Study of monitoring the abrasion of metal cutting tools based on digital image technology *
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ABSTRACT

As monitoring the abrasion of tools becomes more and more important during metal cutting, many research efforts have been made in this aspect. This paper proposed a new method that detect and measure it directly by digital image technology and developed a detecting and measure system based on digital image. It is prone to automatically disposed and to integrate with machining and control information.

A new filter method that average many same size images when acquiring images is proposed. At the same time, a new edge detection way by wavelet transform is also proposed. A new wavelet function is given when selection wavelet functions, which describe gray change of images more availably, as well as may avoid the jamming of noise.

The rule of three is proposed to calibrate this system in this paper, and calibration precision arrives at application requirement. Functions of the software of this system include acquiring and processing images, edge detecting and segmenting images, and measure and analysis images. Images of tools are acquired by camera and CCD and video card. It can automatically differentiate and pick-up available information of the original image, such as area and perimeter and width and length and the location of the center of the abrasion region, by image processing and segmenting.

Keywords: Wavelet transform, Monitoring on tools' wear, Digital image technology

1. INTRODUCTION

The concept of tool condition monitoring has gained considerable importance in the manufacturing industry. This is mainly attributed to the transformation of the manufacturing environment from manually operated production machines to CNC machine tools and the highly automated CNC machining centers. For modern machine tools, 20% of the downtime is attributed to tool failure, resulting in reduced productivity and economic losses. A reliable monitoring system could prevent these problems and allow optimum utilization of the tool life, which is highly desirable [1].

It has been demonstrated that the key factor for production characterization is tool abrasion, and it must be monitored very carefully. It is also important to understand that the direct measurement of wear requires experienced personnel, its accuracy depends on the personnel capabilities and thus it is not easily repeatable.

In the modern machining center, where human interaction is reduced to a minimum, there is a need for the machine to be able to recognize automatically the wear condition of the tool [2].

Research efforts have been made in developing and applying thermal, force, vision, acoustic and acceleration sensors to machines and by implementing intelligent systems to detect directly or indirectly the tool abrasion condition and their application and characteristics have been discussed by Dimla and Dimla [3]. Tool abrasion estimation systems can be subdivided into two main classes: direct and indirect. Direct tool abrasion estimation systems are able to measure directly the tool abrasion by means of tool images, tactile sensors, etc. Their application is very simple and the reliability is high.

In the past, several methodologies to determine the wear land were used such as by using a profile projector, an optical section microscope, surface analyzers and radioactive sensors, as described in Ref. [4]. Indirect tool abrasion estimation methods are based on measurement and comparison of signals (for example, cutting forces) that are connected indirectly to tool abrasion. The main advantage of indirect methods is that they are applied online. Unfortunately, these methods are very complex to design and apply because of the lack of knowledge of how wear can affect the measured signal, the geometry of cutting and the unpredictable behavior of the wear process itself. Moreover, the application of these methods has a limited reliability and the sensor cost is still very high.

However, the automated application of direct tool abrasion estimation system is difficult because the detection system should be able to detect the wear zone and measure it. This problem is very complex as the wear zone has noisy contours and a lot of disturbing failures can be present (for example, scraps, lubricant, reflections, etc.). Therefore, the detection software must be carefully designed. In this paper, an innovative algorithm for tool abrasion zone identification and a detection system is presented.
2. HARDWARE OF THE TOOL ABRASION MONITORING SYSTEM

2.1. Hardware compose of the system

Direct measurement of tool abrasion can be made either by means of optical devices or by using a tactile sensor. The application of tactile sensors is not very common, while optical devices such as toolmaker microscopes and cameras are more practical and their cost is low. The basic system for tool abrasion measurement using optical devices is illustrated in Fig. 1.

Panasonic CCD with Computar M1214-MP FA lens is used in the field to capture an image of tool abrasion, which is transmitted to computer and transformed to digital images by Daheng video acquire card. Then the worn zone can be identified and measured. During image acquisition the illumination of the tool should be made very carefully to avoid the presence of reflections, which will produce fake edges.

