Development of a Non-contact Measurement System for In-situ Tool Profile Monitoring

Tai-An Cheng*, Choung-Lii Chao**, Der-Chyuan Lou*, and Chung-Woei Chao***

** Department of Electrical Engineering, Chung Cheng Institute of Technology, National Defense University*
*** Department of Mechanical and Electro-Mechanical Engineering, Tam-Kang University,*
**** Department of Information Management, Hsing-Wu College*

ABSTRACT

Single crystal diamond tool has the highest known hardness, good wear resistance, high conductivity, low in thermal expansion which makes it an ideal tool material for cutting precision diffractive optical elements, aspheric metal optical components etc. As long as tools are in use, it is only the matter of time tool will experience attritious wear, micro-fracture and eventually worn out. Since the surface roughness and form accuracy are very much depending on the sharpness and shape accuracy of the tool. Whatever is happened on the cutting edge will reflect on the workpiece. An effective and precise tool profile monitoring technique is of essential importance in ultra-precision diamond turning operation. The optical/non-contact way of tool profile monitoring has the advantage of not having to touch the tool, but its resolution is limited by the optical diffraction limit and the resolution of the CCD device used (mm/pixel). A non-contact precision tool profile monitoring system is developed and built in this study. The results showed good agreement with the profile data obtained by SEM micrographs and data measured by the precision profilometer.

Keywords: non-contact measurement, tool profile monitoring system, tool wear, sub-pixel

非接觸式線上刀具輪廓監測系統之研究

鄭泰安* 趙崇禮** 婁德權* 趙崇偉***

*國防大學中正理工學院電機系 **淡江大學機電系 ***醒吾技術學院資管系

摘 要

單晶鑽石刀具以高硬度、高耐磨度、高熱導係數、低熱膨脹係數著稱，因此常被作爲切削精密繞射光學元件等光學元件之理想刀具材料，惟刀具一經使用必將產生磨耗及微破裂。由於工件之表面粗糙度與形狀精度和刀具之銳利度與形狀精度息息相關，所有在刀具邊緣發生之現象，都將忠實的轉寫至工件上，故一個有效且精確之刀具輪廓監測方法，係超精密鑽石切削之作業要件。光學式/非接觸式刀具輪廓監測方法，有不須接觸到刀具之優點，但其解析度常受到光學繞射特性與 CCD 裝置解析度之限制。本研究發展一種非接觸且高精度之刀具輪廓監測方法來提昇現有系統之效能，本研究結果顯示與電子掃描顯微鏡及精密輪廓量測儀之數據具高度之一致性。

關鍵詞：非接觸式量測，刀具輪廓監控系統，刀具磨耗，次像素

文稿收件日期 94.12.7；文稿修正後接受日期 95.11.6.
Manuscript received December 7, 2005; revised November 6, 2006

I. INTRODUCTION

Diamond tools have the virtue of extreme hardness, high conductivity and good wear resistance, which make it very suitable for ultra-precision turning operation. Since the surface roughness and form accuracy rely heavily on the sharpness and profile accuracy of the diamond tool, precision measurement of tool profile has become a key issue for ultra-precision diamond turning operation. The traditional ways of measuring the tool profile are done mainly by contact inspection and typically laborious and inefficient. It is running the risk of damaging the delicate tool and the resolution is limited by the stylus geometry. A non-contact and accurate way for precision tool profile measurement is therefore in great demand.

Many attempts such as using real-time optical inspection systems, capacitance detecting technique and laser interferometer technique have been made recently to measure the diamond tool profile[1-4]. However, these methods are not easily adapted in practical in-situ precision measurement application. The major problem for optical tool profile monitoring is that the achievable accuracy is limited by the resolution of the image system and this resolution is not quite sufficient for ultra-precision turning operation.

