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Intelligent Monitoring and Prediction of CNC Tool Wear: Signal Driven, Data Driven and Virtual Real Fusion

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Abstract. This paper focuses on the intelligent monitoring and prediction method of tool wear of computer numerical control (CNC) machine tools, systematically analyzed three representative, technology paths, signal driven, data driven and virtual real fusion. Research shows that the existing methods still have shortcomings in complex working condition adaptability, unsupervised self-label reliability, digital twin real-time performance and cross-process generalization ability. Aiming to these problems, this paper proposes to improve the signal feature extraction, wear state self-identification and visual online detection by combining multi-source sensing information fusion, timing depth clustering, migration learning and digital twin technologies. The research shows that the intelligent tool wear monitoring and prediction needs to be gradually developed from the independent optimization of single technology path to the fusion driving direction of multi-technology collaboration, and the cross-fusion of multidisciplinary methods will definitely become an important direction to promote the transformation to the industrial application with high reliability and strong generalization ability.

Keywords: Tool wear monitoring, intelligent monitoring and prediction, multi-source sensing information fusion, digital twin technologies

1. Introduction

In recent years, tool wear condition monitoring and prediction has become a key supporting technology in intelligent manufacturing field. In the cutting process, as the teeth of the machine tool, the wearing state of the tool directly affects the machining accuracy, surface quality and the operation safety of the machine tool. Statistics show that over 75% of equipment failures are caused by tool failure, and about 20% of machine tool shutdowns are caused by tool failure [1]. The traditional mode of relying on manual experience or regular tool change has been difficult to adapt to the flexible manufacturing needs of multiple varieties and small batches [2]. Therefore, the research on tool wear detection based on multi-source sensing and intelligent algorithm has important engineering and academic value. With the rapid development of sensor technology, signal processing method and artificial intelligence algorithm, tool wear state monitoring technology is evolving from traditional offline empirical judgment to data-driven online intelligent monitoring, which provides technical support for realizing adaptive control of machining process and tool life cycle management [3].

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Some progress has been made in signal feature extraction, intelligent modeling and visual detection. Aiming at the milling process of Inconel 718, Kumar et al. proposed an airborne monitoring method based on vision and convolutional neural network (CNN) integration. The microscope image acquisition system was used to capture the high-resolution images of the side cutting edges, and an EFFICIENT-Net-b0 classification model was constructed based on migration learning, realizing the accurate identification of four combined wear states [4]. Zheng et al. proposed a multi-feature fusion monitoring method based on the hidden Markov model for the drilling process, and extracted multi-dimensional features such as time domain, frequency domain, wavelet domain and fractal dimension from the drilling force through the wavelet transform and fractal theory to realize the identification of three typical wear states of the drill bit [5]. Nie et al. systematically reviewed the research progress of intelligent tool wear monitoring methods, summarized various sensing technologies of direct method and indirect method, reviewed time domain, frequency domain and time domain feature extraction methods, and compared and analyzed the application characteristics of traditional machine learning and depth learning models [6]. Wang et al. proposed a monitoring method based on multi-classification support vector machine to solve the problem of multi-state identification under small samples. By extracting the multi-dimensional characteristics of cutting force and vibration signal in time domain, frequency domain and wavelet packet energy, a one-to-multiple strategy was adopted to construct SVM classifier, and effective identification of three wear states was realized [7]. However, the existing studies on the independent optimization of multi-focus single technical path lack a systematic analysis on the internal correlation of signal driving, data driving and virtual-reality fusion methods, and the generalization ability and robustness under complex working conditions are still to be improved.

Based on the above analysis, this paper focuses on the intelligent monitoring and prediction method of NC machine tool wear. Firstly, the system sorts out the technological evolution of tool wear monitoring technology from signal driving to data driving and then to virtual and real fusion, and summarizes the representative results of feature extraction, modeling methods and visual detection. Secondly, the limitation of each method is reviewed from the aspects of complex working condition adaptability, unsupervised self-label reliability and digital twin real-time, and the targeted optimization suggestions are put forward. Finally, the summary and prospect of the future development direction provide a theoretical reference for the establishment of intelligent manufacturing oriented tool life cycle management system.

2. Classical research conclusions and advantages

In the field of intelligent tool wear monitoring and prediction, many scholars have carried out a lot of effective exploration from multiple technical paths. In order to systematically comb the current research progress and identify the applicable boundaries and common limitations of various methods, three representative research tasks are selected in this paper. Focusing on signal-driven wear regression prediction, unsupervised data-driven wear state self-identification and virtual and real fusion visual online inspection, the core methods, technical contributions and improvement directions are summarized and analyzed, as shown in Figure 1.

