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A Review of Industrial Robot Fault Diagnosis and Fault-tolerant Technology

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ABSTRACT

Industrial robots are the most representative equipment in the field of intelligent manufacturing. The fault problem of industrial robots is prominent, which seriously affects the safe production and economic benefits of enterprises. For these reasons, the fault diagnosis and fault-tolerant technology of industrial robots gradually become the focus of research. This paper first summarizes all kinds of common faults of industrial robots, and then gives an overview of the fault diagnosis methods of industrial robots from three aspects, summarizes the fault-tolerant technology. Finally, looks forward to the future development trend of fault diagnosis and fault--tolerant technology of industrial robots, points out that the integration of mixed fault diagnosis methods and fault-tolerant technology of industrial robots will be the development trend in the future.

KEYWORDS

Industrial Robot; Fault Diagnosis; Fault-tolerant Technology; Data-driven.

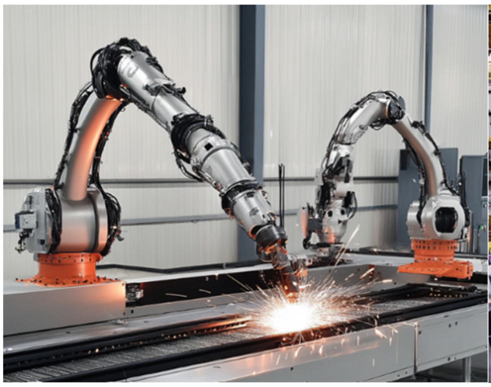
1. INTRODUCTION

Manufacturing industry is a direct reflection of national productivity level, an important main body of the national economy, and an important foundation for maintaining the international competitiveness of a country. Industrial robots, known as the "crown jewels of manufacturing" [1], are increasingly replacing workers in monotonous, repetitive, and time-consuming tasks. The continuous advancement of industrial robot technology has improved social productivity and promoted social development. Therefore, once an industrial robot breaks down, it can lead to a "paralysis" of the production line, causing huge economic losses to the enterprise and even potentially triggering safety accidents. Currently, after most industrial robot malfunctions occur, engineers need to be present on-site to analyze the cause of the error and repair, which is a fault diagnosis method with the disadvantages of high cost, longtime consumption, and low maintenance efficiency. The blind regular inspection and repair of industrial robots for enterprises also lead to increased maintenance costs and low efficiency [2].

Therefore, under the background of promoting the strategy of manufacturing power, it is of great theoretical and practical significance to develop the fault diagnosis and fault-tolerant technology of industrial robots, and it is particularly important to quickly and accurately diagnose, locate the fault position of robots and ensure that robots can take corresponding fault-tolerant strategies to maintain their basic functions after the fault occurs .

2. COMMON FAULTS AND DIAGNOSIS DIFFICULTIES OF INDUSTRIAL ROBOT SYSTEMS

According to their application fields, industrial robots can be divided into welding robots, assembly robots, handling robots, spraying robots, etc, as shown in Fig.1. For industrial robots, the common fault types can be divided into hardware system fault, software and control system fault, sensor fault, according to their physical composition.




(a) welding robot (b) assembly robot


(c) Transfer robot (d) Spraying robot

Fig 1. Industrial robots are classified according to their application fields

2.1. Hardware System Fault

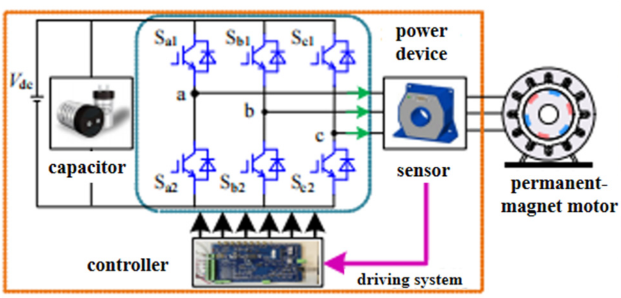


Fig 2. Diagram of motor drive system structure

The fault of industrial robot hardware system includes two types of faults, which are mechanical fault and electrical fault. Mechanical fault includes fault of components such as reducer, bearing, ball screw, and so on. Electrical fault is divided into motor body fault and motor drive system fault. Motor body fault is the internal fault of the motor, including the demagnetization fault of motor, the inter-turn short circuit fault of motor, the eccentricity fault of rotor, and so on. Motor drive system fault includes power device fault, sensor fault, capacitor fault and other faults [3]. A typical motor drive system is shown in Fig. 2.

