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An in-depth study of tool wear monitoring technique based on image segmentation and texture analysis

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ABSTRACT

We present a new micro-vision system for tool wear monitoring, which is essential for intelligent manufacturing. The tool wear area is divided into regions by a watershed transform, then subjected to automatic focusing and segmentation. The individual pixel gray values in each region are then replaced with the corresponding regional mean gray value. A hill climbing algorithm based on the sum modified laplacian (SML) focusing evaluation function is used to search the focal plane. In addition, we implement an adaptive Markov Random Field (MRF) algorithm to segment each region of tool wear. For our MRF model, the connection parameter value is adaptively determined by the connection degree between regions, which improves image acquisition of more integral tool wear areas. Our findings suggest that automatic focusing and segmentation of the tool wear area by region (within the tool wear area) enhance accuracy and robustness, and allow for real time acquisition of tool wear images. We also implement a complementary tool wear assessment procedure based on the surface texture of the workpiece. The optimal texture analysis window is determined using the entropy metric – a texture feature generated using a Gray Level Co-occurrence Matrix (GLCM). In the best texture analysis window, entropy remains monotonic as tool wear increases, demonstrating that entropy can be used effectively to monitor tool wear. Information from combined measurements of tool wear and workpiece texture can reliably be used to monitor tool wear conditions and improve monitoring success rates.

1. Introduction

Modern manufacturing is becoming increasingly intelligent and automated. Tool wear monitoring is essential in manufacturing industries [1–3]. Research has shown that reliable tool wear monitoring technology can reduce downtime caused by technological factors and human subjectivity by up to 75% while improving production efficiency by 10–50% [4].

Work parameters such as cutting force, acoustic emission and vibration, can be used to characterize tool wear conditions. Sensors that detect force, acoustic emissions and vibration produce signals that may be used to indicate tool wear [5,6].

For example, since there is a direct correlation between cutting force magnitude and tool wear, cutting force can be used to monitor tool wear. However, force sensors are generally large and expensive, and the scope for their installation is often restricted. Moreover, cutting force is influenced by the properties of the workpiece material, cutting parameters, the degree of tool wear, and other factors. It is therefore difficult to identify all of the factors responsible for an observed change in the cutting force.

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There are similar problems with the use of acoustic emissions to assess tool wear. Because the wear conditions of the cutting tool vary, its acoustic emissions also change during machining. However, the acoustic signal is also affected by the position of sensor installation, the sensor's operating mode, the properties of the workpiece material, and the cutting parameters.

With the rapid development of computer vision and image processing technology, researchers have started using micro-vision to investigate tool wear. An early approach of this sort was developed at the National University of Singapore. In this method, two binary images of the tool are acquired and moment invariants are then used to detect the wear boundary area [7].

Atli et al. developed an alternative image analysis technique called DEFROL (deviation from linearity) to distinguish sharp drilling tools from dull ones. However, their studies focused on changes in point angles and linearity deviations in cutting edges due to wear; there have been no reports on the use of DEFROL to assess flank wear [8].

Liang and Chiou introduced a technique for measuring flank wear in multilayer-coated twist drills using image processing. They detected the edges of the wear profile on the cutting plane using a spatial moment edge detector with subpixel accuracy, then smoothed the edges using a B-spline. They then applied the Gaussian low-pass filtering technique to smooth the curves, after which a statistical process control measure was used to identify a threshold value that would produce an accurate wear profile. This resulted in the development of a technique capable of precisely measuring the width of maximum flank wear [9].

Zhang used machine vision to acquire and analyze images of tool wear by attaching a charge-coupled device (CCD) camera to a ball-end cutter. Tool wear images were captured before and during machining to assess wear over time by comparison [10].

Danesh also proposed a vision-based method for determining tool wear in metal cutting. This approach evaluates tool wear on the basis of wear-induced surface irregularities. He used the undecimated wavelet transform (UWT) to decompose the surface image of the workpiece into sub-images whose texture was analyzed by using the texture features of a Gray Level Co-occurrence Matrix (GLCM) to identify wear on the cutting tool [11].

Another researcher, Datta, applied the Voronoi tessellation concept to analyze the texture of machined surfaces. Two texture features were extracted: the number of polygons with zero cross moment, and total void area of the Voronoi diagram of machined surface images. A study of the correlation between flank wear measurements and extracted texture features was performed to identify effective ways of quantifying tool flank wear [12].

Kurada and Bradley captured images of tool flank wear using a CCD camera and lights guided by two optical fibers. Both lights were adjusted to illuminate the region of tool flank wear. They initially calibrated their images horizontally and vertically to convert pixel units to length units (microns). Then they applied a texture-based image segmentation technique in a stepwise fashion, using image enhancement (with a cascaded median filter) to reduce noise. They also used a global threshold to segment images, as well as a variance operator to extract the flank wear region from background. Finally, they used morphological operations (blob analysis) to extract image features and performed flank wear calculations using boundary and regional descriptors [13].

Compared to other monitoring techniques, monitoring with micro-vision has obvious advantages [14–18]. First, the necessary apparatus is easy to install. Second, it can recognize various types of tool wear. Finally, it can provide comprehensive information on the tool wear area, roughness of the workpiece surface, location of the wear area, and the initial state of the workpiece [19–21].

In previous studies, image segmentation of the tool wear region was primarily based on the threshold segmentation method. However, this does not provide ideal segmentation. Moreover, the texture analysis used was not robust. To address these issues, we conduct a detailed study on a tool wear monitoring technique based on micro-vision. The system described in this paper comprehensively uses information about tool wear and the texture features of the workpiece surface to monitor tool wear conditions. Compared with a single criterion monitoring technique, our method offers superior accuracy and robustness.

The technique involves the use of a tool wear monitoring system, automatic focusing, tool wear region segmentation, analysis of workpiece surface texture, and information synthesis [22–26].

The paper is structured as follows. In Section 2 we discuss the tool wear monitoring system. The automatic focusing of the tool wear monitoring system is described in Section 3. Tool wear region segmentation is described in Section 4. We describe the analysis of workpiece surface texture in Section 5. The synthesis of information for the analysis of tool wear is discussed in Section 6. Finally, the paper concludes with a brief discussion in Section 7.

2. The tool wear monitoring system

A micro-vision-based tool wear monitoring system generally consists of an image acquisition module and an image processing module. The hardware devices include the working machine, ring-shaped cold light sources, an acquisition card, a microscope, CCD cameras, and computers (see Fig. 1).

Ring-shaped cold light sources are used to provide uniform illumination during two types of image acquisition. One source is used to help to capture images of tool flank wear and is set in the tool retracting position. The other is used to help to capture images of the workpiece surface during machining and is set just above the workpiece. The compressed air nozzle emits air to remove metal chips around the image acquisition area. During image acquisition, the distance between the camera lens and the tool or the workpiece must be held constant and chosen to avoid shadows from the lens.

Tool wear occurs in three stages: the sharp, initial wear, and severe wear stages. Images of tool flank wear and of