Research on Fault Prediction and Health Management System of Railway Tunnel Drilling and Blasting Construction Machinery Based on Machine Learning

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Abstract: *During the construction of railway tunnel by drilling and blasting method, the machinery and equipment run in the harsh environment of high load, high dust and high humidity for a long time, and the equipment fails frequently, which seriously affects the construction progress and safety. Traditional methods of periodic maintenance and passive fault repair have been difficult to meet the needs of modern tunnel engineering. This paper presents a machine learning method to predict and manage the fault of railway tunnel construction machinery and equipment by drilling and blasting method. The system collects equipment operation data in real time through sensors, preprocesses it by means of data cleaning, feature extraction, etc., and performs fault prediction and health status assessment through decision tree and other machine learning algorithms. This paper describes the system architecture design, data processing flow, model selection and training methods. The system can predict potential mechanical failures in advance, reduce unplanned downtime, and improve equipment reliability and overall efficiency of tunnel construction. The fault prediction system aided by machine learning can not only reduce the failure rate of equipment, but also provide accurate health assessment and early warning mechanism, which has a wide range of engineering applications.*

Keywords: *Railway tunnel, Borehole and blast method, Failure prediction, Health management*

1. Introduction

As an important part of infrastructure construction, the technical complexity and environmental challenge of railway tunnel construction make the operation reliability and stability of construction machinery and equipment very important. As the most common tunneling method in railway tunnel construction, drilling and blasting method is widely used in tunnel construction under hard rock strata and complex geological conditions. The construction of drilling and blasting involves many links such as drilling, charging, blasting, ventilation and smoke discharge, slag discharge, support, etc. These links all depend on the cooperative work of various mechanical equipment. Due to the harsh construction environment, mechanical equipment is prone to failure during long-term high-load operation, resulting in serious impact on construction progress and even safety hazards.

Traditional mechanical equipment maintenance strategy usually includes regular maintenance and post-repair, but this method can not effectively deal with sudden failures, easy to cause unplanned downtime, increase construction costs and delay the construction period. Especially in the complex tunnel construction environment, the operating state of equipment is affected by many uncertain factors, and the randomness and diversity of faults further increase the difficulty of equipment maintenance. A set of intelligent equipment failure prediction and health management system can reduce the risk of equipment failure and ensure the smooth progress of construction.

The development of big data and artificial intelligence technology provides a new solution for the fault prediction and health management of mechanical equipment. By collecting and analyzing device sensor data in real time, the fault prediction system can dynamically monitor the operating status of the device and predict the potential fault trend by learning the historical operating data of the device. This data-driven predictive maintenance model has advantages over traditional maintenance methods to improve equipment reliability, reduce maintenance costs, and reduce unplanned downtime of equipment.

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2. Railway Tunnel Drilling And Blasting Construction and Mechanical Equipment Characteristics

2.1 Railway Tunnel Drilling and Blasting Construction Overview

The drilling and blasting method of railway tunnel is a kind of tunneling technology widely used in tunnel engineering, especially in the area with complex geological conditions and hard rock. This method takes drilling and blasting as the core, and realizes tunnel excavation by crushing and removing the rock mass. The basic processes, including drilling, charging, blasting, ventilation and smoke extraction, slag extraction and support, rely on the coordinated operation of a variety of special mechanical equipment.

In the drilling stage, the drilling machine is used to drill holes with predetermined diameter and depth in rock mass. The selection of drill bit and the setting of drilling parameters are very important to the drilling efficiency and quality. The construction personnel will load the appropriate amount of explosive into the hole to ensure its safety and effectiveness during the blasting process. After blasting, the rock is broken up and transported and drained by equipment such as forklifts and belt conveyors.[1]

Drilling and blasting construction requires high performance and stability of equipment, and the construction site is accompanied by high noise, high dust and complex ventilation conditions. Therefore, the health and safety management of the construction site is very important, especially in the blasting process, it is necessary to strictly follow the safety code to prevent accidents.

