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RAIL DAMAGE DETECTION SYSTEM BASED ON FUSION OF PLANAR CAPACITIVE SENSING AND VISION

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Abstract: This research addresses the specific and crucial application scenario of railway track damage detection by designing and implementing a comprehensive intelligent detection system solution. At the hardware architecture level, the system meticulously selects the high-performance STM32F103 microcontroller as the core control unit. This unit offers fast processing speed, low power consumption, and high reliability, laying a solid foundation for the system's stable operation. Centered around this core control unit, the system integrates various functional modules, including high-precision detection modules like planar capacitive sensors for real-time and accurate collection of track status data. Simultaneously, the OpenMV visual processing module is utilized to achieve precise machine vision recognition of track surface defects, significantly enhancing the intuitiveness and accuracy of detection. Additionally, the system is equipped with a motor drive module to enable precise movement of the detection device. The system not only features excellent hardware configuration but also possesses powerful data processing capabilities, enabling real-time and efficient analysis and processing of the collected massive data, thereby significantly improving detection accuracy and timeliness. In terms of material selection, the system innovatively adopts new energy-saving and environmentally friendly materials, which not only substantially reduce the overall energy consumption of the system but also effectively extend the equipment's service life, markedly enhancing its durability. This system integrates numerous advantages such as efficient detection, energy saving, environmental protection, and low-cost operation, demonstrating broad application prospects and significant market promotion potential in the field of railway operation and maintenance. It is expected to provide a solid and powerful guarantee for the safe and stable operation of railways.
Keywords: Microcontroller; Sensor; Rail damage; Planar capacitance; High efficiency and energy saving; OpenMV visual processing

1 INTRODUCTION

In recent years, China's rail transportation industry has achieved rapid development. High-speed rail networks crisscross the country, and subway lines extend in all directions. These modern rail transportation facilities have deeply integrated into our daily lives, becoming the preferred mode of transportation for people. At the same time, as a critical national infrastructure, rail transportation plays an irreplaceable key role in promoting regional economic development, driving industrial upgrading, and stimulating employment. However, with the continuous growth of rail transit operational mileage and the rapid increase in transport volume, the track system faces increasingly severe challenges. Due to the long-term high-speed operation of trains, intense friction occurs between the wheels and rails. Coupled with the tracks' long-term exposure to complex and variable external environments such as wind, sun, rain, and snow erosion, a series of safety hazards requiring urgent solutions arise. For instance, minor cracks may appear on the rail surface or internally, the track geometry may deform, or uneven wear may occur on the rail contact surface. These seemingly minor damage issues, if not detected and addressed promptly, will seriously affect the train's running stability. In mild cases, this leads to increased train vibration and reduced passenger comfort; in severe cases, it may trigger major safety accidents such as train derailments, resulting in casualties, property losses, and even causing a chain reaction of social problems. In response to this situation,various rail damage detection technologies have been developed. Zhang et al. proposed an enhanced blind separation method for rail defect signals using a time-frequency separation neural network and smoothed pseudo Wigner-Ville distribution [1]. Mao et al. introduced a novel similarity measure based on a dispersion-transition matrix and Jensen-Fisher divergence for detecting rail short-wave defects [2]. Gong et al. optimized magnetic flux leakage detection equipment for rail surface inspection through finite element simulation [3]. Ding et al. developed a rail defect detection framework under class-imbalanced conditions based on an improved YOLO network [4]. Additionally, the Transportation Technology Center expanded the rail flaw library to enhance rail integrity [5], while Chang et al. proposed a defect detection method for ferromagnetic rails using an EMAE-based peak-to-peak method and confidence probability indicator [6]. Santur et al. adopted 3D laser cameras combined with ResNet50 for rail surface defect detection [7], and Zhao et al. applied the hybrid laser ultrasonic method in rail inspection [8]. Drawing on these research foundations, this design innovatively proposes a rail dama this design innovatively proposes a rail damage detection system solution based on the fusion of planar capacitive sensing and vision. Through multi-sensor data fusion and intelligent analysis algorithms, this system can achieve precise detection and intelligent diagnosis of rail damage, offering significant advantages such as high detection accuracy, fast response speed, and strong adaptability. It will provide robust technical support for the promotion and application of rail damage detection technology.

