплекс для автоматизированного мониторинга сельскохозяйственных полей, объединяющий беспилотные летательные аппараты и алгоритмы глубокого обучения. Приведены результаты экспериментального тестирования системы на основе модели детекции YOLOv8.

Ключевые слова: беспилотный летательный аппарат, искусственный интеллект, YOLOv8, мониторинг полей, детекция аномалий, точное земледелие.

Потери урожая от сорняков, болезней растений и засухи достигают 30–50%, при этом традиционные методы визуального осмотра и наземных обследований остаются трудоемкими, субъективными и не обеспечивают оперативного покрытия больших площадей. Спутниковый мониторинг характеризуется низким пространственным разрешением, зависимостью от облачности и ограниченной частотой съемки. Наземные датчики дают лишь точечные измерения, не формируя целостной картины поля, а их масштабное развертывание сопряжено с высокой стоимостью. Коммерческие дронные системы представляют собой закрытые проприетарные решения с дорогими лицензиями, что ограничивает возможность их адаптации под конкретные агротехнические задачи. Существующие научные разработки предлагают отдельные высокоэффективные алгоритмы детекции, но редко интегрированы в законченные, готовые к практическому применению программно-аппаратные комплексы.

В связи с этим актуальной задачей является создание открытой модульной системы мониторинга, объединяющей беспилотные летательные аппараты для оперативного сбора данных и алгоритмы глубокого обучения для автоматизированного выявления аномалий.

В рамках работы разработан программно-аппаратный комплекс для автоматизированного мониторинга сельскохозяйственных полей, архитектура которого включает три ключевых уровня: бортовой модуль сбора данных, серверную часть для обработки и хранения, а также веб-клиент для визуализации результатов (рис. 1).

На борту дрона установлен компактный компьютер (в текущей реализации – Raspberry Pi, в перспективе – NVIDIA Jetson), камера и GPS-модуль. Скрипт на Python с использованием DroneKit циклически захватывает кадры, фиксирует точные координаты и отправляет данные на сервер через REST API. Серверная часть