Design of an Intelligent Orbital Inspection Robot Based on Machine Vision and Ultrasonic Guided Waves

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Abstract

This paper introduces a wheel-foot switching track inspection robot based on machine vision and ultrasonic guided wave for enhancing the automation and intelligence of track inspection.The robot integrates the BeiDou positioning and autonomous traveling system, and combines image processing and ultrasonic guided wave technology to efficiently detect track cracks, settlements and other defects.The innovative wheel-foot switching structure and electro-hydraulic leveling platform improve the multi-terrain adaptability.The defect recognition algorithm based on particle swarm optimization algorithm and support vector machine, as well as the visual data processing platform, realizes the real-time transmission and analysis of inspection data.Tests show that the system has high inspection accuracy and stability, providing a reference for intelligent track inspection.

Keywords: Machine Vision, Rail Inspection, Ultrasonic Guided Wave, Defect Detection

1. Introduction

With the transformation of track inspection from informationization to intelligence, the inspection accuracy is improving, however, the development of autonomous motion, miniaturization and intelligent inspection instruments is slow and cannot meet the demand of intelligent development of rail transportation.Aiming at the above problems, the team members designed a wheel-foot switching track inspection robot, which can realize the application of multiple application scenarios, such as underground railroads, elevated light railways, ground tracks, mine tracks, etc. The product is equipped with multiple types of inspection equipment.The product is equipped with multiple types of inspection equipment, and the data processing platform realizes automatic processing and analysis of inspection data, improves the degree of automation, intelligence and informationization of track inspection, reduces the risk of personnel in hazardous scene inspection, and assists the development of intelligent track inspection industry.Model diagram of rail robot is shown in Fig.1.

Fig.1 Model diagram of rail robot

Intelligent track inspection robot based on machine vision and ultrasonic guided wave is a wheel-foot switching track inspection robot based on machine vision and ultrasonic guided wave intelligent detection, which is dedicated to detecting various defects such as cracks, settlement and unevenness of the track, and at the same time adapts to many kinds of complex terrains, with a wide operating range, and realizes intelligent full-automatic inspection.The track inspection robot applies Beidou positioning and automatic traveling, ultrasonic guided wave detection, image processing and other technical means to make the robot carry out inspection tasks according to the preset track traveling route, and utilizes the image processing technology and Beidou positioning system to accurately obtain the track image information and location information of the route, and then compares and identifies them through the track surface image enhancement algorithm of ACE and the data processing system, and transmits the location information of the inspection results to the rail transit system.The position information of the result is transmitted to the rail transportation platform.Meanwhile, ultrasonic guided wave equipment is added to carry out inspection, which can carry out high-precision inspection of internal defects of rails, determine the location, shape, size and other information of defects and cracks inside the rails, and solve the problems such as crack defects inside the rails which can not be detected by the machine's vision, so as to improve the accuracy of rail inspection.

Solving the speed inefficiency of manual inspection, leakage detection and misdiagnosis pressure low detection frequency is the primary goal of this product, through a more intelligent, efficient and safe way to replace manual labor, while saving manpower, material resources, financial resources, in order to achieve better operational results and economic benefits.Secondly, it is to strengthen the process of intelligent urban rail inspection and management, to build an intelligent urban rail inspection and management system by perfecting the integrated

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monitoring system, and to make the product walk in the forefront of the times by combining the modern 5G wave - Internet of Things and other advanced technologies.Through the continuous iteration of the product and the joint efforts of the company, the product has the advantages of high degree of integration, good compatibility and high applicability, and realizes the goals of high precision of track inspection, accurate on-site monitoring data, and good continuity and stability of system operation.

The rest of this article is organized as follows. The second section introduces the hardware components of the intelligent rail inspection robot, including the wheeled-leg switching structure, intelligent leveling platform, and the power system. The third section presents the defect detection system, which incorporates machine vision and ultrasonic guided wave technologies to identify and analyze rail defects. The fourth section discusses the innovative defect rating algorithm, which processes and evaluates defect data for effective classification and visualization. The fifth section describes the product's digital design, highlighting material selection, structural optimization, and system modeling. Finally, the sixth section provides the results of functional testing, including normal operating conditions and simulated fault scenarios, to validate the performance and reliability of the proposed system.