2 SYSTEM OVERALL DESIGN SCHEME

In this system design, the system primarily uses the STM32F103C8T6 as the main control board. Planar capacitive sensors serve as the acquisition module to collect and process information related to track damage. The collected relevant information is uploaded to a WeChat mini-program. Within the mini-program, a pre-trained rail damage detection system is used to perform preprocessing, feature extraction, and classification of the rail damage severity. The condition of the rail damage is then displayed on the WeChat mini-program interface, facilitating real-time understanding of the rail damage status by relevant personnel. Using a 4G module, the collected rail damage information can achieve data communication between the device end and the WeChat mini-program via a serial port. If the rail condition is damaged, relevant personnel can use the information viewing function pushed by the mini-program to understand the rail damage situation and make corresponding judgments, thereby enabling more convenient and accurate detection of rail damage. Simultaneously, relevant personnel, after authorizing login via WeChat to the mini-program, can encrypt and manage user information, protecting user privacy rights and enhancing the security and credibility of user data. The overall system framework structure diagram is shown in Figure 1.

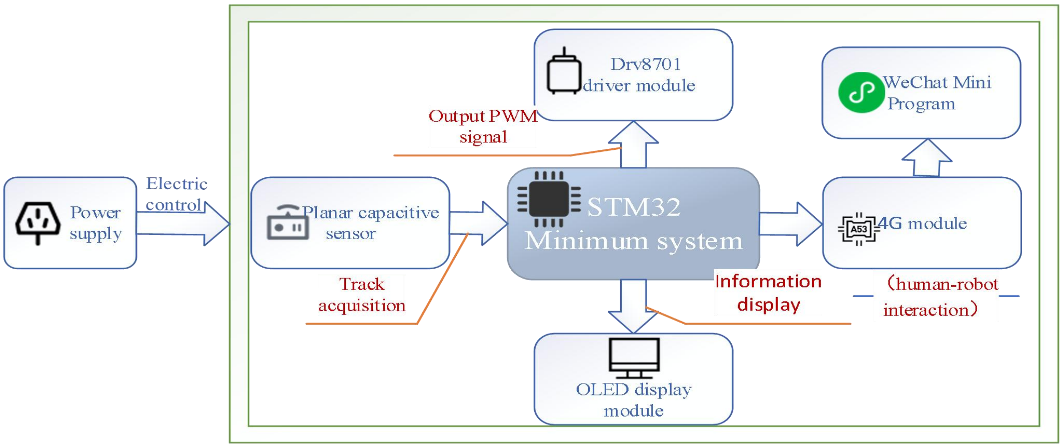


Figure 1 Overall System Framework Diagram

The rail damage detection car based on the BiFPN-YOLOv8 algorithm model and the WPD-CNN compensation capacitor fault diagnosis method deeply integrates sensor technology, embedded technology, and wireless communication technology with a WeChat mini-program to build an intelligent Internet of Things (IoT) system. This system consists of three main structural layers: the perception layer, the transmission layer, and the application layer. The perception layer is composed of the STM32 main controller and planar capacitive sensors; the transmission layer consists of the 4G module; and the application layer is the WeChat mini-program end. Relevant personnel at the application layer receive the rail damage data acquired by the perception layer and uploaded by the transmission layer. Subsequently, they use the WeChat mini-program's information recognition and analysis functions to better judge the damage status of the rails, thereby achieving accurate identification and real-time monitoring of rail damage. The overall system architecture block diagram is shown in Figure 2.