2.2. Hardware calibration of the system

All the measurement benchmarks for the tool abrasion monitoring system is a pixel whose real size is related to the hardware performance indexes including CCD image transducers, camera lens, and lamp-houses. It is necessary to calibrate the tool abrasion monitoring system, so ascertain pixels’ corresponding real size.

2.2.1. Principle of calibration

For the identical camera lens and CCD image transducer and video acquire card, i.e., the same imaging system, the proportion of the pixel number to its real size is fixed. The problem of calibration is resolved if only this proportion is gained, as calculated in the formula (1).

\[
\frac{\text{size of the standard circularity(known)}}{\text{pixels of the criterion circularity(measured)}} = \frac{\text{size of the object(unknown)}}{\text{pixels of the object(measured)}} \quad (1)
\]

2.2.2. Procedures of calibration

The calibration is undertaken by standard circularity, the diameters of which are 1.5mm, 0.6mm, 0.15mm, and 0.07mm, respectively. First, lamp-houses, CCD and camera lens are adjusted to gathering all the images of standard circularities. The image area of the standard circularity, i.e. the pixel number for this standard circularity, is measured by software. Second, the real area (square millimeters, mm\(^2\)) of this standard circularity is calculated available using its known diameter. Accordingly, the proportion of the pixel number to its real size is obtained. In principle, the effect of standard circularities with different diameters on the resultant is very small. But, in fact there is a little error produced by software measuring. And if this error is larger than a prescribed range of error, repetitive manipulation should be done to scale down this error. The result of calibration for standard circularity is written down as shown in the table (1).

The data on proportion of pixel number to physical dimension is measured available using the same imaging system with different intensities of lamp-house adjusted under the prerequisite of imaging clearly. The data that are averaged out are acquired as calibration, a pixel being represented millimeters. Therefore, a function is established between a spot in an image and a spot in a scene. Saving the calibrations is used as a precondition to next measure.

<table>
<thead>
<tr>
<th>Table 1 Calibrate results with various diameter</th>
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<tbody>
<tr>
<td>Diameter of standard circularity (mm)</td>
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<tr>
<td>Calibration results (mm/pixel)</td>
</tr>
</tbody>
</table>
3. SOFTWARE OF THE TOOL ABRASION MONITORING SYSTEM

This system is developed based on LabVIEW(IMAQ). LabVIEW is a tool developed by NI company that is devoted to graphic virtual instrument. IMAQ is a special module on machine vision. The main window of the system is shown as Fig.2.

3.1. Acquire and preprocessing standard images

Acquire standard images is not only a most fundamental problem but also one of key problems in designing the tool abrasion image monitoring system. In order to reduce the noise in images acquiring, a filter that average out several same images is applied. During filtering, the still part of images remains unchanged, while different noise patterns are usually accumulated at slow rates.

Suppose that an aggregate consists of M images, which takes the following form:

\[ D_i(x,y) = S(x,y) + N_i(x,y) \]  \hspace{1cm} (2)

Where \( S(x,y) \) is an ideal image of interest, \( N_i(x,y) \) is a noise image caused by grains of films or electronic noise in digitized system. Every image in the aggregate is degraded by these different noise images. Although it is uneasy to understand exactly these noise images, they are supposed to result from an ample aggregate of random noise images which are mutually dissociated and whose noise average equals zero.

This signifies

\[ \mathbb{E}\{N_i(x,y)\} = 0 \]  \hspace{1cm} (3)
\[ \mathbb{E}\{N_i(x,y) + N_j(x,y)\} = \mathbb{E}\{N_i(x,y)\} + \mathbb{E}\{N_j(x,y)\} \] \hspace{1cm} (4)
\[ \text{And } \mathbb{E}\{N_i(x,y)N_j(x,y)\} = \mathbb{E}\{N_i(x,y)\} \mathbb{E}\{N_j(x,y)\} \] \hspace{1cm} (5)

\( \mathbb{E}\{} \) expresses the mathematical expectation, that is to say, \( \mathbb{E}\{N_i(x,y)\} \) equal to the average of the noise images at spot \((x,y)\) in the aggregate.