There are many ways to improve the precision/resolution of the image measurement system, upgrading the image sensor is one of them. However, upgrading the hardware often means a big rise in cost and, very frequently, problems can not be solved merely by improving the hardware. Recently, efforts have been made to develop new image process algorithms to improve the precision of measuring system. [5-6]

Object localization has always played a key role in image measurement system. It is designed to extract information from digital image and can be classified into two levels: pixel-level and subpixel-level detection. The pixel-level measurement can only localize edges to the nearest pixel. It has the advantage of fast in detecting edge but suffered by low in precision. Operators such as Canny, Laplacian of Gaussian (LOG) and Sobel are amongst those commonly used for pixel-level measurement.[7] The subpixel-level methods such as geometric, Legendre and Zernike moments, have the advantage of high precision but in the expense of long computation time.[8-13] A technique which combining the two-stage edge detection scheme has been reported to have the advantages of improving detection precision and shortening the run time. [14, 15]

This paper presents an on-line/non-contact submicron-precision image measurement technique to be used in ultra-precision diamond turning operation.

II. THE OPTICAL IMAGE ACQUIRING SYSTEM

Shown in Fig. 1 is the measuring system used in this study. The diamond tool is mounted on the tool holder and the CCD camera was vertically above the tool. A lighting pad was used as a light source to illuminate the tool. The CCD camera and frame grabber catch the tool image $f(x, y)$ which is subsequently analyzed using image processing technique. The image resolution used in the present study is in the order of 2.46 μm per pixel. This is too rough for the diamond turning operation. A two dimensional sub-pixel analyses technique was so adopted to determine the tool geometry.

III. OBJECT LOCALIZATION ANALYSIS TECHNIQUES

Upon acquiring the tool images, two different edge detection operators were used to calculate tool profile points based on an optimized threshold value. The Sobel operator was first used to detect tool profile to pixel-level precision, the Zernike operator was then used to refine the profile to the subpixel accuracy.

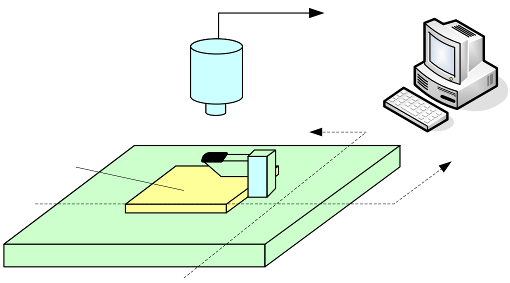

Fig. 1. Optical tool measuring system used in this study.

3.1 Sobel operator [7]

In comparison to other operators such as Laplacian and Canny, Sobel operator is relatively simple, fast computing and insensitive to noise. It is based on a pair of 3x3 convolution kernels (horizontal and vertical). The kernels are used to convolve with the input image and detect the horizontality and verticality gradients (G_x and G_y). Those kernels are given by:

$$G_x = \lfloor f(x+1,y-1) + 2f(x+1,y) + f(x+1,y+1) \rfloor - \lfloor f(x-1,y-1) + 2f(x-1,y) + f(x-1,y+1) \rfloor \qquad (1)$$

$$G_y = [f(x-1,y+1) + 2f(x,y+1) + f(x+1,y+1)] - [f(x-1,y-1) + 2f(x,y-1) + f(x+1,y-1)] \qquad (2)$$

The magnitude of the gradient at each point can be expressed as: $G(x,y) = \sqrt{Gx^2 + Gy^2}$. The pixel will be regarded as part of the tool profile if $G(x,y)$ is large than the threshold value. These pixel-level "profile points" detected by Sobel operator have to be refined by Zernike moments operator.

3.2 Zernike moments operator [15]

Zernike function is a set of complex orthogonal functions which forms a complete orthogonal basis over the unit circle. The Zernike moment of order *m* with repetition *n* for a digital image $f(x,y)$ is defined as follow:

$$Z_{mn} = \frac{m+1}{\pi} \sum_x \sum_y f(x,y) W_{mn}^*(r,\theta) \qquad (3)$$

where $(x^2 + y^2) \le 1$, The Zernike polynomials $W_{mn}(r,\theta)$ of order *m* are defined as:

$$W_{mn}(r,\theta) = R_{mn}(r) e^{-jn\theta} \qquad (4)$$

$R_{mn}(r)$ is real radial polynomial which defined as:

$$R_{mn}(r) = \sum_{k=0}^{(m-|n|/2)} \frac{(-1)^k (m-k)!}{k!((m+|n|)/2-k)!((m-|n|)/2-k)!} r^{m-2k} \qquad (5)$$

where *m* is a nonnegative integer, *n* is an integer subject to the constraint $m-|n|$ is even.

