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FEATURE EXTRACTIONS IN MICRO MACHINING: A REVIEW AND APPLICATION IN MODERN MANUFACTURING

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ABSTRACT
Micro machining has become pivotal in advanced manufacturing due to the growing demand for miniaturized components across various industries such as electronics, biomedicine, and aerospace. A key element in enhancing the precision and quality of micro-machined components is feature extraction, which aids in monitoring, analysing, and optimizing machining processes. This paper provides a comprehensive review of feature extraction techniques in micro machining, focusing on the integration of sensor data, signal processing, and machine learning algorithms to optimize the manufacturing process. We examine different feature extraction methods, discuss their applications, and evaluate their effectiveness in various micro machining operations such as laser micromachining, micro milling, and micro electrical discharge machining (micro-EDM).

Introduction
Micro machining involves the manufacturing of parts with dimensions typically in the range of microns to millimetres. Given the high precision required, real-time monitoring and control of machining processes have become essential to ensure product quality.[1] Feature extraction, as an integral part of this, refers to the process of identifying relevant characteristics or patterns from sensor data or other types of signals generated during machining. These features can be used to assess tool condition, surface finish, or machining efficiency.[3] The goal is to enhance process control, reduce errors, and predict potential failures before they occur.
This paper aims to review the state-of-the-art in feature extraction techniques applied in micro machining processes. Additionally, we provide a detailed comparison of these methods based on their applications, advantages, and limitations.

Micro Machining Techniques
Laser Micro Machining
Laser micro machining uses high-intensity laser beams to remove material with extreme precision. Due to its non-contact nature, it is particularly suitable for delicate or hard materials. Feature extraction in laser micro machining often involves the use of optical sensors and high-speed cameras to monitor the ablation process and ensure optimal beam positioning.[2]

Micro Milling
Micro milling is a subtractive manufacturing process that uses micro-scale cutting tools. Tool wear and deflection are major concerns in micro milling, as they can lead to dimensional inaccuracies. Feature extraction in this domain involves analyzing force signals, acoustic emissions, and vibrations to detect tool wear and prevent breakage.
The need to fabricate high accuracy miniature components with dimensions ranging from a few hundred microns to a few millimetres or features ranging from a few hundreds of microns has encouraged research on development of micro manufacturing processes. [6] Despite successfully machining of miniature parts and complex shapes with high accuracy, this encountered problems such as tool wear and tool failure (Fig. 1). Tools which are small and long, could not withstand the generation of contact machining forces leading to tool formation, chatter and vibration, and tool stress, thereby causing tool breakage. [7, 8].

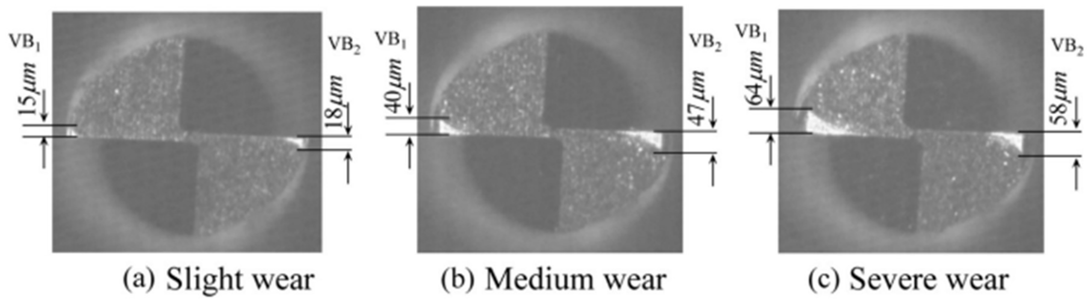


Fig. 1. Tool Wear Stages

2.3 Micro Electrical Discharge Machining (Micro-EDM)

Micro-EDM is a thermal erosion process that removes material via electrical discharges. Given the intricacies of spark generation and material removal, feature extraction techniques in micro-EDM are primarily focused on real-time monitoring of discharge signals to ensure the consistency and quality of the machined part.[4]

Feature Extraction Methods in Micro Machining

Time-Domain Features

The time domain analysis is the variation of the system with respect to time. It shows changes in amplitude with respect to time, i.e its independent variable is time. With this, the stability and accuracy of the system can be analysed. However, the time domain analysis cannot give the frequency component of the signals [4,8].Time-domain features are derived directly from raw sensor signals over time. In micro machining, features such as peak amplitude, signal energy, and variance are commonly extracted from force, vibration, and acoustic emission signals. Time-domain analysis is simple and computationally efficient, making it suitable for real-time monitoring systems.