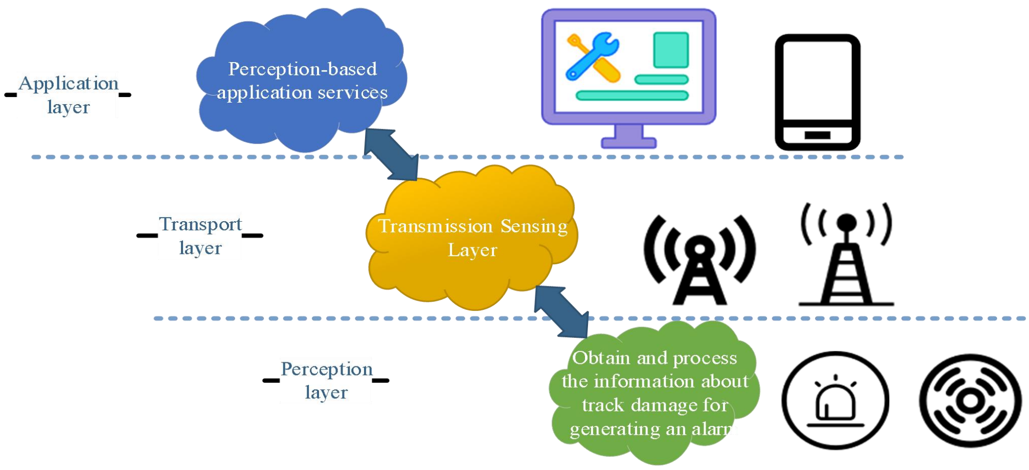
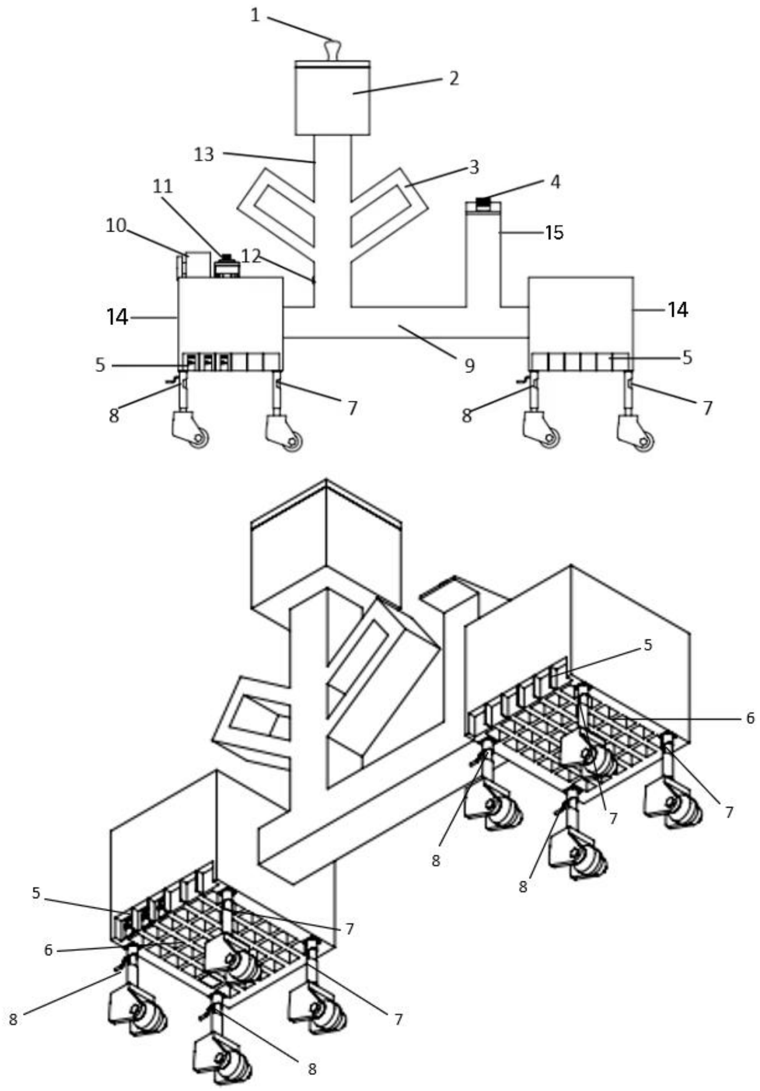


Figure 2 System Overall Architecture Diagram

The system model design is shown in Figure 3. The entire system consists of two 6x6 planar capacitive sensor matrices, two storage racks placed on connecting rods, two fixed wheels and two manually adjustable wheels, one OLED display, etc. The outer skin of the car is made of zinc-iron sheet with strong anti-rust capability, allowing the car to adapt to various conditions. The front bottom of the car also has a row of tracking sensors, enabling the car to better control its direction. The bottom ends on both sides of the car feature two fixed wheels and two manually adjustable wheels, which help the car adapt to different rail conditions, making detection more comprehensive and efficient.



