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# A strategy for improving the form accuracy of ultra-precision single point diamond turning

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**Abstract**

Ultra-precision single point diamond turning is widely used in the production of infrared optics. The key for achieving high form accuracy are the precise tool setting and the tool path control. The common practise for tool setting depends mainly on the machine operator. The tool path is controlled by the feed drive system and the tool path compensation which is done by offline measurement and tool path correction software. Such working method is very time consuming. This paper introduces a machine vision based tool setting system which measures the X position of the centre point, the height and the radius of the tool with micron accuracy and sets the tool parameter in the CNC controller automatically. The closed-loop compensation of form error is done then by combining an in-situ form error measuring probe with tool path correction software integrated in the controller of the CNC system. The compensation of the form error is carried out based on the in-situ measured form error data. The machining experiment was carried out. The results show that form accuracy of the work piece could be improved in the sub-micron range with this machine vision tool setting system and closed loop form error compensation.

Single point diamond turning, optical tool setting system, surface form accuracy, in-situ measurement

## 1. Introduction

The key to achieve submicron surface form accuracy is the precise control of tool path. Visual tool setting device has made many academic and commercial achievements [1, 2, 3], but the measurement accuracy of commercial optical tool setting device is not high enough and the operation efficiency is low. It is easy to introduce the subjective error of the operator in use, such as manually selecting three points to fit the tool tip arc or manually judging the clarity of the visual image. The application of high precision optical tool setting device is the main development direction of tool setting device of ultra-precision machine tool. How to reduce the dependence on machine operators, reduce adjustment time and realize intelligent tool setting is an urgent practical technical problem to be solved.

Surface form error is inevitable in the actual production and processing of ultra-precision single point diamond lathe. It is necessary to use measurement and compensation technology to correct the machining trajectory to make surface form error within the allowable range [4]. Firstly, the error of machined surface is obtained by appropriate detection means, and the error data is processed and analyzed. Finally, an appropriate compensation method is used to correct the target value of each motion axis to improve the surface form accuracy. Scholars have conducted in-depth research on the measurement and compensation methods of ultra-precision machining errors [5-9]. The tool path is controlled by the feed drive system, and the tool path compensation which is done by offline measurement and tool path correction software. This working method is very time consuming. Therefore, how to quickly and accurately obtain and compensate the surface form error of the machined surface has become a very important problem in the process of single point diamond turning.

Based on the above analysis, in order to realize sub-micron form accuracy in ultra-precision turning, this paper studies the optical tool setting system based on machine vision which can measure the X position of the centre point, the height (Y position) and the radius of the tool with micron accuracy and sets the tool parameter in the CNC controller automatically. The closed-loop compensation of form error is realized by combining the in-situ form error measuring probe with tool path correction software integrated in the NC system controller.

## 2. Design of ultra-precision visual tool setting system

For ultra-precision turning, tool offset will affect the quality of turning parts, especially on large aperture parts.The precise adjustment of tool tip will affect the machining surface form accuracy. Therefore, it is of great significance to study the method of tool offset correction and find an efficient and precise tool offset correction method to improve the form accuracy.

### *2.1 Influence of tool offset on turning surface form accuracy*

The basic structure of ultra-precision single point diamond lathe is shown in Figure 1. The structure is composed of X-axis and Z-axis linear feed axes and workpiece spindle. The workpiece spindle is installed on the X-axis slide and the turning tool holder is installed on the Z-axis slide.

In processing, tool setting operation is required. First, adjust the tool installation height so that the highest point of the cutting edge of the tool is in the same horizontal plane as the spindle axis; Secondly, move the X-axis to realize that the center of the cutting-edge arc is in the same vertical plane as the spindle axis.