Application Example

In micro milling, time-domain features like root mean square (RMS) of force signals can be used to detect tool wear and breakage in real time. The RMS value increases as the tool wears out, allowing for timely interventions in the machining process.

Frequency-Domain Features

In the frequency domain analysis, the signal is represented as the function of frequency. To get the frequency information of a signal, the time domain signals (periodic and non-periodic) must be converted into the frequency domain using Fourier series or Fourier transform respectively. The frequency domain consists only the frequency information of a signal Frequency-domain analysis involves transforming time-domain signals into the frequency domain using techniques such as the Fourier transform [5,7]. Features such as dominant frequencies and bandwidth provide insights into the machining dynamics, tool condition, and material properties.

Application Example

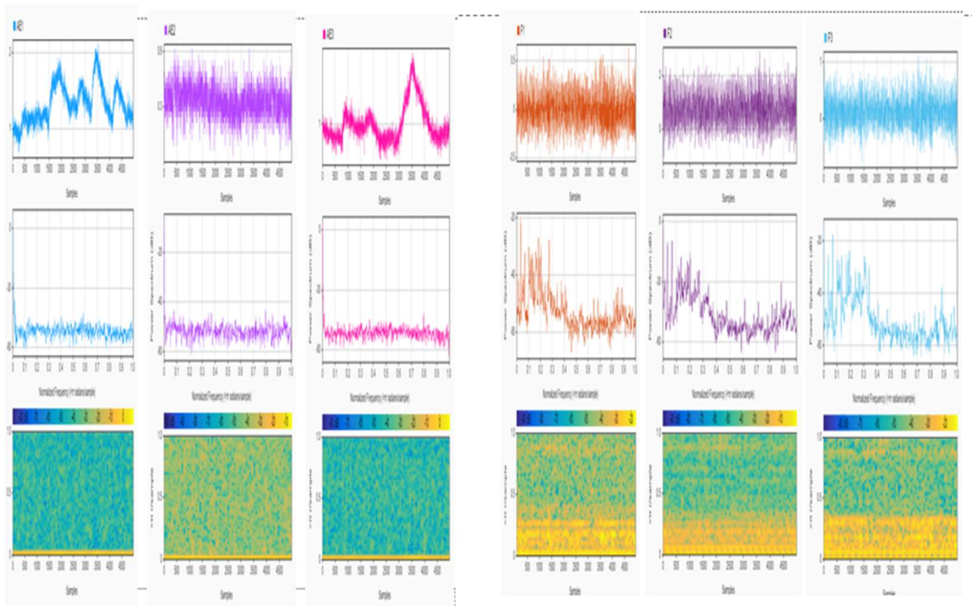
In micro-EDM, frequency-domain features extracted from discharge current signals can be used to differentiate between stable and unstable machining conditions. Higher frequency components often indicate unstable discharge events, which may result in poor surface finish or tool wear.

Time-Frequency Features

Time-frequency analysis combines time-domain and frequency-domain methods, offering a more comprehensive representation of signal characteristics. Techniques like the wavelet transform allow for the extraction of features that vary over both time and frequency, which is crucial for processes like micro milling where tool wear can change both gradually and suddenly.

Application Example

Wavelet-based feature extraction in laser micro machining has been used to detect surface defects during real-time processing. The multi-resolution nature of wavelets enables better identification of transient features, such as those caused by sudden fluctuations in laser power.



a. Time-Domain Representation b. Frequency-Domain Representation

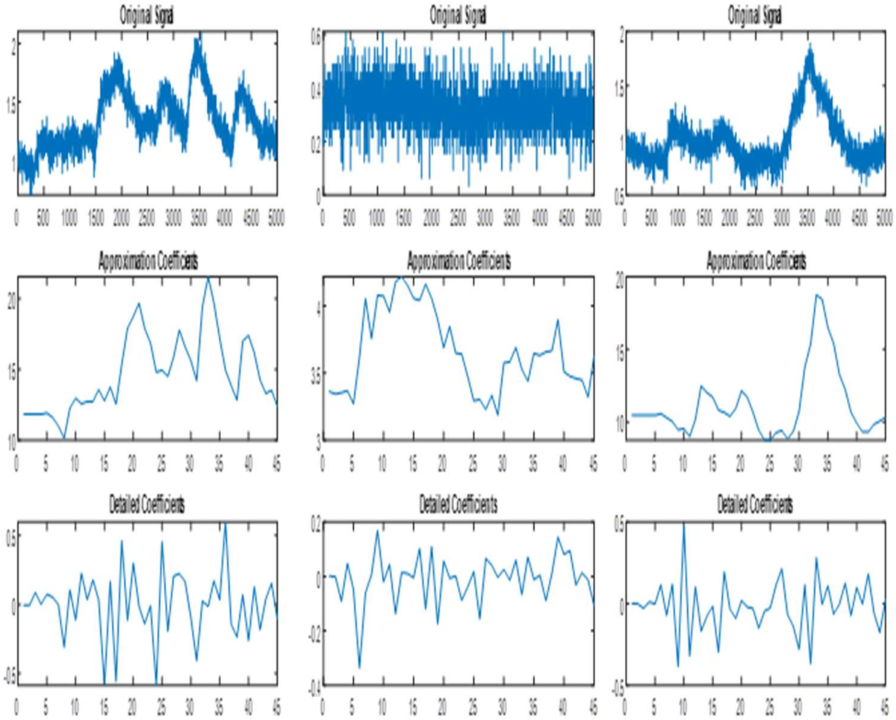
Time-domain, frequency-domain, and Energy Spectra