2. Hardware Part

2.1. Wheel-foot switching structure

The main body of the team adopts mechanical dog mechanical structure, which can realize precise control and movement, accurate positioning, strong stability, and be able to realize a variety of complex actions and movement modes, and the track inspection robot adopts quadrupedal, five-degree-of-freedom design and wheel-foot switching model, which can adjust the leg posture and gait according to the needs of the terrain conditions and environmental changes in which it is located, and realize smooth walking and and, satisfy the multi-topography movement, with a very strongAdaptability.It can solve the problem that conventional inspection robots need to be manually carried to the rails for inspection.Physical diagram of track inspection robot with wheel and foot switching is shown in Fig.2.

Fig.2 Physical diagram of track inspection robot with wheel and foot switching

Placing the robot in a variety of complex external environments, as the end rail wheel can be freely switched to paving and iron wheel movement modes for walking, running, jumping and other tests, the leveling platform can realize a variety of complex actions and movement modes, and it can be used to walk on the complex railroad roads, so that the robot has a good function of obstacle-crossing.

2.2. Intelligent leveling platform

In the field of high-precision measurement, it is crucial to ensure that the measurement equipment is in a stable state, which directly affects the accuracy of the data.At present, the traditional leveling method has the problem of low efficiency.The electro-hydraulic leveling platform developed in this project is designed to generate corresponding movements by driving the connecting rods connected to the electro-hydraulic rods through the telescopic movements of the electro-hydraulic rods.This design utilizes a notch fit mechanism between the rods to convert the horizontal movement of the electro-hydraulic rods into vertical adjustments in the X and Y axes.In addition, the platform incorporates a PID control algorithm to provide fast and intelligent adjustment of the leveling module in the robot system.

Key components of the system include four miniature gyroscopes on the auto-leveling base plate that automatically monitor and evaluate the platform's flatness.These gyroscopes compare the attitude information collected with the ideal level and quickly relay the information to the microcontroller via the data transfer module.The microcontroller then controls the rotational speed of the gimbal servos to adjust the attitude of the instrumented gimbal to achieve precise leveling.Model of leveling platform is shown in Fig.3. Engineering diagram of leveling platform is shown in Fig.4.

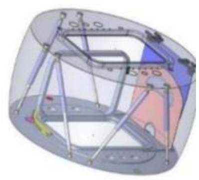

Fig.3 Model of leveling platform

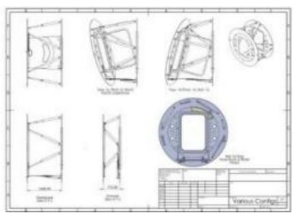

Fig.4 Engineering diagram of leveling platform

2.3. Power system

The intelligent track inspection robot based on machine vision and ultrasonic guided wave is powered by 4S lithium battery, which has higher energy density and can provide longer endurance time.It has a low self-discharge rate and can maintain a high state of charge when stored for a long time.With good charging and discharging performance, it supports fast charging and high-speed discharging, which improves the efficiency of the

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device.With proper use and charging, the lithium battery has a long service life, which can reduce the frequency of battery replacement and lower maintenance costs.

In a variety of complex external environments, the test track inspection robot in the foot structure speed can be up to 0.5m/s, on the track after the wheel foot switch to the wheel structure for detection, detection speed up to 20km/h. Robot built-in Li-ion battery pack + magnetic coupling resonance type without automatic charging, the efficiency of transmitting and receiving device distance of 0.3m is as high as 95%, compared with traditional wireless charging equipment, has a Compared with the traditional wireless charging equipment, it has the advantages of long transmission distance, high transmission efficiency and high transmission power.In practical applications, the use of lithium phosphate batteries, charging 5h can be filled, in normal operation can work continuously for 8 hours, range 140km, compared with the traditional artificial detection, greatly improving the detection speed and unit detection mileage.[1]

3. Defect Detection System

3.1. Internal and external recognition inspection system

The track inspection robot utilizes advanced machine vision technology to perform comprehensive crack detection, deformation analysis and other defect and abnormality identification on the track surface.During the inspection process, ultrasonic waveguide technology is used to identify potential defects in the track and ultrasonic signals are collected to determine the exact location of the defects in the axial and circumferential directions of the track.Subsequently, the robot collects a structured light image of the detected defect area using machine vision technology to form a rectangular image.

