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Novel texture-based descriptors for tool wear condition monitoring

Aco Antić [a,*], Branislav Popović [b], Lidija Krstanović [c], Ratko Obradović [c], Mijodrag Milošević [a]

[a] University of Novi Sad, Faculty of Technical Sciences, Department of Production Engineering, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
[b] University of Novi Sad, Faculty of Technical Sciences, Department of Power, Electronic and Telecommunication Engineering, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
[c] University of Novi Sad, Faculty of Technical Sciences, Chair for Computer Graphics, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia

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ABSTRACT

All state-of-the-art tool condition monitoring systems (TCM) in the tool wear recognition task, especially those that use vibration sensors, heavily depend on the choice of descriptors containing information about the tool wear state which are extracted from the particular sensor signals. All other post-processing techniques do not manage to increase the recognition precision if those descriptors are not discriminative enough. In this work, we propose a tool wear monitoring strategy which relies on the novel texture based descriptors. We consider the module of the Short Term Discrete Fourier Transform (STDFT) spectra obtained from the particular vibration sensors signal utterance as the 2D textured image. This is done by identifying the time scale of STDFT as the first dimension, and the frequency scale as the second dimension of the particular textured image. The obtained textured image is then divided into particular 2D texture patches, covering a part of the frequency range of interest. After applying the appropriate filter bank, 2D textons are extracted for each predefined frequency band. By averaging in time, we extract from the textons for each band of interest the information regarding the Probability Density Function (PDF) in the form of lower order moments, thus obtaining robust tool wear state descriptors. We validate the proposed features by the experiments conducted on the real TCM system, obtaining the high recognition accuracy.

1. Introduction

Tool Condition Monitoring (TCM) in a turning process is very important in manufacturing processes and has been of great interest to many academic and practical researches. In order to prevent possible damages to the work-piece or the machine tool, reliable monitoring techniques are required to provide fast response to the unexpected tool failure [1]. The application of signal processing and information technology has resulted in the use of multiple sensors for the effective monitoring of tool wear conditions, which presents crucial feedback information to the process control and tool wear prediction [2]. Tool failure can be prevented by efficiently monitoring conditional changes in the tool. Cho et al. [3] divide tool conditions into following categories: tool breakage, tool chipping, and tool wear. A key issue for an unattended and automated machining system is the development of reliable and robust TCM systems.

* Corresponding author.
E-mail addresses: antica@uns.ac.rs (A. Antić), bpopovic@uns.ac.rs (B. Popović), lidijakrstanovic@uns.ac.rs (L. Krstanović), obrad_r@uns.ac.rs (R. Obradović), mido@uns.ac.rs (M. Milošević).

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There are many different ways to gather information about the tool failure by the usage of adequate sensors and thus the corresponding signals used in TCMs. Those can be divided into two groups: direct, which consist of laser, optical, and ultrasonic sensors to provide direct measurement, e.g. [4], and indirect, based on sensors which infer the machining state by sensing cutting forces, vibrations, temperatures, current consumption, etc. Direct methods are very expensive and difficult to apply in the machining process environment, while indirect methods are much more economical. Among indirect methods, those that are based on signals obtained from vibration sensors (i.e., accelerometers) are proved to be highly correlated to the surface roughness in turning operations [5], as well as cutting-tool wear [6], so widely applicable in TCM tasks. They are the subject of this paper.

