A Vision-based On-machine Micro-Cutter Positioning Error Measurement and Compensation System for Micro Milling Machines

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To perform an accurate micro machining process, accurately aligning the micro cutter with respect to the local coordinate frame for machining is essential. Due to the fragility of the micro tool, traditional cutter alignment method used in industry is no longer proper for micro machining. Utilizing machine vision technology with 2 CCDs, a micro tool positioning error measurement and auto-compensation system was proposed. In the measurement method, Power Law Method was first used to enhance the image taken by a CCD. Canny Edge Method and image projection method were then used to identify the contours of the cutter and the workpiece from the image. Finally, the deviation of the cutter can be determined through calculating the number of pixels between the cutter and the workpiece. By using 2 CDDs respectively locating in x side and y side, the 3-dimension position errors of the cutter can be measured. The error compensation system can automatically generate NC codes which can move the cutter with the distances equal to the position errors so that the cutter can be accurately re-located. Experiments were conducted on a micro machine tool, and the results have shown the effectiveness of the proposed system.

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NOMENCLATURE

c, γ= positive constants
$B[i,j]$ =image matrix
$H[i]$, $V[j]$ = pixel accumulation numbers

1. Introduction

Micro-machining plays an important role in Non-MEMS micro manufacturing field. To perform an accurate micro machining process, accurate alignment of the micro cutter is necessary. Non-accurate micro tool positioning generates initial errors that will deteriorate the micro machining accuracy.

Due to the tiny size and fragility of the micro tool, the traditional cutter alignment method used in industry is no longer proper for micro machining. Many researchers had devoted lots of efforts on development of micro machines tools and investigation of micro machining dynamics. However, not many efforts had been paid to develop a proper method for micro tool alignment. Because the micro tool is very fragile, the alignment method must be non-contact and auto-executable. Vision-based measurement is a quite appropriate method which provides advantages of low cost and easy setup for non-contact measurement. As PCs have become more powerful, and resolution of CCD camera system has been significantly improved, machine-vision systems had been used in many inspection applications [1-3]. For on-machining application, J. Jurkovic [4] used a CCD camera to obtain high resolution grey-level images of the tool wear projected with a laser vision-based measurement method. The beam pattern was connected to a interface card (grabber) in a PC, and equipped with image capturing software. Johan Baeten [5] exploited a hybrid vision/force control approach at corners in planar-contour following resulting in a more accurate and faster task execution. The vision system was used for online measurement of the contour and to watch out for corners. Once a corner is detected, a finite-state controller is activated to take the corner in the best conditions. Liangyu Lei [6] utilizes a machine-vision system for inspecting the inner and outer diameters of bearings and realizes a highly-efficient, accurate and reliable inspection method for bearing diameter measurement. Adopting machine vision technology, coordinate transformation, and NC-code compensation technology, an on-machine micro tool positioning error measurement and auto-compensation system was developed. Experiments on a toggle-type micro machine tool were conducted to verify the effectiveness of the system.

Section 2 addresses the principle of the measurement method. The NC-code-based auto-error compensation method is introduced in Section 3. Experimental results are discussed in Section 4. Finally the conclusion is addressed in Section 5.

2. Principle of The Measurement Method

The measurement method is composed of two parts: (1) edge detection, and (2) error identification. When performing measurement, the cutter is moved to close to the workpiece so that both of the cutter and workpiece edges can be within the filler of view (F.O.V.) of the camera. The edges of the micro cutter and the workpiece are detected from the images taken by two cameras. According to the detected edges, the center line of the cutter and cutter tip are calculated and used to calculate the distance from the cutter tip to the workpiece surface (i.e. the the z-dir. Positioning error) and the distance from the center line of the cutter to the two edges of the workpiece (i.e. the x- and y-dir. Positioning errors). According to the measured positioning errors, a NC program will be automatically generated and sent to CNC controller to move the micro cutter to the origin of machining. Figure 1 shows the measurement procedures.

2.1 Edge Detection

To determine the positioning error of a micro cutter, the cutter is first moved to close to the workpiece so that both of cutter and workpiece edges are within the filler of view (F.O.V.) of the camera.