The power SNR(Signal-to-Noise Ratio) for the random spot of the image is defined as:

\[ P(x, y) = \frac{S^2(x, y)}{\mathbb{E}\{N^2(x, y)\}} \]  \hspace{1cm} (6)

Average M sheets of images,

\[ P(x, y) = \frac{S^2(x, y)}{\mathbb{E}\left[ 1/M \sum_{i=1}^{M} N_i(x, y) \right]^2} \]  \hspace{1cm} (7)

Numerator remains unchanged, because calculating the average not affects signal part. \( M^{1} \) is selected out denominator.

\[ \overset{1}{P}(x, y) = \frac{S^2(x, y)}{M^2 \mathbb{E}\left[ \sum_{i=1}^{M} N_i(x, y) \right]^2} \]  \hspace{1cm} (8)

or

\[ \overset{2}{P}(x, y) = \frac{M^2 S^2(x, y)}{\mathbb{E}\sum_{i=1}^{M} \sum_{j=1}^{M} N_i(x, y)N_j(x, y)} \]  \hspace{1cm} (9)

Denominator is divided into two part available using characteristic of formula (4).
\[ P(x, y) = \frac{M^2 S^2(x, y)}{E\left(\sum_{i=1}^{M} N_i(x, y)^2\right) + E\left(\sum_{i=1}^{M} \sum_{j=1}^{M} N_i(x, y)N_j(x, y)\right)} \quad (i \neq j) \] (10)

The second part of the denominator is decomposed according to formula (5), and the first part equal to summation of the expectation.

\[ \tilde{P}(x, y) = \frac{M^2 S^2(x, y)}{\sum_{i=1}^{M} E(N_i(x, y)^2) + E\left(\sum_{i=1}^{M} \sum_{j=1}^{M} N_i(x, y)N_j(x, y)\right)} \quad (i \neq j) \] (11)

The second part of the denominator equal to zero according to formula (7), furthermore, M sheets of noise take sample from same sample aggregate, so all parts of the first sum formula are identical.

\[ P(x, y) = \frac{M^2 S^2(x, y)}{ME\left(N^2(x, y)\right)} = MP(x, y) \] (12)

So, the square SNR of every spot in the image increases of M times. The range SNR is square root of the power SNR.

\[ \overline{SNR} = \sqrt{\overline{P(x, y)}} = \sqrt{MP(x, y)} \] (13)

The square root value increases with the total number of the averaged image.

### 3.2. Edge detection of the tool’s abrasion zone

The key to identifying the tool abrasion zone is to detect precisely the edge of this zone. Too much noise that arises from complexity in the process of machining makes the traditional edge detect algorithm such as Roberts, Sigma, Differentiation, and Prewitt undesirable. In this paper, an algorithm of edge detection using wavelet transformation is proposed.

A function \( \psi(x) \) is called a wavelet if its average is equal to 0.

The DWT can be designed as a multiscale edge detector that is equivalent to Canny edge detector.

Suppose that is a differentiable smooth function whose integral is 1 and converges to 0 at infinity. Let wavelet \( \psi(x) \) be the first order derivative of \( \theta(x) \).

\[ \psi(x) = \frac{d\theta(x)}{dx} \] (14)

Then

\[ W_j f(x) = f \ast \psi_j(x) = f \ast \left(2^j \frac{d\theta_j}{dx}\right)(x) = 2^j \frac{d}{dx}(f \ast \theta_j)(x) \] (15)

The wavelet used in this paper is the Mallat wavelet (Mallat and Zhong, 1992). The corresponding \( \theta(x) \) is a cubic spline, and thus \( \psi(x) \) is a quadratic spline.