1.Ellipsoidal alarm; 2. OLED display; 3. Storage rack; 4. Control terminal; 5. Infrared sensor; 6. Capacitive sensor matrix; 7. Wheel; 8. Hand-cranked lifting wheel; 9. Connecting rod one; 10. Servo motor; 11. OpenMV camera; 12. Rechargeable power module; 13. Connecting rod two; 14. Car body; 15. Connecting rod three.

Figure 3 System Model Design Diagram

3 HARDWARE OVERALL DESIGN

The system control circuit consists of electrical components such as the OLED display module, planar capacitive sensors, and tracking sensors.

3.1 Microcontroller Circuit

This system selects the STM32F103C8T6 produced by STMicroelectronics as the main control chip. This is a high-performance 32-bit enhanced microcontroller. As a representative product of the STM32F1 series, this microcontroller adopts the ARM Cortex-M3 core architecture, with a maximum operating frequency of 72 MHz (Note: Corrected from potentially erroneous "2MHz" in original, standard for Cortex-M3 in STM32F103 is up to 72MHz), capable of meeting real-time data processing requirements. In terms of storage resources, the chip has built-in 64 KB of SRAM for data caching and is equipped with 256 KB of Flash memory for program storage. These resource configurations provide the hardware foundation for implementing complex control algorithms. It is particularly worth mentioning that this microcontroller possesses relatively strong image processing capabilities, enabling it to handle video data acquisition and processing tasks. To ensure the stable operation of the microcontroller, the system designs a complete minimum system circuit, including essential peripheral circuits such as the crystal oscillator circuit, reset circuit, and power supply circuit. Its specific circuit connection method is shown in Figure 4. This minimum system circuit provides the basic working environment for the microcontroller and is the foundation for subsequent functional expansion.

