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Multi-sensor information fusion for remaining useful life prediction of machining tools by adaptive network based fuzzy inference system

Jun Wu[a,*], Yongheng Su[a], Yiwei Cheng[b], Xinyu Shao[b], Chao Deng[b,*], Cheng Liu[c]

[a] School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan, China
[b] National Engineering Research Center of Digital Manufacturing Equipment, Huazhong University of Science and Technology, Wuhan, China
[c] Department of Aeronautics and Astronautics, Stanford University, CA, USA

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ABSTRACT

Remaining useful life (RUL) prediction of machining tools is a typical multi-sensor information fusion problem. It involves the use of the monitoring information acquired from different types of sensors installed on computer numerical control machine to realize the RUL prediction of the machining tools in cutting process. Owing to the nonlinear and stochastic nature between the extracted features and tool wear level, the promptness and precision of online RUL prediction of machining tools are still difficult to be obtained. In this paper, a multi-sensor information fusion system for online RUL prediction of machining tools is proposed. The system includes sensor signal preprocessing based on ensemble empirical mode decomposition method, statistics feature extraction based on time domain and frequency domain analysis, optimum feature selection based on Pearson correlation coefficient, monotonicity and autocorrelation, feature fusion based on adaptive network based fuzzy inference system and RUL prediction model based on polynomial curve fitting method. We report a practical application of this multi-sensor information system and estimate its prediction performance. The proposed system may be applied to the industrial field. Meanwhile, the comparison between the proposed method and other standard methods is carried out using several statistical indices.

1. Introduction

As one key component of computer numerical control (CNC) machine, machining tools have always been a crucial issue in both academia and industrial fields. Machining tool failures such as wear and breakage have an important effect on processing quality, machining efficiency and production costs [1]. Moreover, unpredictable failures may also affect other components in the CNC machine [2]. Thus, online remaining useful life (RUL) prediction techniques of machining tools are urgently needed so as to change the machining tools in time and avoid the failures.

A considerable amount of research on RUL prediction of machining tools has been done during the last decade. In general, there exist two main kinds of RUL prediction methods, namely model-based methods and data-driven methods [3–5]. The model-based methods use empirical/mechanistic models describing physics of failure to estimate the RUL. The models quantitatively characterize failure behavior of the machining tools. And the data-driven methods use condition monitoring data acquired from sensors to realize the RUL prediction. The data-driven methods include methods based on computational intelligence such as artificial neural networks [6,7] and fuzzy inference systems [8]. However, the data-driven methods are much easier than the model-based methods in terms of implementation owing to the uncertainty of model parameters and the complexity of failure mechanisms of the machining tools in cutting process.

In the data-driven methods, sensor signals including forces, vibrations, acoustic emission, currents, etc. are collected and applied to predict the RUL of the machining tools. Compared to a single type of sensor signals, multi-sensor signals make the result of RUL prediction more reliable [9–11]. Therefore, in order to get a more specific and accurate RUL, multi-sensor information fusion techniques have been put forward. A systematic data-level fusion methodology was developed in [12] to construct a composite health index via the combination of multiple sensor signals collected under multiple operational conditions. In [13] a hybrid method was proposed and investigated for fault signal classification based on sensor data fusion by using the support vector machine (SVM) and short term Fourier transform techniques. A three-stage method was

* Corresponding authors.
E-mail addresses: wuj@hust.edu.cn, wujun_hust@126.com (J. Wu), dengchao@hust.edu.cn (C. Deng).

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proposed in [14] for assessing the machine health degradation and forecasting the RUL based on vibration signals fusion by using the Cox's proportional hazard model and SVM. Soft computing techniques combined with the classical methods like Kalman filtering [15], Bayesian estimator [16,17], and logistic regression [18] were applied for undertaking the fusion. Traditionally, feature extraction is essential to implement the multi-sensor formation fusion. Many effective features have been extracted using statistical analysis methods, time-frequency analysis methods and deep learning methods. In [19] vibration signals were processed in the angle-frequency domain, and feature extraction algorithms including kernel principal component analysis and locally linear embedding were used to identify the most distinct features. A method named convolution neural networks with training interference was proposed in [20] to automatically extract representative features from raw temporal signals. However, due to the nonlinear and stochastic nature between the extracted features from sensor signals and the observed tool wear level, the promptness and precision of the RUL prediction for the machining tools still do not meet the practical needs.