Through image processing technology, the robot is able to extract the centerline of the light bar in the structured light image, and use the powerful function of MATLAB software to realize the three-dimensional visualization of the local area of the track.By combining the ultrasonic guided wave inspection results and full-focus imaging technology, the robot is able to accurately locate the defects on the track and comprehensively assess the severity of the defects. Polar coordinates for circumferential localization is shown in Fig.5.

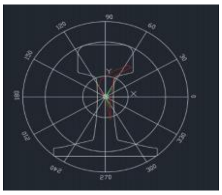


Fig.5 Polar coordinates for circumferential localization

The image processing system built by the team realizes accurate track image processing. In order to retain the characteristic information of the inspection items completely, the team chooses 24-bit RGB model color camera as the image acquisition equipment for the product, meanwhile, since the target surface of the CCD camera is a real light-sensitive component, there is no algorithm to fill in the simulation of the color situation, which can reduce the processing time and retain the contrasting characteristics of the original data, as well as carry out the image model conversion to convert the three-dimensional data into the image model.image model conversion, the three-dimensional data information is proposed to become single-channel data.[2] Rail seam image model conversion is shown in Fig.6.

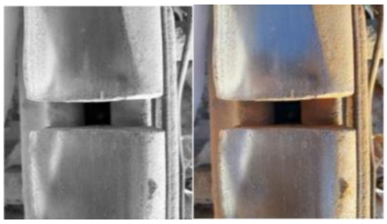


Fig.6 Rail seam image model conversion

When the intelligent rail inspection robot based on machine vision and ultrasonic guided wave acquires image data, it encounters a variety of factors that cause the image quality to be impaired, such as fluctuations in the detection speed, vibrations during operation, and changes in the ambient light, which may introduce noise points on the image.In order to improve this problem, an adaptive weighted median filtering technique is used to denoise the image, effectively eliminating the disturbing noise.By adjusting the size of the filtering window, different processing effects can be obtained, which also provides a strong support for accurate identification of track defects.[3] Improved weighted median filtering track image processing results is shown in Fig.7.

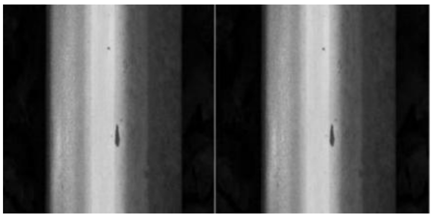


Fig.7 Improved weighted median filtering track image processing results

3.2. Roadbed settlement detection

The vibration characteristics of the vehicle will change significantly under the condition of roadbed settlement.Based on this phenomenon, the vertical coupling model of vehicle - track - roadbed is constructed.The model shows that when the roadbed settles, the track structure will have corresponding deformation under the influence of its own gravity, which will cause the track surface to be uneven.Through the application of this model, the influence of roadbed settlement on track and train operation can be predicted, which provides scientific basis for the maintenance and management of railroad engineering. Railroad bed structure model is shown in Fig.8.

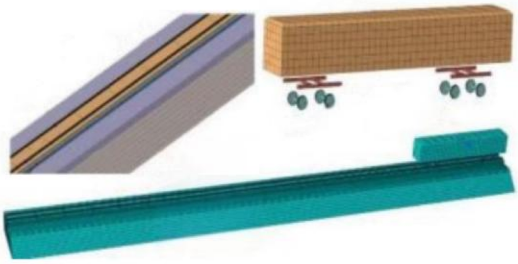


Fig.8 Railroad bed structure model

By analyzing the vibration response curve of intelligent rail inspection robot based on machine vision and ultrasonic guided wave under different settlement conditions, the uneven settlement of roadbed can be effectively identified.This method not only improves the feasibility of monitoring, but also can visualize the impact of settlement on train operation by extracting and analyzing the vibration data. Vehicle vertical acceleration time course curve under different settlement amplitude is shown in Fig.9.