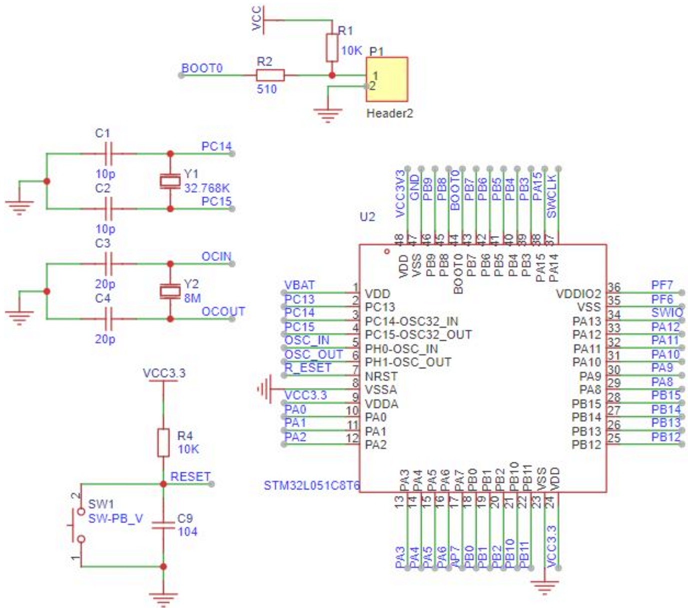


Figure 4 STM32F103C8T6 Minimum System Circuit Diagram

3.2 Power Module Circuit

This protection circuit uses the widely adopted TP4056 charging management chip as the core control device. This chip features stable performance and high reliability. The entire peripheral circuit design is concise and efficient, requiring only a few components to achieve complete lithium battery charging protection functions. It can effectively prevent overcharging, over-discharging, overcurrent, and other abnormal conditions during the charging process, thereby ensuring charging safety and battery lifespan. The circuit uses a standard +5V external power supply. The positive terminal of the lithium battery is connected to pin 5 of the TP4056 chip, and the negative terminal is connected to the GND of the chip. Regarding charging status indication, the red LED indicator remains steadily lit when the battery is charging. When the battery is fully charged, the green LED indicator automatically lights up. This intuitive indicator design facilitates users to grasp the charging status at any time. The PROG pin (pin 2) of the chip is used for charging current detection; the charging current can be precisely set by an external resistor. The TEMP pin (pin 1) is the battery temperature detection terminal. In this design, this pin is directly connected to GND, simplifying the circuit design and making the circuit more practical. The complete circuit connection schematic is detailed in Figure 5 of this paper, which clearly shows the connection relationships and working principles of the components.

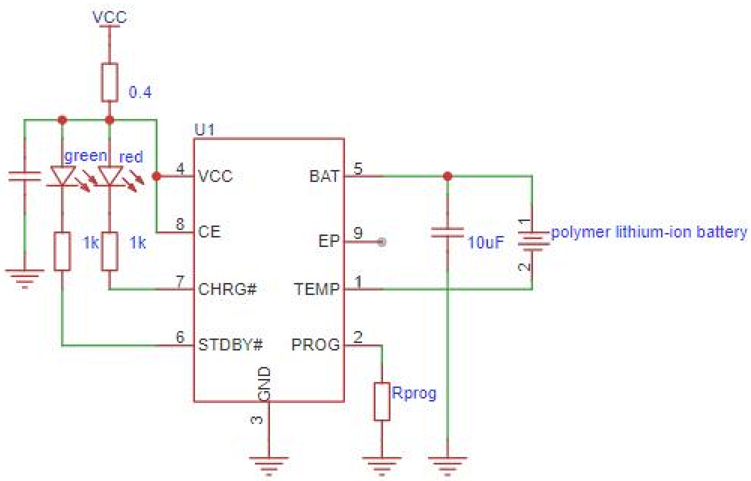


Figure 5 Power Module Circuit

3.3 Detection Sensor Circuit

Working principle of planar capacitive sensor detection is A planar capacitor consists of two parallel plates. The capacitance value follows the formula $C = \frac{\varepsilon S}{d}$, where ε is the dielectric constant of the medium between the plates, S is the opposing area of the plates, and d is the distance between the plates. When track damage occurs, it indirectly changes one or more of these three parameters, causing a change in capacitance. The detection circuit converts the capacitance change into a readable electrical signal, which is then used to judge the track damage condition. If the track deforms or settles, it causes the distance d between the sensor plates to change; for example, track subsidence brings the plates closer, d decreases, capacitance increases. If cracks or wear appear on the track, it may cause misalignment of the plate installation position, changing the opposing area S; for example, cracks cause plate misalignment, S decreases, capacitance decreases. If impurities enter the damaged area of the track, they change the equivalent dielectric constant of the medium between the plates, also causing capacitance changes.

3.4 OLED Display Circuit

This circuit uses a 3.3V DC power supply. To ensure power stability, a filter capacitor C9 is set in the power supply loop to effectively filter out high-frequency noise and interference signals from the power source. Simultaneously, a voltage divider circuit composed of resistors R8 and R9 allows for precise regulation and stable control of the operating voltage. The OLED display uses the I²C communication protocol for data interaction with the main control chip. The SCL clock signal line is connected to the main control's IO22 pin, and the SDA data signal line is connected to the IO21 pin. When the system detects track damage, the main control chip sends the damage data to the OLED display via the I²C bus. The dedicated driver circuit integrated within the OLED then accurately controls the light emission state of each pixel based on the received data information, clearly displaying the specific location and severity of the track damage. The complete circuit connection method and component layout design of the entire OLED display module are detailed in the circuit schematic shown in Figure 6.