Wavelet Decomposition

Due to the nature of machining processes, the signals are usually time varying and nonstationary. Wavelet analysis overcomes the pitfalls of short time Fourier methods and is adapted for processing nonstationary signals. It has been widely studied to analyse machining signals in TCM, such as [9-11]. It was found that wavelet analysis can capture important features of signal that are sensitive to different tool wear states but is insensitive to the variation of working conditions and noises. This makes wavelet analysis a powerful and robust tool for TCM.

The most interesting part of data analysis is the representation of transient changes in acquired signals. Unfortunately, the time-domain and frequency domain does not represent these abrupt changes. To provide a compromise between the time-domain and frequency-domain, wavelet transforms are used. Different wavelets transform methods are adopted for proper analysis and condition monitoring of tool states. These are continuous wavelet transform (CWT), discrete wavelet transforms (DWT), wavelet packet transform (WPT) and wavelet scattering transform (WST).

Features such as mean, rms, standard deviation, skewness, kurtosis spectral density, entropy, peak-to-peak amplitude, frequency spectrum were extracted. Features with trends were selected to train a prediction model.



Wavelet Decomposition Using WPT

Statistical and Machine Learning-Based Features

Statistical techniques and machine learning algorithms such as Principal Component Analysis (PCA), Support Vector Machines (SVM), and Artificial Neural Networks (ANN) have been increasingly applied for feature extraction in micro machining. These methods allow for the identification of complex patterns that may not be evident in time or frequency-domain analyses.

Application Example

In micro milling, an SVM-based model can be trained on multiple sensor signals (e.g., acoustic emission and vibration) to classify tool wear conditions. Once trained, the model can predict tool wear in real-time, thereby enabling predictive maintenance.

Challenges in Feature Extraction

Despite advancements in feature extraction techniques, several challenges remain in their application to micro machining. The small-scale nature of micro machining introduces additional noise and uncertainty into the sensor data, making it difficult to extract reliable features. Additionally, real-time feature extraction requires computationally efficient algorithms that can process data at high speeds without introducing significant delays into the control loop.

Sensor Integration

The integration of multiple sensors (e.g., force, vibration, temperature, and acoustic emission sensors) into the micro machining process can provide a wealth of information for feature extraction. However, fusing data from multiple sensors is non-trivial and requires advanced signal processing techniques to ensure meaningful and consistent feature extraction.

Computational Efficiency

Micro machining requires real-time monitoring and control, which imposes strict requirements on the computational efficiency of feature extraction algorithms. Techniques like wavelet transforms or machine learning models, though powerful, can be computationally intensive and may not be suitable for all real-time applications.

Future Directions

The future of feature extraction in micro machining lies in the integration of advanced sensors, real-time monitoring, and machine learning. Emerging trends include:

- **Data-Driven Feature Extraction**: Leveraging big data and deep learning techniques to automatically extract complex features from large datasets.
- **Edge Computing**: Utilizing edge computing devices to process sensor data at the machine level, reducing latency and enhancing real-time monitoring capabilities.
- **Hybrid Techniques**: Combining multiple feature extraction methods (e.g., time-frequency analysis and machine learning) to improve robustness and accuracy.

Conclusion

Feature extraction plays a critical role in enhancing the performance and reliability of micro machining processes. This paper has reviewed various feature extraction techniques, including time-domain, frequency-domain, time-frequency, and machine learning-based approaches, discussing their applications and challenges. As micro machining technology continues to evolve, the integration of advanced sensors, signal processing techniques, and machine learning algorithms will further improve process control and product quality.

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