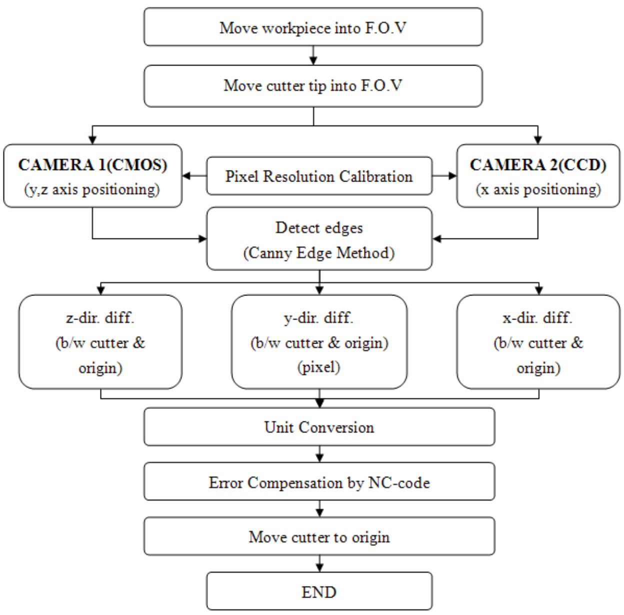

Fig. 1 Tool positioning error measurement & compensation flowchart

Two images are taken by two cameras which are set up as shown in Fig. 2. The camera 1 and 2 takes image from x and y direction separately. The Canny Edge Detection algorithm [10] was used to search for the optimal edges of the image. The Canny Edge Detection has better detection results relative to traditional binary methods. The main characteristics of Canny Edge Detection are as follows:

1. Smoothes the image with a Gaussian filter;
2. Computes the gradient magnitude and orientation using 2×2 first-difference approximations for the partial derivatives;
3. Applies nonmaxima suppression to the gradient magnitude;
4. Uses a double threshold algorithm to detect and link edges.

Because the Canny Edge Detection algorithm is a quite well-known method in the machine vision field, the details of the method is omitted.

2.1.1 Cutter Edge Identification

Because of the imperfection of the cutter shape and run out due to the eccentric cutter clamping, it is difficult to find the accurate location of the cutter tip and the center line of the cutter, if the image is taken when the cutter is still.

Therefore, the images need to be taken while the cutter is rotating. However, taking image from the rotating cutter will have residual shadows existing in the image that will result in inaccurate edge identification. To resolve this problem,Power Law Method was used to enhance the contrast of the image so that the edges can be clearly differentiated. The basic equation of Power Law Method is

$$s = cr^{\gamma} \qquad (1)$$

Where c and γ are positive constants. Since large value of γ can map the high grey level pixels to a narrow output range, high value of γ is chosen to condense the residual shadows. Figure 3 shows the original image of a rotating cutter and the image with enhancement by Power Law method. It can be seen that the residual shadow effect has been improved.

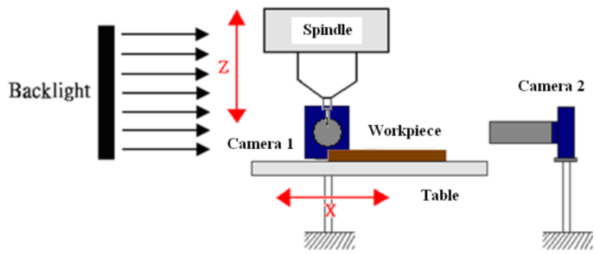

Fig. 2 Setup of measurement system

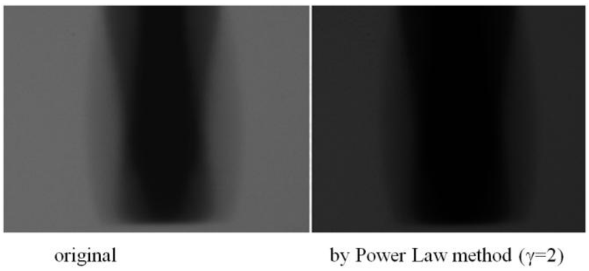

Fig. 3 Image of a rotating cutter

2.1.2 Workpiece Edge Detection

To determine the workpiece edge, the vertical and horizontal projections of the binary image are first conducted. The projection ($H[i]$) of row pixels and projection ($V[j]$) of column pixels equations can be expressed as

$$H[i] = \sum_{j=1}^{m} B[i,j] \quad ; \quad V[i,j] = \sum_{i=1}^{m} B[i,j] \qquad (2)$$

Where $B[i,j]$ is an image matrix. $H[i]$ and $V[j]$ are the pixel accumulation numbers.

Based on $H[i]$ and $V[j]$, the initial edge line is set at the location with the largest accumulation number. The neighboring edge pixels around the edge line are then searched. Finally the average location of all the searched pixels is set as the final edge line that represents the edge of the workpiece.