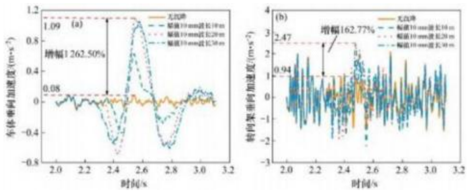


Fig.9 Vehicle vertical acceleration time course curve under different settlement amplitude

According to the analysis of the data presented in the graph, with the increase of settlement amplitude from 0mm to 30mm, the maximum vertical acceleration of the vehicle body, bogie and wheelset when passing through the settlement area increased significantly by 754.55%, 234.02% and 16.73%, respectively.[4] This phenomenon indicates that the vertical acceleration of the car body and bogie has a high sensitivity to the degree of roadbed settlement, which provides an important basis for judging whether there is uneven settlement of the roadbed.In classifying and identifying the track roadbed settlement, an identification method based on particle swarm optimization algorithm (PSO) and support vector machine (SVM) is used.This method improves the performance of the identification model by optimizing the algorithm, and then realizes the accurate identification of different types of roadbed settlement. PSO-SVM identification process of roadbed settlement is shown in Fig.10.

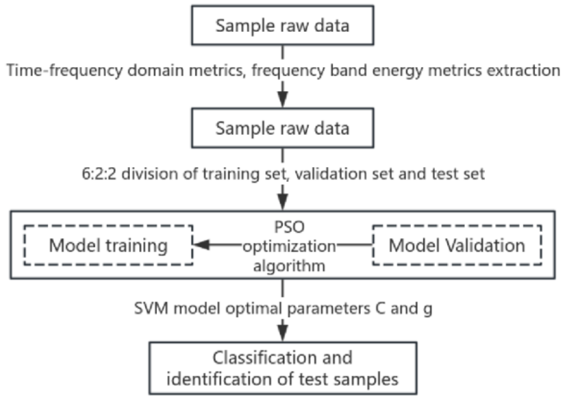


Fig.10 PSO-SVM identification process of roadbed settlement

After collecting the time series data of vehicle vertical acceleration under different working conditions, we performed feature extraction for each set of data, including feature indicators such as time domain and frequency band energy.These feature metrics constitute the sample set, where X represents the feature metrics and Y represents the corresponding working condition labels.The sample set is divided into training set, validation set and test set in the ratio of 6:2:2.

Using the particle swarm optimization algorithm, we trained the model on the training and validation sets to find the optimal key parameters C and g, in order to construct an efficient ballasted track subgrade settlement identification model.After several rounds of training and parameter optimization, we obtained a classification model with the best performance.After inputting the test set into this model, according to the output results of the model and the corresponding labels, we can accurately classify and recognize different types of roadbed settlement conditions. Recognition rate of settlement wavelength/amplitude based on PSO-SVM is shown in Fig.11.

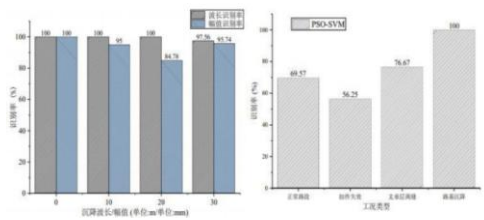


Fig.11 Recognition rate of settlement wavelength/amplitude based on PSO-SVM

The recognition accuracy reaches 95% and 84.78% when the settlement amplitude is 10mm and 20mm, respectively.This shows that the algorithm is able to maintain a high accuracy in the case of small settling amplitude, although the recognition ability of the algorithm decreases.[5] For the case of no settling and different settling wavelengths, the algorithm's recognition accuracy is almost perfect.These results show that particle swarm optimization combined with support vector machines is effective in identifying uneven settlement of roadbeds.With these data, we can conclude that the algorithm shows high reliability in dealing with the settlement problem, especially when the settlement magnitude is large.The algorithm is still able to provide reliable identification results even when the settlement magnitude is small.