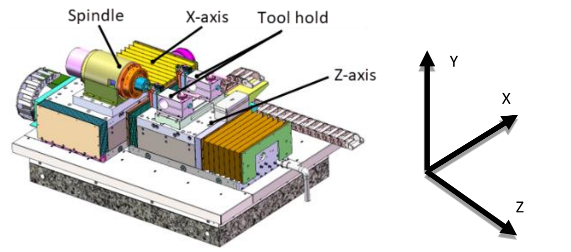


**Figure 1.** Schematic diagram of structure and coordinate system of single point diamond lathe

Tool setting offset is divided into X offset and Y offset. When the tool offset exists, over cutting or under cutting occurs when machining with ultra-precision lathe. Next, the relationship between the tool setting offset and the form error is analyzed. Assume Y offset $\delta_2=0$ when X offset $\delta_1\neq0$, the tool feed is along the positive direction of X axis. The workpiece coordinate system is used in machining programming. In order to facilitate subsequent machining programming, the tool path is described in the workpiece coordinate system. For a convex sphere, in the XOZ plane of workpiece coordinate system, the theoretical tool path equation is:

$$\begin{cases} z=\sqrt{R^2-x^2}-R \\ y=0 \end{cases}, x\in\left[-\frac{D}{2},0\right] \quad (1)$$

Where: $R$ -- the radius of machined convex sphere.

Considering the X offset $\delta_1$, the actual tool path equation is:

$$\begin{cases} z=\sqrt{R^2-(x-\delta_1)^2}-R \\ y=0 \end{cases}, x\in\left[-\frac{D}{2},\min(0,\delta_1)\right] \quad (2)$$

Then the surface form error value $\Delta Z$ along Z coordinate is

$$\Delta Z=\sqrt{R^2-(x-\delta_1)^2}-\sqrt{R^2-x^2}, x\in\left[-\frac{D}{2},\min(0,\delta_1)\right] \quad (3)$$

It can be seen from formula (3) that each cutting point on the actual cutting path deviates from the theoretical value due to X offset, which affects the machining surface form accuracy. When X offset is negative, the surface form error $\Delta Z$ is negative, and the workpiece is overcut; On the contrary, the value of surface error $\Delta Z$ is positive, the central area of the workpiece is not processed to form a boss.

In the case of Y offset, the machining surface form error $\Delta Z$ is:

$$\Delta Z=\sqrt{R^2+{\delta_2}^2-x^2}-\sqrt{R^2-x^2} \quad (4)$$

According to the above theoretical analysis, the theoretical numerical simulation method is used to simulate the theoretical surface form error.when turning a convex sphere with a radius of curvature of 50mm and a diameter of workpiece of 60mm, it is assumed that the tool offset is 100μm(Arbitrarily assumed) respectively in both directions. The effects on surface form error of a meridional interface contour are shown in figure 2 and figure 3.

The following conclusions can be drawn from Figure 2 and Figure 3:

1) The form error of the turning surface caused by X offset changes with the direction of the tool offset and the shape of the machined surface. The maximum error is located at the edge of the workpiece. When X offset is 0.1mm and -0.1mm respectively, the corresponding maximum surface form error is 74.42μm and -75.20μm.

2) When Y offset is 0.1mm, the surface form errors gradually decreases from edge to center point, and the maximum absolute value of the error is 0.125μm, which has little influence on the surface form error. The surface error has nothing to do with the direction of bias, but only with the concave and convex shape of the machined surface. The Y offset causes a residual boss in the center of the workpiece, which affects the appearance and optical performance of the workpiece. In actual production, the Y offset is required to be less than 2μm.