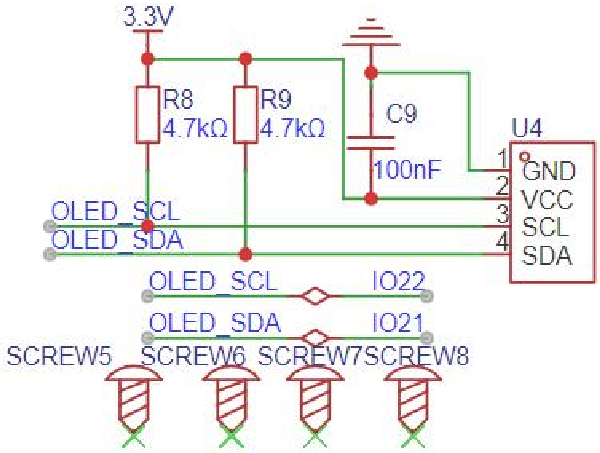


Figure 6 OLED Display Circuit Diagram

3.5 Alarm Module Circuit

In the daily maintenance of rail transit, the rail damage car plays a crucial role. It is equipped with an advanced alarm module circuit. When the car is running on the track and detects track damage, it quickly triggers the alarm mechanism. Upon receiving the signal, the precise vibration device inside the alarm immediately activates, generating an audible alarm through its internal vibration, promptly alerting surrounding personnel. The alarm module circuit diagram is shown in Figure 7, which details the circuit connections and working principle of the entire alarm system, providing a clear and accurate reference for technicians performing system maintenance and troubleshooting.

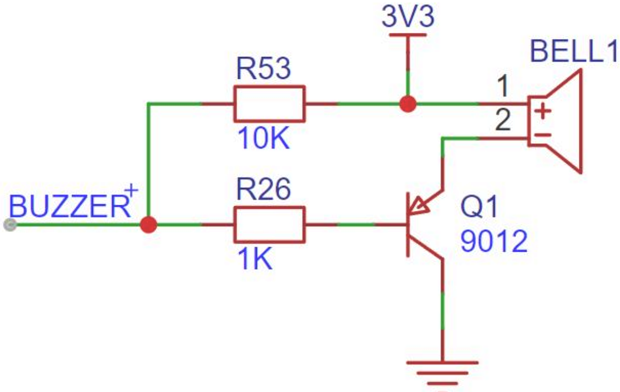


Figure 7 Alarm Module Circuit Diagram

4 SOFTWARE OVERALL DESIGN

In the software architecture developed for this project, we adopted a multi-language collaborative development strategy. Specifically, in the visual processing module part, we chose Python as the primary development language. Based on the PyQt5 framework, we conducted in-depth programming development for the OpenMV embedded vision module, achieving efficient image acquisition and processing functions. Simultaneously, by introducing the YOLOv8 algorithm model and leveraging the hardware acceleration capability of the psc module (Note: Assuming 'psc' refers to a specific hardware accelerator, possibly a typo or project-specific term), the performance of OpenMV in object detection and recognition was significantly enhanced. In the underlying control module aspect, we used C language for firmware development on the STM32 microcontroller under the Keil5 integrated development environment, achieving precise motor control and sensor data processing. Furthermore, we integrated advanced planar capacitive sensor technology, combined with the WPD-CNN algorithm, greatly enhancing the STM32's capabilities in non-contact measurement and environmental perception. Finally, through communication protocols and system integration solutions, these functional modules work together to drive the track inspection car to achieve multiple intelligent monitoring functions, including track identification, obstacle detection, and automatic navigation, see Figure 8.