4. Innovative rating Algorithm

The visualization data processing platform receives and processes a large amount of raw data, adopts independent innovative algorithms and automatically analyzes and rates the rail crack data, and after the defect information is processed, the platform shows the defect data in the form of charts, maps, etc. Firstly, the rail defect detection based on ultrasonic guided wave and machine vision is carried out.

First of all, the platform will be based on ultrasonic guided wave and machine vision rail defect detection, through the ultrasonic guided wave detection of rail defects, ultrasonic guided wave signals are collected, the axial coordinates of the defects and axial positioning polar coordinates, the location of the defects are determined, and the advanced visualization equipment is used for three-dimensional visualization, and then the location of the rail defects are located, and the degree of defects is assessed by fusion of the rail defects.Using defect classification algorithm, image processing, analysis, real-time, non-contact points can be very good luck for rail detection.

Team members constructed a comprehensive database of rail defect data collected through field research.Using this database, we trained and developed an algorithmic model.On the PyQt5 software development platform, we encoded images captured by ultrasonic guided waves and machine vision techniques for data analysis of rail defects.The process first recognizes the ultrasound guided wave and machine vision images, extracts the features of the track defects, and identifies them, providing possible identification results and relevant attribute information.Through target identification and classification, we were able to determine the specific type of defect.In the actual test, we measured a defect with a circumferential length of 7 cm and calculated its circumferential angle to be approximately 59.44°. By further analyzing the polar plot, we determined the angle of the circumferential defect to be 61.4°, with an error of only 3.3%. Compared with the traditional detection method, the detection precision is improved by 2.3% and the accuracy is 95.2%. Defect database is shown in Fig.12.

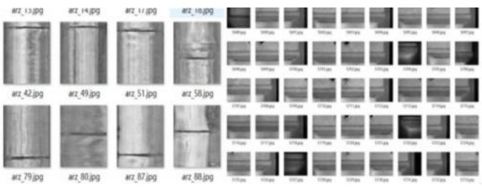


Fig.12 Defect database

The defect types obtained by the software processing platform are then rated by the team's self-developed rating algorithm based on the depth, length, width and other information of the defects to determine the severity of the defects and classify them for subsequent processing.The analysis uses the OpenCV library to read the images uploaded by the user and convert them into a processable format.The XML file is parsed using the ElementTree library to extract the category and location information for each object.Then, based on the information in the XML file, the system draws a rectangular box for each object on the image and displays its category label inside the box, and saves the annotated image to a specified folder for subsequent use or sharing. It has good scalability, which helps the user to cope with the annotation needs of different tasks. Innovative Defect Rating is shown in Fig.13.

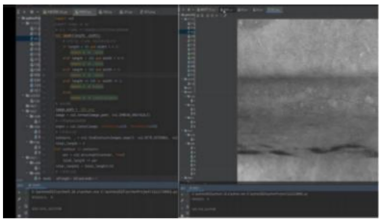


Fig.13 Innovative Defect Rating

The visualized data platform for railroad track crack detection provides a window for real-time information transmission between the robot and the track service personnel, transmits the inspection data to the data processing platform, and the defect rating algorithm of the platform efficiently receives and processes a large amount of raw data, including extracting and analyzing the defect location, the amount of settlement of the roadbed, the shape of the track cracks, the size, the density and other characteristics, and automatically analyzes and rates the track crack data.Rating.It provides users with high quality data support, helps users to quickly and accurately identify the type, size, location and other information of defects, provides important reference for subsequent maintenance and repair work, and helps to make maintenance plans and decisions in a timely manner.

5. Product Digital Design

5.1. Robot structure design

The team chose aluminum alloy, which has low density, high strength, excellent corrosion resistance and long service life, as the main component material of the product body.One-piece stamping technology is utilized to manufacture the various components of the body, a method that not only improves the efficiency of material use, but also enhances the strength and rigidity of the body.In addition, the surface of the aluminum alloy is treated with electrolysis to form an oxide film, which gives the car body excellent waterproof performance.The design of the vehicle body adopts a streamlined drum-shaped aluminum alloy structure, which significantly reduces the air resistance of the vehicle during driving, effectively improves the stability of the vehicle, reduces the risk of rollover, and enhances its wind resistance. This significantly improves the performance and durability of the product. Robot density analysis is shown in Fig.14.