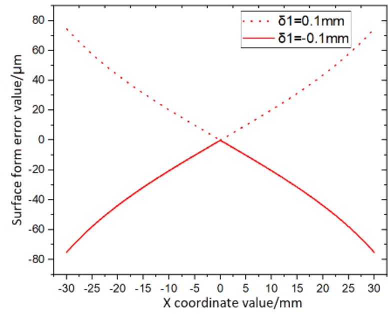


**Figure 2.** The surface form error curves of convex sphere with X offsets of 0.1μm and -0.1μm

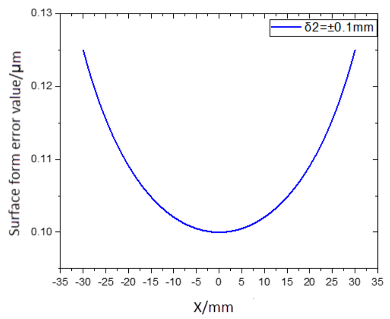


**Figure 3.** The surface form error curve of convex sphere with Y offsets ±0.1μm

### *2.2 Structural design of in-position visual tool setting system*

The main functions of the optical tool setting system designed in this paper include: detecting the radius of the tool tip arc, calculating the center coordinates of the tool tip arc, positioning the tool in X and Y directions accurately, and warning the tool tip wear. The optical tool setting device is installed on the spindle seat of the single-point diamond lathe, as shown in Figure 4, including digital image vision system, calibration gauge and mechanical positioning part.

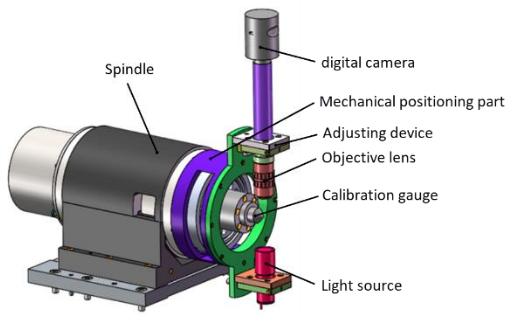


**Figure 4.** Schematic diagram of optical vision tool setting device

The digital camera has a pixel size of 2.9296 pixel/μm×4 pixel/μm, and is used in combination with a 5× objective lens. The image size corresponding to an object of 1×1μm is 5×5μm. Such an image requires 1.706 (H) ×1.25 (V) pixels, so the horizontal pixel equivalent of the image is 586nm/pixel, and the vertical pixel equivalent of the image is 800nm/pixel.

### *2.3 Design of Image processing algorithm*

1) Evaluation method of image sharpness

The tool setting instrument is usually used for manual tool setting of ultra-precision single point diamond lathes, and then the tool setting parameters need to be corrected by trial cutting method to further improve the tool setting accuracy. The focusing accuracy of manual tool tip is poor, which will increase tool setting error, and the tool setting error is 5~20μm. The sharpness of image is distinguished by the sharpness evaluation function to obtain a clear tool tip image, so as to improve the accuracy of tool tip edge detection and wear detection.

In order to verify the unimodal nature of the evaluation function, the imaging process of standard gauge in the test is "fuzzy-clear-fuzzy". A total of 6 images on both sides of the focal point of the tool setting system are captured. Adjust the height of the objective lens by using the precision fine-tuning mechanism of the objective lens, and the adjustment step is 5 μm. The sharpness of the captured 6 images is calculated and analyzed by using sharpness evaluation functions such as variance function, Brenner function, Tenegrad function, energy gradient function and Laplace energy function. The test results are shown in Figure 5. According to the test results, Brenner function has good unimodal and sensitivity. Therefore, Brenner sharpness evaluation is applied to this study to improve the tool setting accuracy.

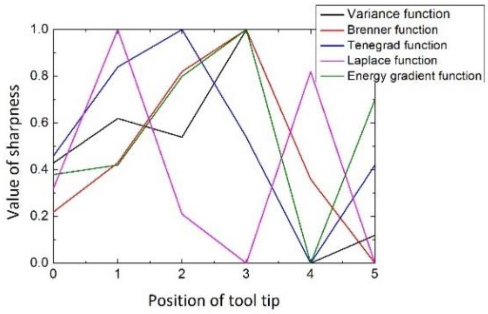


**Figure 5.** A graph of the result of the sharpness evaluation function

2) Filtering of salt and pepper noise

According to the practical application experience, the filtering effect of mean filter and median filter is related to salt and pepper noise density. The greater the noise density, the worse the filtering effect, which directly affects the extraction of effective image information. In this paper, an improved adaptive extremum median filtering algorithm is proposed. Based on the traditional extremum median filtering algorithm, the steps of noise point judgment are added when selecting the neighborhood median to reduce the probability of false diagnosis of noise points.