All intelligent TCM systems, and especially those that use vibration sensors, depend heavily on the choice of descriptors, i.e., features extracted from the particular sensor signals. This is due to the fact that in the case when descriptors do not describe the signal adequately, other techniques, such as feature extraction or feature selection, as well as recognition methodology, fail to be efficient. Bahr at all in [7], and Tsai at all in [8], were the first to apply the descriptors obtained from vibration signals in the TCM tasks. Actually, they used RMS and/or the mean of the vibration sensor signal in order to detect an increase in vibration magnitude, which corresponds to the increase in cutting energy generated due to flank wear. Also in [9], the mean and peak values of vibration sensor signals were used in the TCM task. In [6], Dimla analyzed the correlation between the vibration signal features and the cutting-tool wear, in both time and frequency domains, during turning operations. Time domain features were deemed to be more sensitive to the cutting condition than tool wear, whereas certain peak values in the frequency domain correlated well with the measured wear values. In many recent papers, researchers explore the possibility to combine previously developed time and frequency based features and apply feature selection techniques in order to obtain optimal features in a given TCM task. In [3], the authors proposed descriptors extracted from multiple sensors in time and frequency domain and used them in their multisensor fusion-based tool condition monitoring system which is applied in the end-milling task. In [10], the authors presented a tool wear monitoring strategy based on a large number of signal features extracted from time domain signals, as well as from their frequency domain representation and also their wavelet coefficients. In the same paper, time-domain based features are combined with wavelet based ones, and feature selection using logistic regression is applied in the task of determining whether or not the cutting tool is reliable (two class problems). Also, wavelet analysis emerges as a frequently used time-frequency domain feature extraction technique that is used for tool wear monitoring tasks. In [11], the authors were among the first to use wavelet analysis and lower order moments, such as average value, standard deviation, power value, kurtosis value, harmonics frequency, and skew value, in order to express work piece and spindle vibrations in the X, Y and Z directions. Many of the more recent TCM systems proposed in the literature are also based on wavelet techniques. For example, in [12–15], the authors also used wavelet based features for their TCM systems (those using vibration or acoustic emission signals). More recently, researchers have also focused on the application of more advanced pattern recognition, i.e., classification techniques in the TCM systems [16–20]. Nevertheless, concerning the usage of vibration based signals, those systems in most cases use standard, time-domain and/or frequency-domain extracted features or wavelet based features, mostly developed in previous works, some of which are mentioned above. For example, in [17], the authors used v support vector machine and locality preserving projection as classifiers, as well as wavelet based features, in their TCM system. In [18], the authors used relevance vector machines and classical time-based and frequency-based features, in order to classify the tool wear into tree different classes (new, middle and served). In [19], the authors used I-kaz statistics developed in [21], extracted from classical frequency-based features, as actual descriptors in their TCM system. In [22], the same authors proposed an adaptive network-based fuzzy inference based method as their actual decision making system, using the same, previously mentioned classical frequency-based descriptors.

In this paper, we propose the tool wear monitoring strategy which includes novel texture based descriptors, to be applied in the TCM problems utilizing vibration sensor signals. Actually, the texture based approach to descriptor construction, by means of exploring the texture structure of the time-frequency representation of vibration sensor signal is, to the authors' knowledge, completely novel in the field of TCM. The proposed descriptors obtained from vibration sensor signals are spectral domain-based. They rely on considering the module of the Short Term Discrete Furrier Transform (STDFT) spectra obtained from the particular sensor signal as the 2D textured "image". We identify the time scale as the first dimension and the frequency scale as the second dimension of the module of the STDFT of a particular sensor signal of interest. The 2D textured image obtained in such away is then divided into particular disjoint narrow 2D texture patches, covering a part of the frequency range of interest. Furthermore, by applying an appropriate filter bank, for each predefined frequency band (where those bands form the partition of the whole frequency range), we extract 2D textons [23], i.e., low dimensional feature vectors in filter response space. Our aim is to exploit the mentioned filter response of the corresponding textons, in order to encode the fine differences in the texture structure of the mentioned texture patches. The goal is to increase the discriminativity of the obtained descriptors in the task of tool wear classification. Moreover, we also tend to represent, in the form of low dimensional features, the significant details of the texture patches in order to gain on robustness of the description which corresponds to the tool wear states. Our approach is based on the assumption, which we later confirm in the experiments, that the underlying physical process of tool cutting, generated by different tool wear states, is closely related to the structure of the mentioned textons. However, the main problem that we face when trying to use the texture based approach, is that most features, i.e., descriptors used in texture recognition, are inappropriate for this particular application. The reason is that discriminativity between texture patches belonging to different tool wear condition classes is contained in the vertical lines spread across the entire frequency range and many of the used techniques in texture analysis