The Zernike moments are rotation-invariant transformations. If an image is rotated by an angle ϕ, the Zernike moments of the original image Z_{mn} and the Zernike moments of the rotated image Z'_{mn} have the following relationship:

$$Z'_{mn} = Z_{mn} e^{-jn\theta} \qquad (6)$$

The rotation angle and the edge parameter *L* can be derived as:

$$\phi = \tan^{-1}\left(\frac{\mathrm{Im}[W_{11}]}{\mathrm{Re}[W_{11}]}\right) \qquad (7)$$

$$L = \frac{Z_{20}}{Z'_{11}} \qquad (8)$$

In practical, Zernike moments can be calculated by convolving masks with the image points. [13]

3.3 Optimum threshold value selecting by Zernike moments [16]

To extract the tool profile features, an automatic thresholding algorithm is adopted in this study for image-processing. This technique is based on maximizing the correlation between Zernike moments phases of the gray-level and binary images of the same objects.

The basic idea of this method is that the shapes of the binary image and original image are similar if the phases of two images are close to each other. Let $\phi_g(u,v)$ be the phase of the gray image and $\phi_{th}(u,v)$ be the phase of the threshold image. The optimal threshold is this maximizes the correlation between $\phi_g(u,v)$ and $\phi_{th}(u,v)$. The correlation function can be expressed as:

$$C(t)=\frac{\sum_{u=0}^{n}\sum_{v=0}^{m}(\phi_g(u,v)-\overline{\phi_g})\cdot(\phi_{th}(u,v)-\overline{\phi_{th}})}{\sqrt{\sum_{u=0}^{n}\sum_{v=0}^{m}(\phi_g(u,v)-\overline{\phi_g})^2\cdot\sum_{u=0}^{n}\sum_{v=0}^{m}(\phi_{th}(u,v)-\overline{\phi_{th}})^2}} \quad (9)$$

IV. PRECISION TOOL SHAPE MEASUREMENT

After the diamond tool is set up on the precision stage, a serious of image frames are taken during measurement. In each frame Sobel operator is used to obtain the pixel level tool profile based on the optimum threshold, followed by Zernike moments to refine the profile position.

4.1 Algorithms

The algorithm for the proposed subpixel tool profile measurement consists of five steps:

Step1. capture a serious of tool frames from precision positioning stage.
Step2. use the Zernike threshold method to find the threshold value.
Step3. obtain the pixel level tool profile by using the Sobel detector using the optimum threshold value.
Step4. apply the Zernike moments technique to relocate the single frame subpixel tool profile.
Step5. refine the tool profile position from a set of single frame subpixel tool curves.

4.2 Single -frame tool shape detection (SFD)

(1) Acquiring the optimum threshold of the tool frame: the above mentioned optimum threshold value selecting scheme was used to automatically determine a threshold for the tool images

(2) Extracting tool profile from image frame: Sobel operator is used to locate the tool profile to pixel level precision. The accuracy of the position is limited by the pixel size.

(3) Locating profile position to subpixel precision: calculating Zernike moments for all points $\{(x_1,y_1),(x_2,y_2),\ldots\ldots,(x_n,y_n)\}$ on the profile and convolving these points with the Zernike masks of Z_{11} (the real component), $Z_{11}^{'}$ (the imaginary component) and Z_{20}.

4.3 Multi-frames tool shape detection (MFD)

Two fundamental drawbacks of the SFD measuring technique are 1). small variation in position introduced by background noise cannot be avoided completely 2). information of single image frame is insufficient for correcting edge point.

To rectify minor positioning errors, a centroid technique is used to recalculate the profile and to minimize disturbances caused by the variation of the optical fluctuation and insufficient information. The averaging technique was applied to a serial of tool frames to improve accuracy. Let N be the number of image frame and N/2 be the frame of object tool profile to be measured, P_{SFD_i} denote the curve of tool shape at image frame (i). The multiple frame tool shape P_{MFD} can then be written as the following equations:

$$P_{MFD} = (\frac{1}{N}\sum_{i=1}^{N} P_{SFD\_i}) \quad (10)$$

V. EXPERIMENTATION

Experiments were carried out to validate the image analysis technique developed to measure diamond tool profile at sub-micrometric precision. Images of a serial of fine movements were used to verify the robustness and effectiveness of the proposed method.