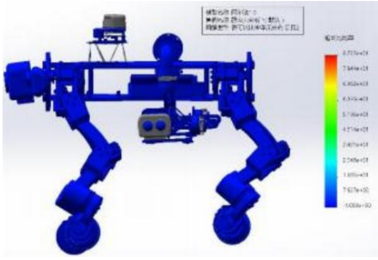
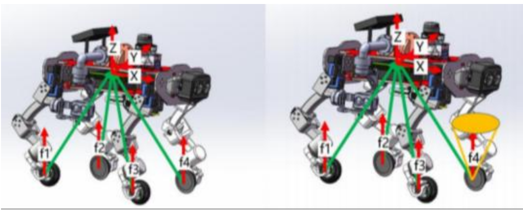


Fig.14 Robot density analysis

Pattern members digitally design the MPC controller for the center-of-mass motion analysis of the robotic dog. The purpose of the MPC controller is to allow the center of mass of the robotic dog to track the latest center-of-mass reference trajectory as much as possible, and then calculate the reaction force required at the end of the foot in the coming period of time, and ultimately generate the system state variables: the position, velocity, acceleration, rotation angle, and angular velocity of the robotic dog, and the system input variables: the quadrupedal touchdown force.The single rigid body model ignores the effect of the legs of the quadruped, and simplifies the motion analysis by considering the robot directly as a whole, i.e., a rigid body, with the ground force on the end of the leg acting directly and equivalently at the center of mass.[6] Dynamics modeling analysis is shown in Fig.15.



Fig,15 Dynamics modeling analysis

5.2. Hardware feasibility test

In order to ensure that the orbital inspection robot maintains a high and stable level of measurement during the measurement inspection, the team members tested and verified the structural aspects of the robot's machine.The overall stress situation was analyzed by SolidWorks software.During the simulation and verification process, the team members analyzed the stress on the main joints of the robot and optimized its structure to meet the transformation and motion strength.This not only ensures that the overall shape of the robot will not be deformed due to the force, but also meets a certain load capacity.Enhance the adaptability.SolidWorks Deformation Analysis of Major Components is shown in Fig.16.

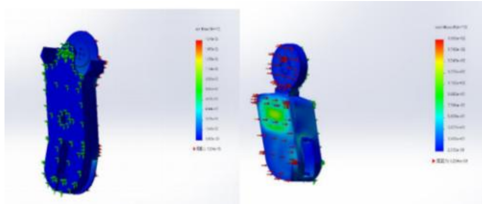


Fig.16 SolidWorks Deformation Analysis of Major Components

In the field of SolidWorks model quality digital design, the integrated application of simulation tools is a key step in achieving comprehensive evaluation and optimization of the design.These tools enable in-depth analysis of designs in a virtual environment, covering mechanical properties such as stress, strain, fatigue, and nonlinear response, as well as multiphysics field issues such as heat transfer and fluid dynamics.This analysis helps ensure the reliability and efficiency of the design in real-world applications.

Through exhaustive quality analysis, the design phase can anticipate potential structural defects, performance limitations, and the many problems that may be encountered during manufacturing and assembly.Avoiding costly modifications and rework at a later stage effectively reduces the overall cost and cycle time of product development.

Model quality analysis also supports interdisciplinary design optimization for comprehensive design solution evaluation.This approach not only accelerates the transition from concept to finished product, but also reduces the cost and time of development by reducing the reliance on physical prototypes and testing.Mass Density Analysis of Inspection Robot is shown in Fig.17.

Fig.17 Mass Density Analysis of Inspection Robot

5.3. Control analysis

Each mechanism must be precisely coordinated with each other and the force is reasonable in order to show the expected function, which requires high machining precision and coordination.And then combined with the knowledge of material mechanics on the limit strength, stiffness, stability analysis of these parts and consider the overall structure and weight of the car body and the comprehensive analysis of the applicable places. Simulation and optimization data of Adams optimized servo parameters is shown in Fig.18.