In order to deal with the aforementioned problems, multi-sensor information fusion system and methods for online RUL prediction of machining tools are proposed in this paper. First, a system schema of the multi-sensor information fusion for the online RUL prediction is presented using massive sensor signals, which includes an offline modelling process and an online prognostics process. Then, ensemble empirical mode decomposition (EEMD) method is employed to eliminate noises from original sensor signals. The processed sensor signals are segmented and statistics features are extracted. Furthermore, a feature selection method is introduced using correlation analysis, monotonicity analysis and residual analysis to obtain the optimal features. Finally, to cut down the effect of the nonlinear nature, adaptive network based fuzzy inference system (ANFIS) model is built to implement the feature fusion, which includes the subtraction clustering and fuzzy space partition of the optimal features. And online RUL prediction of the machining tools is carried out using polynomial curve fitting (PCF) method. The main contributions of this paper are summarized as follows:

(1) To attenuate undesired signals and solve mode mixing problem, EEMD method is proposed for the signal preprocessing of massive sensor signals. Meanwhile, considering the relationship between the local time-varying characteristics of the sensor signals and tool wear level, the processed sensor signals are segmented and statistics features are respectively extracted in time domain and frequency domain.
(2) An ANFIS architecture with subtraction clustering and fuzzy space partition is designed for the feature fusion. The nonlinear relationship between the extracted features and tool wear level is found, and RUL prediction of the machining tools is deduced by PCF method.

The rest of this paper is organized as follows. Section 2 presents a system schema of multi-sensor information fusion for online RUL prediction. Section 3 introduces an EEMD based sensor signal preprocessing method. Section 4 discusses the statistics feature extraction of the sensor signals, and the optimum feature selection based on correlation, monotonicity and autocorrelation of the extracted features. Section 5 explains an ANFIS based feature fusion, and PCF based online RUL prediction of the machining tools. Section 6 describes an experimental case study of the multi-sensor information fusion system. Section 7 shows the results and discussions, and Section 8 draws the conclusions.

2. Multi-sensor information fusion system for RUL prediction

A system schema of multi-sensor information fusion for RUL prediction is proposed in the paper to implement online RUL prediction of the machining tools using the vast amounts of sensor signals. As shown in Fig. 1, the multi-sensor information fusion system includes sensor signal database, sensor signal preprocessing, statistics feature extraction, optimum feature selection, feature fusion and RUL prediction, which involves two processes.

In the offline modelling process, different kinds of sensors installed on CNC machine are utilized to acquire the monitoring data of the machine tools such as motor current signal, acoustic emission signal, vibration signal, etc. And the large amounts of the sensor signals is regularly transferred and stored in the database system. The obtained sensor signals are divided into training data and testing data, which are taken as offline data. Then, the offline data are preprocessed using EEMD method to eliminate the noises in the original signals. The preprocessed sensor signals are segmented and statistics features in time domain and frequency domain are respectively extracted. After the extracted features are normalized, correlation analysis, monotonicity analysis and residual analysis are used to implement the optimum feature selection. The optimal features are picked up for the following feature fusion.

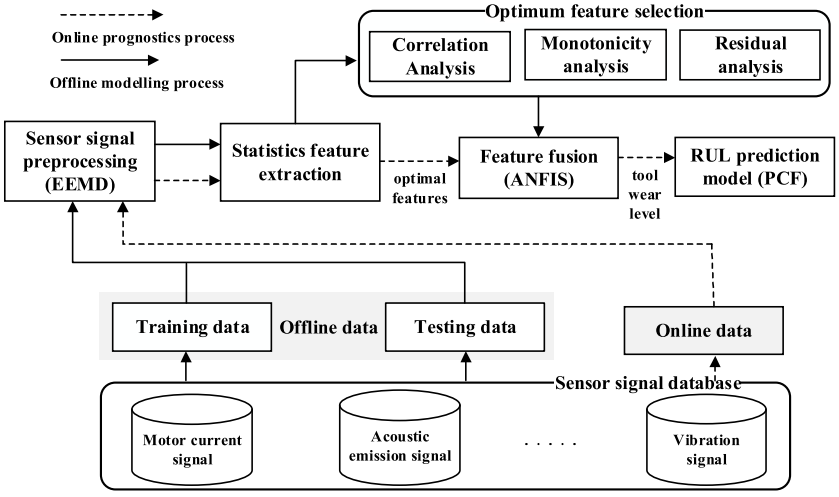

Fig. 1. A system schema of RUL prediction for machining tools.