5.1 Experiment setup

The experimental set-up is shown schematically in Fig.2. A precision positioning stage with positioning accuracy better than 0.05μm was used to carry out the fine movement of the tool. The positioning stage was equipped with aerostatic slides and driven by linear motor. The whole system was placed on a vibration isolated air-suspension table to further minimize the vibration. A PC-based controller with 1 kHz sampling rate and a Hewlett-Packard laser interferometer with wavelength (λ) of 632.991354 nm and resolution of λ/128 position feedback were used in the control system for signal processing and position measuring respectively.

5.2 Method of validation

A serial of fine movements of the diamond tool were achieved by controlling the precision positioning and images of the tool were captured for each steps (200nm). The obtained images were consecutive image frames $F = \{F(1), F(2), \ldots F(n)\}$ and the total sampling distance was the number of frames timed stage steps. Tool images were then processed by proposed method to determine the tool profile.

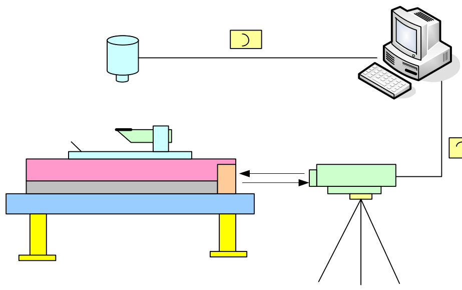

Fig. 2. Schematic representation of the experimental setup.

VI. RESULTS AND DISCUSSION

Shown in Fig. 3 was the SEM micrograph of one of the round nose diamond tools used in this study. The tool profile generated by single frame subpixel detecting technique was overlaid onto the original image and shown in Fig.4. They matched rather well from a macroscopic point of view. However, differences became obvious when taking a microscopic view.

Shown in Fig. 5 were the detailed view of the profiles, representing a small segment of the diamond tool, generated by the SFD and MFD detection method. Note that SFD profile had small fluctuation on the detected profile map due to the noise and the insufficient information.

The detected profile was then compared with the modified profile data measured by the Form Talysurf (Fig. 6). Though certain details were missing in the MFD-generated profile, the general trend of the profiles were in good agreement.

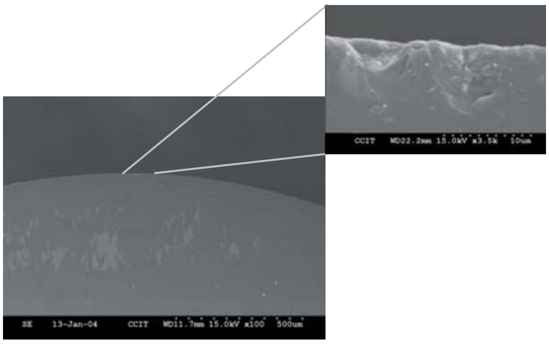

Fig.3. SEM image of round nose diamond tool.

Fig.4. Tool shape detect with Sobel operator.

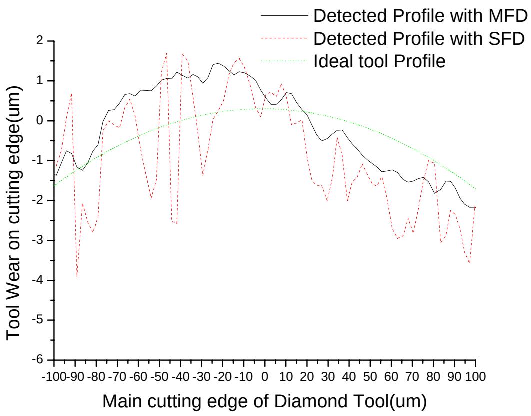

Fig.5. Results of the SFD and MFD detection method.