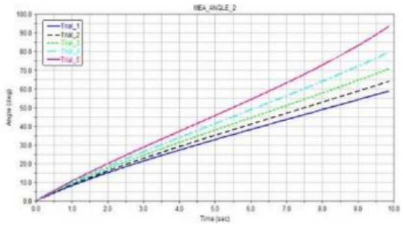


Fig.18 Simulation and optimization data of Adams optimized servo parameters

Based on the above foundation, the team analyzed its operation performance and continuously improved the structure to meet the motion performance. In order to meet the automation of unattended, multi-morphic robots, team members carried out circuit design and circuit simulation simulation, circuit feasibility and can fulfill our preset functions and operating standards.Body Circuit Design is shown in Fig.19.

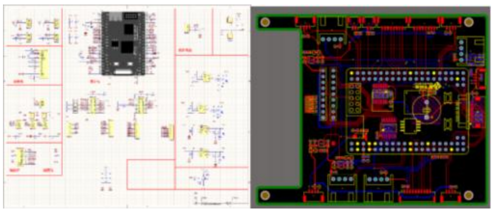


Fig.19 Body Circuit Design

6. Functional Testing

6.1. Track testing under normal operating conditions

- ***Preparation stage***

Before the test, the robot is subjected to a comprehensive system check and calibration to ensure that its sensors, cameras and navigation equipment are in the best working condition.The test route is also planned, and various track types such as straight sections, curved sections and turnout areas are selected as test objects.Robot completes testing preparation is shown in Fig.20.

Fig,20 Robot completes testing preparation

- ***Data acquisition***

Start the robot, drive along the predetermined route automatically, use the omni-directional laser scanner, side gimbaled surface array camera, ultrasonic guided wave and autonomous cruise obstacle avoidance navigation to collect the geometric size data and image information of the track synchronously, and transmit the collected information and data in real time to the back-end processing platform to carry out the preliminary pre-processing and screening of the data.

- ***Data analysis***

The back-end processing platform applies advanced image recognition and data analysis algorithms to analyze the collected data in depth, and automatically generates track condition assessment report, including geometric deviation, surface defect location and severity and other information.The evaluation results are compared with the railroad maintenance standards to identify the areas that need to be paid attention to or potential safety hidden dangers, and the above data are shown in the form of visualized charts and pictures. Detection Data Interface is shown in Fig.21.

Fig.21 Detection Data Interface

6.2. Defect detection under simulated failure scenario

- ***Scene setting***

Set up simulated fault points on the test route, such as artificially created track surface cracks, gauge expansion, unevenness, triangular pit fasteners missing, screws loose and other defects, to ensure that each simulated fault point is representative of a comprehensive test of the detection ability of the rail intelligent inspection robot.Simulated fault points is shown in Fig.22.

Fig.22 Simulated fault points

- ***Inspection process***

The robot drives according to the established route, scans and photographs the whole section of the railroad with high precision, and transmits the data to the back-end data processing platform in real time, processes and analyzes the images through the defect grading algorithm, and evaluates the degree of defects of the railroad in a fusion manner.[7] Railway Intelligent Identification and Detection is shown in Fig.23.

Fig.23 Railway Intelligent Identification and Detection

- ***Emergency response***

According to the grading standard of the innovative grading algorithm, the robot should classify the detected defects into different grades and trigger the corresponding early warning mechanism according to the logic program of the algorithm, and provide detailed location information and defect description as well as remedial measures to the railroad staff through the visualized data processing platform.The robot's emergency response speed and report accuracy are evaluated to verify its practicality and reliability in emergency situations. Defect Rating is shown in Fig.24.

Fig.24 Defect Rating

7. Conclusion

This paper presents an intelligent track inspection robot integrating advanced technologies such as machine vision, ultrasonic guided wave detection, and Beidou positioning. The system achieves high-precision rail defect detection and efficient data analysis, addressing the limitations of traditional methods. Its robust design and innovative defect rating algorithm ensure reliability and adaptability in complex environments. Functional testing confirms its effectiveness in enhancing automation and safety, contributing to the intelligent development of rail inspection.

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