2.2. Software and Control System Failures

Software and control system faults refer to faults that occur when the control software or performance parameters of the industrial robot system change, causing it to be unable to complete or unable to complete the specified task on time, such as the obstacle avoidance system of a mobile robot failing to detect obstacles. This type of fault does not change the inherent characteristics of the robot.

2.3. Sensor Failure

Sensor is a detection device which can sense (or respond to) and detect a certain definite information and convert it into a useful output signal corresponding to it according to a certain rule. It is the basic unit to obtain data in various applications and the normal operation of each part in the system is directly affected by the quality of data collected by the sensor.

According to the signifcant degree of fault characteristics, sensor fault can be divided into sudden fault and slow change fault. The sudden fault mainly refers to the sensor failure fault. The slow change fault includes gain fault and drift fault: when the sensor sampling value becomes k times of the theoretical value, it is called gain fault; when the sensor sampling value has a large amplitude deviation, it is called drift fault, and the mathematical expression of fault characteristics is shown in Table 1.

Table 1. Common types of sensor fault

Fault Type		Mathematical Expression
Mutual fault	Failure to function	y_n=Y
Gradual fault	Gain Failure	y_n=$k_r y_r$
	Drift fault	y_n=y_r+n(t)

Note: y_n is the sensor sample value; y_r is the sensor theoretical output value; Y is a constant; k_r is a constant; n$(t)$is the sensor drift value.

2.4. Diagnosis Difficulties of Industrial Robot System Faults

The difficulty in fault diagnosis of industrial robots is mainly reflected in

(1) Pseudo-fault feature interference: The accuracy of fault diagnosis is crucial. Industrial robot is a system that integrates machinery, electronics and software. Some fault features are similar, and it is difficult to distinguish fault types, locate fault components, and there is noise interference, which brings difficulties to fault diagnosis.

(2) Real-time requirement: In industrial application, fault diagnosis methods are required to be extremely real-time to prevent greater losses from untimely detection.

(3) Early Weak Fault Diagnosis: Some small faults and progressive faults are not obvious and indistinct in the early stage, and there is a need for algorithms with high precision and robustness in extracting fault features.

In summary, in practical application, the requirements of rapidity, accuracy and reliability of fault diagnosis should be considered comprehensively, and the appropriate fault diagnosis method should be selected.

3. FAULT DIAGNOSIS TECHNOLOGY OF INDUSTRIAL ROBOT

3.1. Classification of fault diagnosis technology

Fault diagnosis technology can be divided into three categories according to the diferent treatment methods of characteristic values: analytical model method, signal processing method and data driven method.

3.2. Analytical Model Approach

The core idea of the model-based fault diagnosis method is to establish a precise mathematical model of industrial robots, obtain the theoretical values of joint angles, torques, etc. And realize fault diagnosis by analyzing whether the residuals between theoretical and measured values exceed the threshold. It mainly includes parameter identification method, state observer method, and mixed model method.

Traditional parameter identification methods such as particle filter [4] can not meet the requirements of modern industrial scenarios with high dynamics and strong coupling due to their poor non-linear processing capability, low computing efficiency, and high maintenance cost, and there has been a lull in research in recent years.