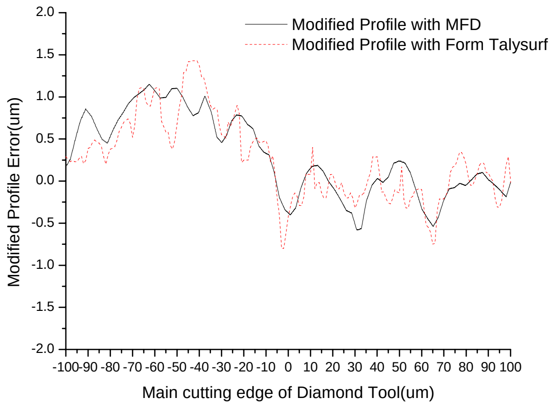

Fig.6. Comparison between the MFD-generated profile and profile measured by Form Talysurf.

VII. CONCLUSIONS

A non-contact precision tool profile monitoring system is developed and built in this study using edge-detection image processing and sub-pixel dividing techniques in conjunction with CNC controller of the precision turning machine to improve the system presently available. The results showed good agreement with the profile data obtained by SEM micrographs and data measured by the precision profilometer (Form Talysurf).

REFERENCES

[1] Pfeifer, T. and Wiegers, L., "Reliable tool wear monitoring by optimized image and illumination control in machine vision," Measurement, Vol. 28, No. 3, pp.209-218, 2000.
[2] Sortino, M., "Application of statistical filtering for optical detection of tool wear," Journal of Machine Tools & Manufacture, Vol. 43, No. 5, pp.493-497, 2003.
[3] Liu, Q. and Altintas, Y., "On-line monitoring of flank wear in turning with multilayered feed-forward neural network," Journal of Machine Tools & Manufacture, Vol. 39, No. 12, pp.1945-1959, 1999.
[4] Choudhury, S. K. and Kishore, K. K., "Tool wear measurement in turning using force ratio," Journal of Machine Tools &

Manufacture, Vol. 40, No. 6, pp.899-909, 2000.
[5] Li, X. P., Rahman, M., Liu, K., Neo, K. S., and Chan, C. C., "Nano-precision measurement of diamond tool edge radius for wafer fabrication," Journal of Materials Processing Technology, Vol. 140, No. 1, pp.358-362, 2003.
[6] Jurkovic, J., Korosec, M., and Kopac, J., "New approach in tool wear measuring technique using CCD vision system," Journal of Machine Tools & Manufacture, Vol. 45, No. 9, pp.1023-1030, 2005.
[7] Gonzalez, R. C. and Woods, R. E., "Digital Image Processing," second edition, Addison Wesley, pp. 416-428, 1992.
[8] Gu, J., Shu, H. Z., Toumoulin, C., and Luo, L. M., "A novel algorithm for fast computation of Zernike moments," Patern Recognition, Vol. 35, No. 12, pp. 2905-2911, 2002.
[9] Kamila, N. K. , Mahapatra, S., and Nanda, S., "Invariance image analysis using modified Zernike moments," Pattern Recognition Letters, Vol. 26, No. 6, pp.747-753, 2005.
[10] Zhenjiang, M., "Zernike moment-based image shape analysis and its application," Pattern Recognition Letters, Vol. 21, No. 2, pp.169-177, 2000.
[11] Li, J., Chen, S., and Wu, L., "An algorithm of sub-pixel edge detection based ZOM and application in calibration for robot vision," Proceedings of the 4th World Congress on Intelligent Control and Automation, pp. 1210-1214, 2002 .
[12] Ghosal, S. and Mehrotra, R., "A moment-based unified approach to image feature detection," IEEE Transactions on Image Processing, Vol. 6, No. 6, pp. 781-793, 1997.
[13] Liao, S. X. and Pawlak, M., "On the accuracy of Zernike moments for image analysis," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 20, No. 12, pp.1358-1364, 1998.
[14] Tsai, P., Chang, C. C., and Hu, Y. C., "An adaptive two-stage edge detection scheme for digital color images," Real Time Imaging, Vol. 8, No. 4, pp. 329-343, 2002.
[15] Qu, Y. D., Cui, C. S., Chen, S. B., and Li, J. Q., "A fast sub-pixel edge detection method using Sobel-Zernike moments operator," Image and Vision Computing, Vol. 23, No. 1, pp. 11-17, 2005.
[16] Belkasim, S., Gu, J., Ghazal, A., and Basir, O., "The optimum automatic thresholding using the phase of Zernike moments," The 47th IEEE International Midwest Symposium on Circuits and Systems, pp. 491-494, 2004.