In the case of noise of the same density, the improved adaptive extremum median filtering algorithm and median filtering algorithm are respectively used for processing, and the processing results are shown in Table 1. The processing result of the improved adaptive extremum median filtering algorithm is obviously better than that of the median filter algorithm. The median filter is too sensitive to the increase of noise density, and the filtering effect deteriorates rapidly with the increase of noise density. The improved adaptive extremum median filtering algorithm has good stability to the change of noise density, which can preserve more effective resolution and image processing details for users.

**Table 1** PSNR of Baboon's original image at various noise densities

| Noise density | median filtering | Improved adaptive extremum median filtering |
|---|---|---|
| 0.35 | 17.4368 | 20.8049 |
| 0.45 | 14.1623 | 20.6204 |
| 0.55 | 11.0235 | 20.4352 |
| 0.65 | 8.7670 | 20.2446 |
| 0.75 | 7.2989 | 20.0705 |

3) Edge detection

The edges involved in this paper are divided into intersecting line segments and circular edges. Canny function is used to binarize the edge detection results and effectively extract the foreground target. The outer edge contour of edge detection is calculated, and the small and discontinuous contour and its points are removed by calculating the contour area, and the coordinate and contour layer information of outer edge pixels are extracted to form the edge contour pixel point set.

4) Geometric calculation of tool offset correction

In machine vision detection and positioning, the extraction of feature points determines the accuracy of tool setting. The bus contour of calibrated measuring tools is detected and extracted by cumulative probability Hough transform. Hough transform method can be widely applied to the fitting of circles passing through edge points, but the fitting accuracy is insufficient. Especially for the image processing with multiple circle features, the edge points are reused, and the detection results can not be used. There is only a single circle feature in the X-direction tool setting offset image. In this paper, the least square method is used to fit the circle feature, which has high fitting accuracy and strong anti-interference ability.

***2.4 Test of tool tip arc radius detection***

In order to verify the effectiveness of edge detection method and tool tip arc parameter calculation method adopted in this paper, diamond turning tools of different specifications are selected, image acquisition of tool system is carried out for many times by in-position vision, then data processing is conducted to output tool tip arc radius. Limited by the resolution of the visual system, the maximum error, average error and standard deviation of statistical data are 2.4μm, 0.81μm and 1.2μm, respectively. The reliability and accuracy of edge detection method and tool tip arc parameter calculation method of visual tool alignment system are verified. The effect of the average error 0.81μm affects the surface form error of the convex sphere (in section 2.1) by about 6μm.

## 3. Measurement and compensation of surface form error

In the actual processing process, the surface shape obtained by infrared optical elements has errors [10]. Because the radius of curvature at each point of aspherical surface is different, it is necessary to use appropriate detection methods to obtain the form errors of the machined surface, process and analyze the error data, and use appropriate compensation methods to correct the target value of each motion axis, so as to improve the surface form accuracy [11]. In this paper, the in-situ measurement and error compensation method of ultra-precision turning are studied.

***3.1 Scheme design of in-situ measurement system***

Based on the working principle of CMM, when turning the rotational symmetric surface, the tool feeds along the meridional section curve. Therefore, only the meridional section curve of the workpiece can be measured for in-situ surface shape measurement. According to the measured surface form errors data, the workpiece can be compensated to meet the requirement of surface form accuracy. Figure 6 shows the principle of the in-situ measurement scheme for rotary symmetric surfaces.