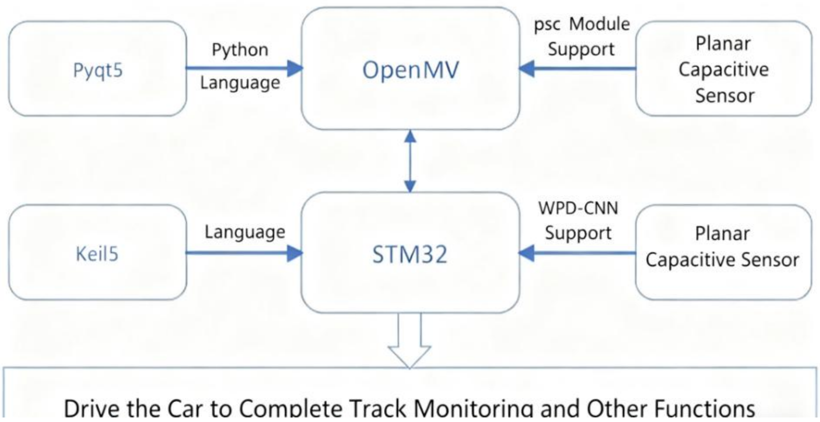


Figure 8 Software Overall Framework

4.1 YOLOv8n Algorithm Improvement

In the original C2f module of YOLOv8n, due to the fixed size and stride of the convolution kernels, the C2f module could only capture local image information and could not fully utilize the entire image's information to improve feature representation and detection accuracy. This limited receptive field problem negatively impacted the performance of the object detection model. In rail damage detection, the shape and size of damage vary widely, and there might be occlusion by foreign objects. To better understand the structure and features of rail damage, the model needs a broader receptive field and stronger contextual perception capabilities to improve detection accuracy and robustness. To solve this problem, this paper reconstructs this module to improve its ability to capture geometric deformations of damage in rail damage images. Specifically, Dynamic Snake Convolution is used to replace the ordinary convolution operation in the original C2f module. Dynamic Snake Convolution can generate convolution kernels of different shapes and sizes according to the shape and size of the rail damage, enhancing the receptive field and feature extraction capability of the C2f module. Meanwhile, after introducing Dynamic Snake Convolution into the C2f module, the shape information of the rail damage can be integrated into the convolution operation, enhancing the expressive power and discriminability of rail damage features, and improving the performance and adaptability of the object detection model. The improved part of the C2f module is shown in Figure 9.

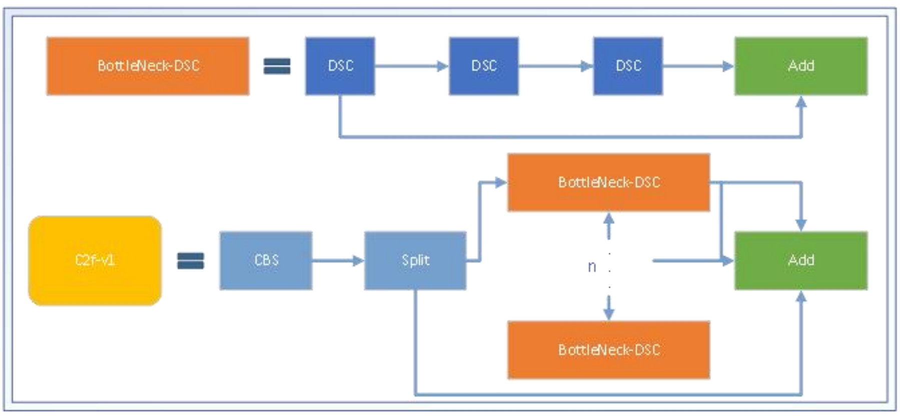


Figure 9 C2f-v1 Module Based on Dynamic Snake Convolution

4.2 WPD-CNN Compensation Capacitance Method

To effectively extract compensation capacitor feature information and achieve effective identification of compensation capacitor faults at different track locations, the WPD-CNN method is adopted for fault diagnosis of compensation capacitors. The overall approach is shown in Figure 10. In the dataset construction stage, power spectrum analysis is used to find the frequency band range that can effectively reflect the characteristics of the compensation capacitor. Then, the wavelet packet transform is used to decompose the original signal, extracting the low-frequency trend component and the wavelet packet coefficients corresponding to the characteristic frequency band of the compensation capacitor to form a feature matrix. In the model training stage, the generated training dataset is input into the CNN network for learning. The model is optimized through the backpropagation algorithm to obtain a model with relatively good performance, which is then validated on the test set. Finally, the trained model is used to achieve fault diagnosis for the compensation capacitors of the rail detection car.