\[ \theta(x) = \begin{cases} 
0 & |x| \geq 1 \\
\theta(-x) & 0 \leq x \leq 1 \\
-8x^3 - 8x^2 + 4/3 & 0.5 \leq x \leq 0 \\
8(x + 1)^2 & -1 \leq x \leq -0.5 \\
0 & |x| \geq 1 \\
-\psi(-x) & 0 \leq x \leq 1 \\
-24x^2 - 16x & 0.5 \leq x \leq 0 \\
8(x + 1)^2 & -1 \leq x \leq -0.5 
\end{cases} \] (16)

\[ \psi(x) = \begin{cases} 
0 & |x| \geq 1 \\
\theta(-x) & 0 \leq x \leq 1 \\
-8x^3 - 8x^2 + 4/3 & 0.5 \leq x \leq 0 \\
8(x + 1)^2 & -1 \leq x \leq -0.5 \\
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-\psi(-x) & 0 \leq x \leq 1 \\
-24x^2 - 16x & 0.5 \leq x \leq 0 \\
8(x + 1)^2 & -1 \leq x \leq -0.5 
\end{cases} \] (17)
In the case of images, two wavelets $\psi_1(x,y)$ and $\psi_2(x,y)$ should be utilized. Suppose $\theta(x,y)$ is a 2-D differentiable smooth function whose integral is 1 and converges to 0 at infinity. The two wavelets are:

$$\psi_1(x,y) = \frac{\partial \theta(x,y)}{\partial (x)} \quad \psi_2(x,y) = \frac{\partial \theta(x,y)}{\partial (y)}$$

Denote

$$\zeta_j = 2^{-j} \zeta(2^{-j} x, 2^{-j} y)$$

The dilation of $\zeta(x,y)$ by $2^j$, the WT of $f(x,y)$ at scale $2^j$ and position $(x,y)$ has two components.

Result images of edge detection by DWT compare with other classic operators are shown in the Fig.3.

The comparison of the image processed by traditional edge detection algorithms and by wavelet transformation proposed by this paper is shown in the Fig.3.

Fig.3 Results of edge detection by WT compare with other classic operators

4. EXPERIMENTS

The abrasive area and width and height of 20 tool images are measured by this system. Data of tools’ abrasion measured by this system and traditionally by personnel are compared, but only four sets of measured data are shown in the table 2 and 3. It is not advantageous to measure the degree of the tool abrasion only by ordinary microscopy because this microscopy reads roughly the abrasive width and height and has not a function of real-time monitoring. By comparison,
this system is simpler to operate in measuring the tool abrasion area, and advantageous in terms of measurement precision that satisfies the requirement of application.

<table>
<thead>
<tr>
<th>Tool image' name</th>
<th>Abrasion area (mm²)</th>
<th>Width (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>640-1</td>
<td>4.9278</td>
<td>3.0148</td>
<td>2.5626</td>
</tr>
<tr>
<td>640-2</td>
<td>4.6118</td>
<td>2.9610</td>
<td>2.4118</td>
</tr>
<tr>
<td>640-3</td>
<td>5.2909</td>
<td>2.7133</td>
<td>2.5734</td>
</tr>
<tr>
<td>640-4</td>
<td>5.0737</td>
<td>2.8102</td>
<td>2.5734</td>
</tr>
</tbody>
</table>

The finally measured results comprise the center coordinate (X, Y) of abrasion area, its area (pixel number), its width and height. It is easy to measure the abrasive area or degree of the tool and analyze the lifetime of the tool, etc. The original image of abrasive tool and the resultant image of the tool abrasion area are respectively shown in the Fig. 4 and Fig. 5. The abrasive area is denoted directly in the Fig.5, and other measured results will be shown in the table.

![Fig. 4 The original image of tools](image1.png)

![Fig. 5 The wear area of tools](image2.png)

5. RESULTS

A new digital image processing system applied to monitoring the tool abrasion area during metal cutting is proposed and researched in this paper. Several conclusions are reached as follows.

1. The calibration by means of rule of three satisfies its requirement of precision.
2. The noise in acquiring tools’ abrasion images is effectively eliminated using an average filter.
3. DWT is successfully used to detect the edge of the tool abrasion area, thus precisely identify its abrasion area.
4. The monitoring precision and stability inherent in this system are experimentally good enough to meet the needs of application.

REFERENCES