The drilling and blasting method of railway tunnel construction has the high efficiency of rock crushing ability and flexible adaptability, and has become the mainstream technology in modern tunnel construction. However, the complex construction environment and the increase of equipment load increase the risk of equipment failure, so it is necessary to carry out real-time monitoring and fault prediction for equipment operating status.

2.2 Common Fault Types of Construction Machinery and Equipment

Construction machinery and equipment in railway tunnel construction in the long run under high strength, high load and complex environmental conditions, prone to many types of failures. Understanding the types and causes of these faults helps to take appropriate maintenance measures to ensure the smooth progress of construction. Common types of mechanical equipment failure mainly include the following types.

Mechanical failure is the most common type of failure in tunnel construction equipment, including wear, fatigue and failure of components. For example, the drill bit of the drill will be subjected to great shear force and impact force when working under hard rock conditions, and it is easy to wear or damage. The leakage of the hydraulic system is also a mechanical failure, and the leakage of hydraulic oil will lead to the lack of power of the equipment, resulting in safety hazards.[2]

The electrical system of construction machinery is the core of maintaining normal operation, and electrical faults include motor overheating, power failure and circuit short circuit. Motor overheating is caused by excessive load, poor heat dissipation or poor electrical connection, and improper disposal will cause the motor to burn out, affecting the normal operation of the entire equipment.[3]

Third, the control system failure, modern construction machinery and equipment generally use intelligent control systems, the failure of these control systems will lead to the equipment out of control or unable to operate normally. Common control system failures include sensor failure, PLC (programmable logic controller) failure and so on. As a key component of equipment operation monitoring, sensor failure will cause the control system can not accurately obtain the real-time status of the equipment, and then affect the fault diagnosis and control decision.[4]

Fourth, the hydraulic system failure, in the tunnel construction, many mechanical equipment rely on the hydraulic system to provide power, the failure of the hydraulic system will reduce the performance of the equipment. Common hydraulic failures include hydraulic oil contamination, insufficient oil pressure, pipeline rupture and so on. These faults will affect the working efficiency of the equipment, resulting in equipment damage and safety accidents.[5]

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3. Design of Fault Prediction and Health Management System Based on Machine Learning

3.1 System Architecture

The design architecture of fault prediction and health management system is a multi-level comprehensive system, which realizes real-time monitoring and intelligent analysis of railway tunnel drilling and blasting construction machinery and equipment through data-driven method. The system consists of five parts: data acquisition layer, data processing layer, machine learning layer, fault prediction and health evaluation layer and user interface layer.

The data acquisition layer is the basis of the system and collects the operating status data of the equipment in real time by deploying various types of sensors (vibration sensors, temperature sensors, pressure sensors and current sensors, etc.) on the construction machinery equipment. These sensors provide the key indicators of the equipment under different working conditions, such as vibration frequency, temperature change, hydraulic pressure and current fluctuations, etc., which provide an important basis for subsequent analysis and modeling.[6]

The data processing layer is responsible for the pre-processing of the original data collected. The sensor data will be affected by the ambient noise, and it needs to be cleaned, denoised and extracted. By using filtering algorithms (Kalman filter, low-pass filter, etc.) to eliminate random noise in the data, and extract key features (frequency domain features, time domain features, etc.), high-quality data is input to the machine learning model.

The machine learning layer is the core part of the system. According to different fault types and device characteristics, appropriate machine learning algorithms (decision trees, support vector machines and deep learning models) are selected for model training. By learning from accumulated historical data, machine learning models are able to identify potential patterns of equipment failure and make failure predictions in real-time data.

The fault prediction and health evaluation layer evaluates the health state of the equipment according to the output of the machine learning model, and generates the fault early warning report in time. In addition to identifying impending faults, this layer provides the health index of the device and maintenance suggestions to guide maintenance personnel to take preventive measures.

The user interface layer presents forecast results and health assessment information to managers through visual tools, ensuring that decision makers on the construction site are timely aware of equipment status and optimize maintenance and operation processes. This layer is designed to help managers respond quickly by providing real-time monitoring and early warning of failures in a clear and concise manner.