Different types of state observers that are commonly used include the Luenberger Observer, the Kalman filter, the sliding mode observer, and the extended Kalman filter. Among them, the Luenberger observer is simple in structure and has high control accuracy; the Kalman filter has strong noise filtering and anti-interference capabilities; however, the applicability of these two observers is poor in nonlinear systems. The sliding mode observer has a good effect on solving the control problem of uncertain nonlinear systems and has the advantages of good robustness and high observation accuracy, and is the first choice for real-time fault detection, but there is a There is a system vibration problem. The extended Kalman filter optimizes the traditional Kalman filter and is suitable for nonlinear systems, but it has high dependence on system parameters and model accuracy, and has high requirements for system computing power. Azimi et al. [5] used the Luenberger observer to study the fault detection problem of robotic systems with linear fractional-order models. George K. Fourlas et al. [6] The observer-Kalman filter identification technique is used to provide a reference for the early diagnosis of sensor fault. Huang et al. [7] proposed a fault diagnosis method based on a second-order sliding mode observer, which uses the information of the manipulator angle, and through the equivalent output injection term of the observer, the fault estimation of the system actuator is realized, and the fault diagnosis task of the manipulator actuator is realized.

In recent years, the model-based fault diagnosis method has developed towards the direction of integrating multiple fault diagnosis methods and simultaneous diagnosis of multiple faults. Moshgani et al. [8] proposed a combined method of unknown input observer and genetic algorithm, using genetic algorithm to determine the optimal observer parameters, and the residual signal was used for adaptive threshold design to realize the fault diagnosis of the robotic arm sensor.The simulation results and their comparison with the extended Kalman filter confirm the efficiency of the proposed observer in the robust fault detection and diagnosis for robots. Ma et al. [9] proposed a collaborative adaptive fault diagnosis method for the single-link flexible-joint robot. Using the angular position deviation, the proposed adaptive distributed fuzzy estimator method is used for parameter estimation of sensor and other faults, and the parameters related to the fault can be accurately estimated in a relatively short time.

The hybrid model method integrates the physical model with the data- driven model to improve the diagnosis ability of complex scenarios. Typical technologies such as digital twin is a research hot point in recent years. For example, Ghanishtha Bhatti et al. [10] proposed an intelligent fault diagnosis mechanism for industrial robot actuators based on digital twin technology, which extracts current, torque and other signals for fault diagnosis. It is proposed in the literature case that when a short circuit occurs on the armature, the current consumption increases, and when this occurs for a specific duration, a peak is formed in the current waveform, thus judging the fault.

3.3. Signal Processing Approaches

Based on the signal analysis and processing method, the time domain and frequency domain fault features are extracted from the data samples after preprocessing. The fault is judged to occur through amplitude mutation, zero point, etc. Student Haoming Zhao from Shenyang Jianzhu University [11] adopted signal analysis methods such as wavelet analysis, Adaptive Wavelet Thresholding Principal Component Analysis, and robust principal component analysis to deeply analyze and study the fault diagnosis of the encoder and driving motor of industrial robots, and improved the effectiveness of fault diagnosis.

In the fault diagnosis of industrial robots, the signal processing method is still the basis, but the research hot point had shifted to the integration of multiple methods. Single signal processing is only suitable for simple faults, such as single sensor anomaly detection, and the diagnosis accuracy of multiple source coupling faults and nonlinear problems is insufficient.

3.4. Data-Driven Approach

The core idea of data-driven method is to analyze a large number of existing fault data and

train it by using artificial intelligence technology to judge the model fitting degree of the measuring data, so as to realize fault diagnosis. Machine learning is a branch of artificial intelligence. The advantage of using machine learning for fault diagnosis is that it is not necessary to understand the system structure and it is not necessary to have prior knowledge.

The number of publications applying machine learning methods to robot fault diagnosis in the past decade was counted based on the search results of Web of Science, as shown in Figure 3. It can be seen from the results of this topic that the number of publications has increased year by year since 2016, indicating that machine learning methods have received more and more attention in the field of robot fault diagnosis in recent years.

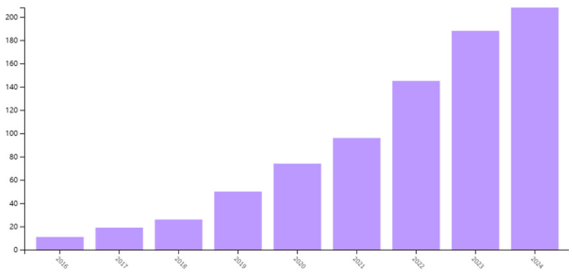


Fig 3. Robot fault diagnosis using machine learning

The machine learning methods applied in the field of industrial robot fault diagnosis can be divided into traditional machine learning and modern machine learning. The difference between the two is that the traditional method has a strong dependence on manual extraction of fault features.