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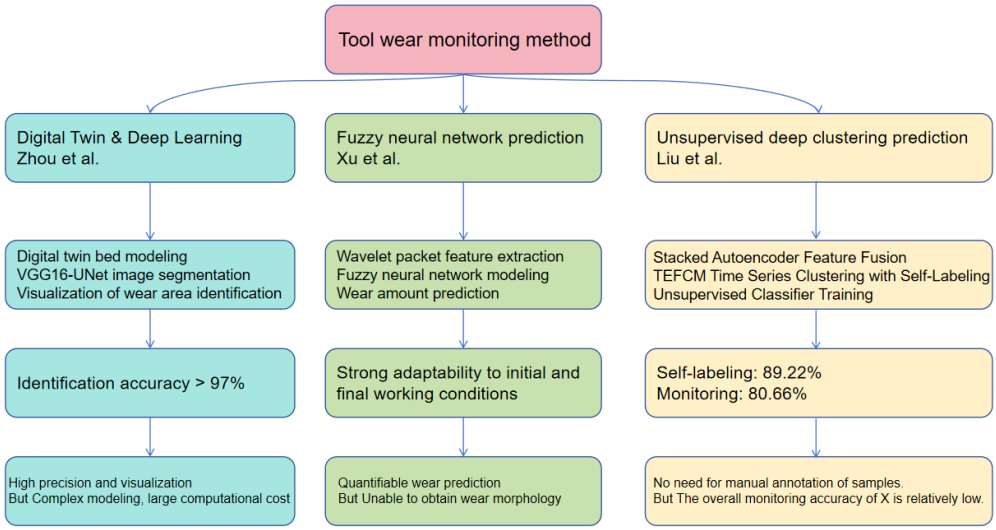


Figure 1. Main contents of three representative works (picture credit: original)

2.1. Time-depth clustering tool wear monitoring scheme

Liu et al. established an online monitoring system without supervision for tool wear monitoring relying on manual marking, traditional clustering ignoring timing rules, poor cross-working generalization and other painful points, innovatively proposed TEFCM timing enhancement clustering algorithm, and completed effectiveness verification through two groups of experiments [8]. Firstly, the wavelet decomposition and sparse self-coder are used to process the multi-source sensing signal to complete the noise reduction, feature extraction and dimension reduction. Secondly, FCM algorithm is improved, time penalty factor and cluster balance coefficient are added to realize abrasion data self-label, and joint loss synchronous optimization model is constructed. Finally, NASA milling data set and superalloy cutting experiment are used to compare with various mainstream algorithms. The accuracy rate of the method is increased by 24.55%, and the wear identification accuracy is increased by 15.33%. The method can adapt to various processing scenarios without manual marking, providing a reliable technical solution for online monitoring of intelligent manufacturing tools.

2.2. Precise prediction of tool wear based on fuzzy neural network

Xu et al. specially designed a new method to accurately calculate the wear thickness of NC machine tools and solve the problem that the old prediction method is inaccurate [9]. The study first uses wavelet packet technology to clean the chaotic signals collected by the machine tool, screen out the noise and extract the key information that can reflect the tool wear. Secondly, a five-layer prediction model is established by combining fuzzy judgment and neural network, and a special level is added to correct the prediction error. Finally, a real machine tool experiment platform is established, and a comprehensive comparison test is made with the three traditional prediction methods. The scheme proposed in this study can accurately predict whether the tool is slightly worn or seriously worn, making up the weakness that the traditional method can only measure the heavy wear, and providing a more reliable technical scheme for the factory to monitor the tool state in real time and reduce the production loss.

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2.3. Tool wear detection based on digital twin and depth learning

Zhou et al. proposed an online inspection scheme for milling cutter wear based on digital twin and VGG16-UNet in view of poor visualization of cutter wear monitoring and easy disturbance of inspection model by working conditions [10]. On one hand, this research establishes a four-layer digital twin system to complete the three-dimensional modeling of machine tool, virtual and real data exchange, and realize the whole process of processing visualization, on the other hand, VGG16-UNet segmentation network is built, the dual network advantages are combined to accurately extract the wear characteristics, and the composite loss function is matched to improve the segmentation effect. The milling experiment shows that the detection accuracy of the model exceeds 97%, the average error of wear measurement is only 3.92%, and the index is superior to many traditional segmentation models. The fusion scheme opens up visual identification and virtual monitoring, realizes automatic online detection of tool wear, and provides a feasible new idea for intelligent manufacturing tool health monitoring.