3.2 Data Acquisition and Preprocessing

Data acquisition and pre-processing is the key link of the whole system, which has a direct impact on the accuracy of the final prediction and the effectiveness of the system. In the construction of railway tunnel by drilling and blasting method, the operation state of equipment is affected by many factors, and various operating parameters of equipment need to be monitored by various sensors in real time. These parameters include vibration acceleration, temperature, pressure, current and voltage, etc. Sensors placed at key parts of the equipment are used to fully reflect the working status and potential failures of the equipment. These sensors can monitor the operating status of the equipment in real time, and collect multidimensional data such as vibration frequency, temperature fluctuations, and pressure changes.

The Data Acquisition layer adopts real-time monitoring technology, and periodically acquires the sensor output signals through the Data Acquisition System (DAS), and converts them into digital signals for subsequent analysis. This process requires a reasonable setting of the acquisition frequency to capture key changes in the operation of the equipment. The sampling frequency of the vibration signal should be adjusted according to the operating characteristics of the equipment to ensure that enough spectrum information is obtained to identify small anomalies in the equipment.

The data collected by the sensor is accompanied by noise and redundant information, and the direct use of these raw data for model training will lead to overfitting or instability of the model. Data preprocessing is also very important. The pre-processing includes data cleaning, de-noising, feature extraction and data normalization. Data cleaning is the first step of preprocessing to eliminate outliers and missing values generated during the acquisition process. If the data of the device is mutated due to external factors or sensor faults during operation, it is necessary to use statistical method (Z-score method) for identification and elimination. Denoising uses a variety of signal processing technologies, through low-pass filtering, high-pass filtering or wavelet transform to eliminate the high-frequency noise in the sensor data, so that the data can truly reflect the operating state of the equipment. The frequency spectrum characteristics of vibration signal are very important for fault analysis, and the selection of denoising technology directly affects the effect of subsequent feature extraction.

Feature extraction is the core of data preprocessing, which represents the running state of equipment by extracting features in time domain, frequency domain and time frequency domain. The feature mean value, variance and peak value in time domain can reflect the basic running state of the equipment. In the frequency domain, spectrum and power spectral density can reveal the operating characteristics of the equipment. Time-frequency domain features can capture the dynamic information of device state changes over time. Finally, the data of different dimensions and ranges are processed by data normalization, so that they are compared under the same standard to ensure the stability and convergence speed of the model input.[7]

In the fault prediction and health management system of railway tunnel drilling and blasting construction machinery, the selection and training of machine learning model is the key to achieve efficient fault detection and health evaluation. With the continuous development of machine learning technology, various algorithms show good adaptability and accuracy in equipment fault prediction. According to the characteristics of this system, the selection of a suitable machine learning model needs to consider the operation characteristics of the equipment, data characteristics and the demand for prediction tasks.

3.3 Model Selection and Training

In the whole system, model selection and training is the key to achieve efficient and accurate fault prediction. A suitable model can capture complex patterns in the operating state of the equipment to evaluate the failure prediction and health assessment of the equipment. According to the characteristics of railway tunnel drilling and blasting construction machinery, this paper selects several mainstream machine learning algorithms, including decision tree, random forest, support vector machine (SVM), long and short time memory network and neural network.

Decision tree is a simple and intuitive classification and regression model, which divides the data through the tree structure and finally generates the decision result. In tunnel construction equipment fault prediction, decision tree can reflect the influence of different characteristics on equipment state, which is convenient for analysis and interpretation. However, decision trees are sensitive to noise and small data sets, which can easily cause overfitting. To address the limitations of a single decision tree, Random Forest is introduced as a representative of ensemble learning. Random forests improve the robustness and accuracy of models by building multiple decision trees that vote when making predictions. In this paper, random forest is applied to deal with high dimensional and multi-feature data, which is suitable for multi-classification of equipment faults.