Before the 2010s, the study of intelligent fault diagnosis focused on traditional machine learning methods [12]. During this period, methods such as artificial neural networks (ANN), support vector machines (SVM), and random forests (RF) appeared. These methods require experts to extract meaningful features from the data and then use these features for model training. An example of traditional machine learning methods is the SCARA robot fault diagnosis system designed by Kai Yu from Heilongjiang University [13]. He collected and processed vibration signals and compared three traditional machine learning algorithms: Back Propagation neural network (BPNN), SVM, and RF based on the proposed features and finally selected the PSO-SVM model to achieve the visualization and systematization of the overall scheme. Overall, traditional machine learning performs well in handling small-scale datasets, but it has limited effects in processing high-dimensional data and large-scale data, with low generalization performance, which reduces the accuracy of diagnosis. Therefore, traditional machine learning has shifted towards modern machine learning.

After the 2010s, the research hot points shifted to modern machine learning, including deep

learning, transfer learning and so on, which directly learn fault features from collected data automatically without the need for manual extraction. Xia et al. [14] proposed a novel deep perception adversarial domain adaptation (DPADA) method for fault diagnosis of industrial robot bearings under variable working conditions, integrating a unique perception loss and a time-stamp-based vibration signal screening technique, and finally the experiment proved that DPADA is superior to traditional methods in diagnosing bearing faults. Fedia Ibrahim [15] utilized four types of machine learning classifiers (RNN, SVM, RF, and ANN) for fault detection of robot actuator faults and sensors, and evaluated the results, RNN achieved the highest overall detection accuracy, and the experiment proved that modern machine learning methods are superior to traditional methods.

In summary, the data-driven method used for fault diagnosis of nonlinear and difficult-to- accurately-model has obvious advantages, but it still has shortcomings such as complex algorithm and long diagnosis time.

4. FAULT-TOLERANT TECHNOLOGY FOR INDUSTRIAL ROBOTS AFTER FAULT

Fault-tolerant means the ability to maintain the basic functions of the system when some components fail. According to the implementation method, fault-tolerant technology is divided into active fault-tolerant and passive fault-tolerant. The passive fault-tolerant is to deal with potential faults in advance through redundant design or robust control. The active fault-tolerant relies on real-time fault diagnosis results to dynamically adjust system structure or parameters to maintain functions after system occur fault. According to the common faults of industrial robots proposed in the previous chapter, this chapter summarizes the fault-tolerant technology of the above faults.

4.1. Fault-Tolerant Strategy of Hardware System

This paper divides the fault tolerance of hardware system into two categories: "redundant design" and "structure optimization", both of which belong to passive fault tolerance methods. Redundant design fault tolerance technology refers to the technology of fault tolerance by increasing additional hardware when the original hardware fails, such as standby power supply, motor redundancy topology [16], etc. Structure optimization refers to the improvement of fault tolerance ability by optimizing the structure of various mechanical components, for example , the stator is divided into segmented structure with complete magnetic isolation by cutting the stator yoke of the permanent magnet synchronous motor in document[17], as shown in Figure 4. The motor can run fault-tolerantly by removing the fault segment. The above fault-tolerant technologies have obvious advantages in improving the reliability and fault-tolerant ability of the system, but we should also pay attention to the problems of resource consumption, increasing the complexity of the system and increasing the cost.

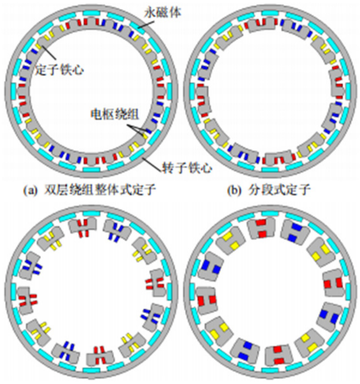


Fig 4. Segmentation of the stator

4.2. Fault Tolerance Strategy of SW & Control System

The fault-tolerant strategies for software and control part are all active fault tolerance, which can be divided into the following four categories:

(1) Redundant architecture switching: Switching to a backup system quickly through a software redundant module. For example, document [18] proposed a N-version programming (NVP) inspired approach that is based on the fusion of the outputs of three redundant deep neural networks (DNN) using a weighted voting scheme, which ultimately improves the model's robustness and accuracy.