3. Limit analysis and corresponding suggestions

3.1. Shortage and optimization of tool wear detection model

Liu et al.'s research mainly focuses on tool wear detection. Although some progress has been made in relying on intelligent manufacturing tool online monitoring, there are still some deficiencies. First of all, the tool wear detection is mainly carried out around the milling experiment, which has not covered the drilling, boring, turning and other typical processing processes, so it is difficult to adapt to the diversified cutting operation scenes in the industrial site, and the applicability of the conclusions is limited. Secondly, the signals collected by the experimental sensor are mainly vibration, acoustic emission and cutting force, and the model stability is not evaluated when the strong noise generated in the real production environment interferes with the sensor in the industrial site. Thirdly, the model can only realize the qualitative classification of tool wear state, and cannot complete the quantitative regression prediction of tool flank wear VB.

In view of the above problems, the following optimization suggestions are proposed in this paper: First, expand the experimental verification system, supplement the test conditions of lathing, drilling, boring and other cutting processes, collect tool wear data sets under different processes, verify and adjust model parameters, and expand the engineering application scope of algorithms. Secondly, different levels of industrial noise are superimposed in the data set to simulate the real workshop interference, the feature extraction process is optimized, and the anti-noise feature screening mechanism is introduced to improve the operation stability of the model when the sensor is disturbed. On this basis, the regression network branch is added on the basis of the existing clustering classification framework, and the combined model of classification and regression is constructed. The quantitative prediction of the specific value of the rear cutter face wear VB is realized while identifying the wear stage.

3.2. The limitation and optimization direction of fuzzy neural network prediction model

Xu et al's research mainly focuses on the prediction of tool wear of computer numerical control (CNC) machine tools. Although the tool wear prediction based on wavelet packet and fuzzy neural network is successful, there are still some limitations. First of all, the experimental conditions are too ideal, and the simulation experiment only uses S45C steel, titanium alloy efficient milling cutter

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and fixed cutting parameters. The experimental conditions do not cover different materials, variable working conditions and cutting fluid changes and other actual processing scenarios, and the robustness and generalization ability of the model are to be tested. Secondly, the structure of the model is fixed and there is a lack of adaptive optimization, and the key parameters of the fuzzy neural network are artificially set. The automatic optimization strategy is not introduced in the algorithm, and it is difficult to dynamically adjust the network structure according to the data characteristics, which limits the migration ability of the model on different tools or machine types. Thirdly, the evaluation indicators are limited and lack of statistical significance test. Only the three indicators of root mean square error, standard deviation and mean absolute error were used in the study. No repeated experiments or K-turn cross validation were conducted, and no confidence interval or significance test results were provided. This diminishes the confidence of the conclusions.

Aiming at the above problems, the following optimization suggestions are proposed in this paper.

First, extend the experimental conditions, increase the test data of different materials such as aluminum alloy and stainless steel and under multiple cutting parameters, and introduce the public data set (such as PHM2010) for horizontal comparison. Secondly, an automatic hyperparametric optimization method is introduced to dynamically search the optimal network structure by using Bayesian optimization or evolutionary algorithm, and to explore a migration learning strategy to improve the model's universality. Thirdly, strengthen the statistical analysis of model validation, use K-turn cross validation and multiple independent repeated experiments, supplemented by t-test or ANOVA analysis to quantify the significance and stability of the model. This can enhance the reliability of research conclusions.

3.3. Shortage and optimization of detection method for digital twin and deep learning

Zhou et al's research mainly focuses on tool wear detection method based on digital twin and VGG16-UNet fusion. Although it has been successful in the visualization of virtual-real mapping and the accuracy of wear area segmentation, there are still some limitations. First, the experimental conditions were set too single, and all verifications were done on only one machining center and fixed milling condition. It does not involve the changes of different machine types, tool materials and cutting parameters, and does not take into account the actual production line interference such as light changes, chip occlusion, etc. It is difficult to prove the generalization ability of this method in a changing production environment. Secondly, the data set is limited in size, including only 546 original images, and it still belongs to small sample learning although enhanced; At the same time, the wear area relies on Labelme manual marking, and the marking consistency is not tested quantitatively, which is easy to introduce subjective deviation and affect the reliability and stability of model training. Thirdly, the comparison dimension of the model is not comprehensive enough. It is only compared with the three classic structures of U-Net, PSPNet and DeepLabv3+. It is not included in the advanced Transformer architecture such as SwinUNet, and the engineering indicators such as reasoning speed and parameter quantity are not evaluated, which is not conducive to the hardware adaptability and industrial implementation potential of the judgment method.