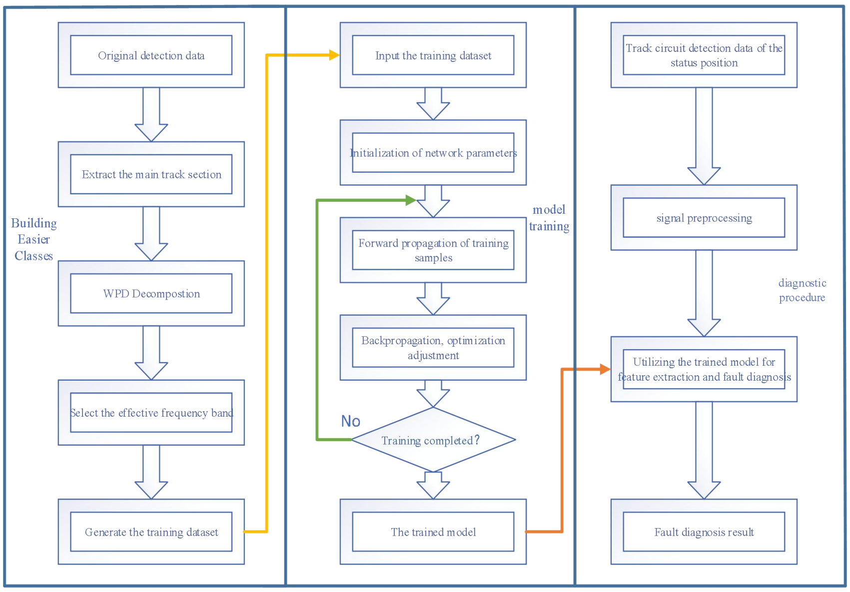


Figure 10 Overall Approach of Compensation Capacitor Diagnosis Method Based on WPD-CNN

5 FUNCTION TEST

Data provided according to simulation experiments are shown in Table 1.

Table 1 Simulation Experiment Data Table

Research Subject	Urban/Rural Rail	Provincial Capital	Detection Rail Efficiency
Group 1	Rail Crack	Rail Breakage	92%
Group 2	Rail Deformation	Rail Wear	95%
Group 3	Rail Wear	Rail Rust	93%
Average Detection Efficiency			94%

As this experiment did not consider other external conditions, the damage conditions for both urban/rural rails and provincial capital rails were mostly limited to rail cracks, rail deformation, rail breakage, and rail rust. Testing with this system revealed that the most common rail damage conditions were rail wear and rail deformation. The average detection efficiency was 94%.

6 CONCLUSION

This project's research innovatively integrates planar capacitive sensing technology and machine vision detection technology to construct an intelligent rail damage detection system. The core of the system lies in using a 6x6 planar capacitive sensor matrix to achieve non-contact identification of internal rail defects through changes in the electric field distribution. Simultaneously, paired with the OpenMV high-definition camera module, it can accurately capture various types of damage features on the rail surface. The system employs the STM32F4 series high-performance microcontroller as the main control chip (Note: Original text mentioned F4 here, but F103 earlier; kept as in original), achieving intelligent detection functions through optimized circuit design, effectively reducing the labor intensity and energy consumption of manual inspections. It is worth mentioning that the system is equipped with a hand-cranked adjustable lifting wheel mechanism, enabling flexible adaptation to track detection needs at different heights. This largely addresses the industry pain points of traditional detection equipment, such as insufficient precision and poor adaptability. This detection system has wide applicability and can be used in various rail transit scenarios such as high-speed rail, subways, and intercity railways. The main innovations of the system are reflected in three aspects. First, it achieves a composite working mode combining intelligent automatic detection and manual adjustment. Second, it innovatively adopts a dual-algorithm fusion architecture comprising the BiFPN-YOLOv8 object detection algorithm and the WPD-CNN feature extraction algorithm, significantly improving the accuracy of rail damage identification. Finally, the system adopts a modular design, where core components such as capacitive sensors support regular calibration or quick replacement, ensuring long-term reliability. The entire system has significant advantages such as high cost-effectiveness, strong portability, and easy maintenance, demonstrating broad application prospects and market promotion value in the field of rail transit operation and maintenance.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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