(2) Model-based fault-tolerant technique: The core idea is to predict faults through a mathematical model and adjust control commands in real-time. For instance, Jin et al.[19] investigated the bias actuator fault on the basis of estimating unknown fault factors, and proposed a new adaptive fault-tolerant control strategy, which achieved the asymptotic trajectory tracking of the azimuth and forward velocity of the mobile robot system.

(3) Data-Driven Fault-Tolerant Technique: This strategy uses AI methods to achieve autonomous decision-making for faults. For instance, Guo et al. [20] analyzed the advantages and disadvantages of fault-tolerant and AI methods represented by reinforcement learning and intelligent trial-and-error algorithms for the control problem of the remaining legs of a hexapod robot after leg failure or injury. The results showed that the combination of fault- tolerant methods and AI methods can enable the robot to better solve the problem.

(4) Task-level fault-tolerant scheduling: To re-plan the path or allocate resources on the task execution layer. Student Yangjun Sun from University of Science and Technology Beijing [21] focused on the problem of robot conflict in logistics field RMFS. Aiming at eliminating dynamic event conflicts, a pre-reactive RMFS dynamic scheduling method driven by conflict prediction is proposed. Finally, the experiment proves that this method can get a scheduling solution with less completion time and shorter path length than the traditional expost scheduling method when dynamic events such as robot failure occur.

4.3. Sensor Fault Tolerant Technology

The tolerance scheme of the sensor mainly considers the following aspects: one is to install multiple alternative sensors in a redundant way, and use the signal of the alternative sensor to replace the signal of the faulty sensor when a fault occurs. This method increases the cost and the complexity of the system. The second is to design an appropriate observer, and use the observer to replace the faulty sensor to work when a fault occurs. This scheme has been studied more in recent years and has achieved good results. Document [22] proposed a sliding mode observer based on the reconstruction of current space vector error, which realized the simultaneous observation of rotor position and phase current error. Since the current error construction module is independent of the motor parameters, the proposed fault-tolerant control strategy has strong robustness. The third is to adopt data-driven methods for fault-tolerant control. Dong et al. [23] proposed a fault- tolerant control strategy based on iterative learning when the dynamic characteristics are completely unknown. The experimental results show that the proposed scheme has small tracking error and better data signal-to-noise ratio.

5. CONCLUSION AND PROSPECT

This paper analyzes and summarizes the latest research results of fault diagnosis and fault-tolerant technology of industrial robots in recent years. It summarizes the hardware fault, software and control fault, and sensor fault of industrial robots. It also introduces various fault diagnosis methods and typical fault-tolerant schemes. It analyzes the advantages and disadvantages of various schemes and development directions, and makes the following outlook for future trends:

(1) Integration of multiple fault diagnosis methods: The three categories of fault diagnosis methods summarized in this paper have their own advantages and disadvantages. The three methods are not completely independent of each other, but have a certain degree of overlap and integration. It is expected that more integrated diagnosis methods will be used in the future to complement each other's strengths and weaknesses in order to achieve faster and more accurate fault diagnosis and location.

(2) Multiple Faults Integrated Diagnosis: As the fault diagnosis methods for single fault are inefficient and can not meet the actual industrial needs, the fault diagnosis technology will inevitably move towards the direction of simultaneous diagnosis and location of multiple faults.

(3) In industrial applications, fault diagnosis and fault-tolerant control are usually integrated and inseparable. There is not much practical significance in the separate research on fault diagnosis technology. We must closely integrate fault diagnosis with fault-tolerant control, and consider the fault-tolerant control after fault in industrial robots, so as to ensure continuous and stable operation. The combination of the two is more theoretically and practically significant, and has economic value.

(4) Finally, it is still a great challenge to study how to make these industrial robot fault diagnosis and fault-tolerant schemes not only stay in the scientific research experiment, but also apply to the actual industrial circle.

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