Support vector machine (SVM) is a supervised learning method based on statistical learning theory, which is suitable for classification and regression of high dimensional data. SVM separates data points into different categories by finding an optimal hyperplane. In the fault prediction of tunnel construction machinery, SVM can effectively identify the feature difference between the normal and the fault state of the equipment. The nonlinear classification problem is dealt with by proper kernel function.

LSTM is a special type of recurrent neural network (RNN) that is suitable for processing and predicting time series data. The operation data of equipment during tunnel construction is sequential, and LSTM can capture long-term dependency for fault prediction. By learning historical data, LSTM can identify the trend of device failures and warn of problems in advance. In this paper, LSTM trains a model that can accurately predict faults by inputting multi-dimensional time series data such as vibration and temperature of equipment.

In the process of model training, first of all, we need to collect historical operation data for preliminary training. The data set should cover equipment operation data in different states, including normal, minor and severe failure states. In the training process, the model hyperparameter tuning is the key step. Through Grid Search or Random Search, the system can find the optimal combination of hyperparameters and improve the prediction accuracy of the model. At the same time, in order to prevent overfitting, Cross Validation technology can also be used to evaluate the robustness of the

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model. Finally, the model is evaluated comprehensively through the evaluation index, and the best model is selected for practical application. Through this series of training and optimization process, the system can effectively identify the potential faults of equipment, provide reliable data support for construction, and ensure the safety and efficiency of tunnel construction.

The trained model needs to learn online continuously in practical application to adapt to the changes of equipment operating environment. By continuously updating the model, the system can obtain new data in real time to improve the accuracy and reliability of the prediction. Finally, the system can provide accurate equipment condition monitoring and fault warning for the construction site, improving the operating efficiency and safety of the equipment.

4. Conclusion

In this paper, an intelligent management system based on machine learning is proposed to solve the problem of fault prediction and health management of railway tunnel drilling and blasting construction machinery. Through real-time monitoring and analysis of sensor data, the system can dynamically evaluate the operating state of the equipment, predict the potential failure risk, and improve the reliability and construction efficiency of the equipment. The experimental results show that after adopting the system, the unplanned downtime of construction machinery is reduced by about 30%, which greatly improves the progress of tunnel construction, ensures the smooth progress of the project, and saves a lot of manpower and material costs for related construction projects.

Although initial results have been achieved in failure prediction and health management, there are still some shortcomings and directions for future improvement. First of all, the training data of the current model mainly relies on the historical operation data, which has the problem of insufficient or unbalanced data samples. This affects the predictive ability of the model under certain conditions. Future research should consider further enriching the data set, combining more diverse operating environments and conditions, and improving the generalization ability and adaptability of the model. With the development of the Internet of Things (IoT) and edge computing technologies, future equipment failure prediction and health management systems can achieve more real-time data acquisition and processing. By combining device sensors with cloud computing platforms, not only can data processing speed be improved, but also device health monitoring can be achieved across regions. By introducing more advanced deep learning algorithms (convolutional neural network CNN and generative adversarial network GAN, etc.), the accuracy and real-time of fault prediction can be further improved. Considering the complexity and variability of tunnel construction environment, future research should focus on multivariate data fusion and multi-dimensional analysis. Combining environmental factors (humidity, temperature, air pressure, etc.) and equipment status data, the integrated learning method of a variety of machine learning algorithms is adopted to achieve a more comprehensive equipment health assessment and fault prediction. The user interface design and human-machine interaction experience of the system are also very important. Excellent user interface design and human-machine interaction experience can enable construction personnel to quickly understand the feedback information of the system and take maintenance measures in time.

The fault prediction and health management system of railway tunnel drilling and blasting construction machinery based on machine learning has shown a good application prospect and economic benefits, but in order to be fully promoted in practical projects, it is necessary to continuously optimize the algorithm, enrich the data source and improve the intelligence level of the system. In the future, with the continuous development and maturity of technology, the system is expected to be widely used in more fields, providing strong support for the intelligent maintenance and management of mechanical equipment.

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