In response to the above issues, this paper proposes the following optimization suggestions. Firstly, expand the multi working condition experimental system, introduce different combinations of machine tools, cutting tools, and cutting parameters, and collect images with interference such as oil stains and vibration blur to verify the robustness of the method. Secondly, semi-automatic annotation tools are used to assist manual annotation and consistency verification is introduced to reduce human errors. At the same time, data augmentation strategies based on generative adversarial

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networks are explored to enrich the diversity of wear patterns. Once again, include the Transformer architecture model in the comparison and supplement the inference latency and memory usage testing of the model on edge devices, providing a basis for subsequent lightweight deployment.

Table 1. Limitations and optimization suggestions within three studies

Comparison Dimension	Digital Twin+Deep Learning [8]	Fuzzy neural network prediction [9]	Unsupervised deep clustering monitoring [10]
Core Technology	Digital twin+VGG16 UNet image segmentation	wavelet packet analysis+fuzzy neural network stacked	autoencoder+TEFCM temporal clustering
limitation	① Single experimental condition, limited to milling and single machine tool only	① Ideal experimental conditions, insufficient coverage of materials and working conditions	① Only covers milling processes, not extended to turning, drilling, boring, etc
	② The dataset size is limited (546 images) and relies on manual annotation	② Network hyperparameters rely on human settings and lack automatic optimization	② Model stability under strong noise interference has not been evaluated
	③ The comparative model does not cover advanced architectures such as Transformer	③ Not conducting multiple repeated experiments and significance tests	③ Only achieving qualitative classification, unable to quantitatively predict VB values
Optimization suggestions	① Expand experiments with multiple machine tools, multiple cutting tools, and multiple interference conditions	① Add multi material testing and public dataset validation for aluminum alloy, stainless steel, etc.	① Supplement process testing conditions for cars, drills, boring, etc
	② Introducing semi-automatic annotation and GAN data augmentation	② Introducing Bayesian optimization/evolutionary algorithm for automatic optimization	② Evaluating anti-interference ability by superimposing industrial noise
	③ Incorporate Swin UNet architecture and evaluate edge deployment performance	③ Using K-fold cross validation and t-test/ANOVA to enhance statistical validation	③ Add regression branches to construct a classification regression joint model and achieve quantitative prediction using VB

Table 1 provides a horizontal comparison of three types of tool wear detection methods from three dimensions: core technology, limitations, and optimization suggestions. As shown in the table, Zhou et al. constructed a digital twin model and integrated VGG16 UNet to achieve accurate segmentation of wear areas. However, its limitations lie in the single experimental conditions, limited dataset size, and insufficient model comparison. Xu et al. used wavelet packets and fuzzy neural networks to achieve numerical prediction of wear, but the experimental conditions were relatively ideal, the network hyperparameters relied on manual settings, and lacked statistical significance testing. Liu et al. used stacked autoencoders and TEFCM temporal clustering to achieve unsupervised wear state classification, but only covered milling processes, did not evaluate noise interference, and could not quantitatively predict VB values. In response to the above limitations, three literature have proposed optimization paths from the directions of expanding multi condition experiments and data augmentation, introducing hyperparameter automatic optimization and

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strengthening statistical verification, supplementing multiple cutting processes, and constructing classification regression joint models, providing clear improvement directions for subsequent research.

4. Conclusion

This paper systematically reviews and analyzes three technical paths for intelligent monitoring and prediction of tool wear in CNC machine tools: signal driven, data-driven, and virtual real fusion. Through in-depth analysis of three representative works, namely time series deep clustering, fuzzy neural network prediction, and digital twin fusion detection, the common shortcomings of current research in complex working condition adaptability, unsupervised self labeling reliability, and model generalization ability have been revealed. In response to the above limitations, this article proposes specific optimization suggestions from the perspectives of expanding multi process experimental verification, introducing automatic hyperparameter optimization and transfer learning, and constructing a classification regression joint model, clarifying the improvement directions of each technical path.

Overall, intelligent monitoring technology for tool wear is gradually evolving from independent optimization of a single method to a fusion driven mode of multi technology collaboration. Signal processing provides the foundation for feature extraction, data-driven implementation of state recognition and prediction, and digital twin endows visualization and interaction capabilities, all of which complement each other. Future research should focus on the construction of cross working condition transfer learning frameworks, the design of deep fusion strategies for multi-source sensor information, and the industrial deployment verification of lightweight models, in order to promote the transformation of tool wear monitoring technology towards high reliability and strong generalization ability in industrial applications.

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