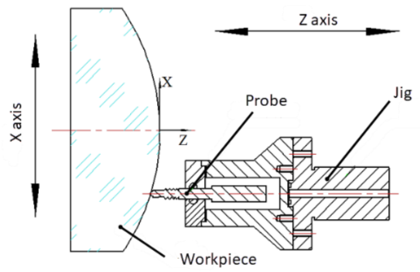


**Figure 6.** Principle of the in-situ measurement scheme

The high-precision displacement sensor is installed and fixed on the tool holder, and according to the bus equation of the surface shape to be measured, the NC detection program is generated, and the surface shape of the workpiece is measured relying on the motion accuracy of the NC equipment.

As shown in figure 7, the coordinate of theoretical measurement point P is (x,z), the coordinate of probe center is (X,Z), and the theoretical compression of the probe is zero.

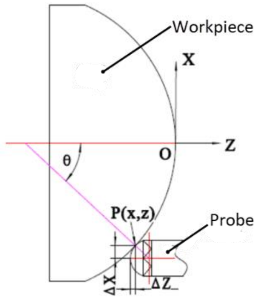


**Figure 7.** Schematic diagram of actual contact points for in-situ measurement

The theoretical detection point P(x,z) and the corresponding probe track coordinate (X,Z) satisfy:

$$\begin{cases} X = x - r_{probe} * \sin\theta \\ Z = z - r_{probe} * (1 - \cos\theta) \end{cases} \quad (5)$$

Where: $r_{probe}$ -- probe radius; $\theta$ -- Angle between the normal line at the point P(x, z) and the Z-axis, clockwise is positive.

The sensor installation error can not be accurately measured, so this paper compensates the probe installation error by numerical method.

***3.2 Design of error compensation strategy***

The comprehensive error compensation method compensates multiple errors at the same time without separating the errors one by one. Compared with the single error compensation method, it has higher efficiency and good effect. Therefore, this paper adopts the method of comprehensive error compensation to measure and compensate the machining surface form error in place to form a closed-loop control of surface form accuracy. In-situ measurement of surface form errors has been realized in the previous paper. The measured surface form errors data is processed to obtain the error curve of the tool path along the Z-axis direction. On this basis, the tool path is corrected and compensated.

The tool holder of the ultra-precision single point diamond lathe in this paper cannot rotate. The Z-direction direct compensation method is adopted in the test design, and the sensitive direction of the probe is parallel to the Z-axis.

The error compensation function is regarded as a special function of NC system to realize in-situ detection and automatic tool path correction according to the error data, and generate a new NC machining program to compensate the form error in the next machining.

## 4. Experimental research

Machining test is conducted. The PV values of machined surface measured by in-situ measurement system and profilometer are compared. The workpiece is an aspheric optical element with a diameter of 15.3mm and a curvature radius of 76.91mm. The goal of compensation machining is to achieve surface form errors less than 1μm.

The experimental results are shown in Table 2. After two compensation machining, the surface form errors PV value is less than 0.001mm, and the measurement data of the in-situ measurement system is similar to the results of the profilometer, which verifies the feasibility of the in-situ measurement system and compensation method proposed in this paper.

**Table 2** PV values of machined surface

| Processing order | In-situ measurement system/μm | Profilometer (Taylor Hobson) /μm |
|---|---|---|
| 1 | 9.585 | 9.3746 |
| 2 | 4.043 | 3.8438 |
| 3 | 0.952 | 0.7641 |

## 5. Conclusion

This paper analyze the influence of tool offset on surface form accuracy, and design an in-position tool setting system based on machine vision. Brenner function is used to evaluate the sharpness of the collected images, and an improved adaptive extremum median filtering algorithm is proposed to preserve the effective resolution and image processing details. The reliability and accuracy of edge detection method and tool tip arc parameter calculation method are verified by experiments.

A method of measuring the aspheric surface with rotational symmetry is proposed, and the trajectory of the probe is planned during the measuring process. After two times of compensation machining, the PV value of workpiece surface shape reaches 0.7641μm, which meets the requirements of sub-micron machining accuracy. Experiments verify the feasibility of the in-situ measurement and compensation method proposed in this paper, which can effectively improve the machining accuracy of rotary symmetric aspheric surface and meet the practical production application.

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