2.2 Determination of Positioning Error

When edges of cutter are detected, the cutter tip can be identified, and the centerline of the cutter can be calculated. As the workpiece edge is detected, the relative locations of the cutter and workpiece can be obtained as Fig. 4. As shown in the figure, the distance (ΔZ) from cutter tip to the edge line 2 is the z-dir. Positioning error, and the distance (ΔX) from center line of the cutter to the edge line 1 is the x-dir positioning error. Similarly, the positioning error (ΔY) is the distance from center line of the cutter to another horizontal edge line. Figure 5 shows the flowchart of the positioning error determination.

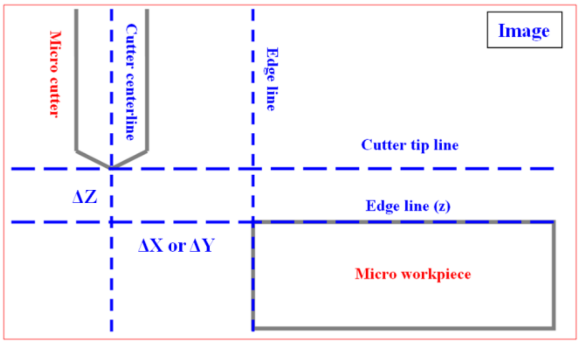

Fig. 4 Relative locations of the cutter and workpiece

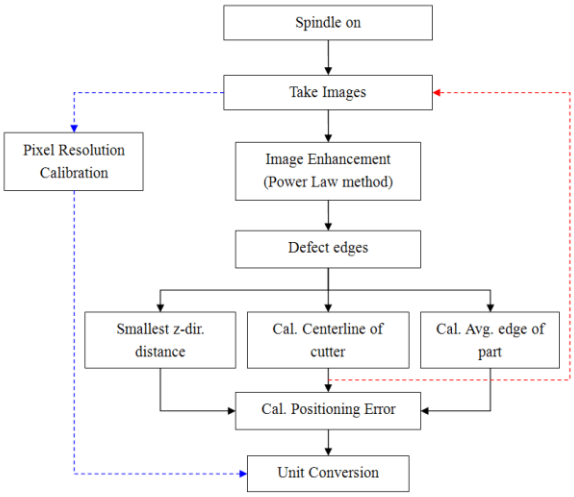

Fig. 5 Tool positioning error measurement flowchart

3. The NC-code Based Error Compensation Method

When positioning errors are determined, a NC program will be generated to move the micro cutter for the distance, X, Y and Z. The NC program is edited with respect to the local (machining) coordinate frame, and offsets the cutter before the machining starts. An auto NC-code editing system written by Matlab language was developed for automatically generating the NC program. To reduce the influence of the servo control error, the positioning errors compensation needs to be performed recursively till the positioning errors are within the defined tolerance. Figure 6 shows the error compensation process.

4. Experiments

Two experiments were conducted on a toggle-type micro machine tool. The measurement system with 2 cameras was installed on the machine as shown in Fig. 7. CMOS (U800C) with Telecentric 4X Lens was used for measurement.

4.1 Assessment of Measurement Accuracy

To assess the accuracy of the measurement system, the developed measurement system measure the micro movement of the micro machine, and the measurement results were compared to the measurement made by a laser measurement system. Movement of 10 μm was made each time, and each test has 10 movements. 4 tests were performed. Table 1 shows the experimental results.

It can be seen that the maximum error is 0.85μm and the root mean square of the measurement errors is 0.48μm. Because the pixel resolution of the camera is 0.44μm, the measurement error less than 2 pixels is quite reasonable.

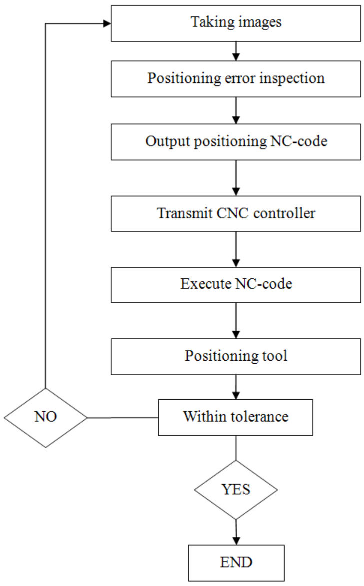

Fig. 6 Flowchart of auto-positioning

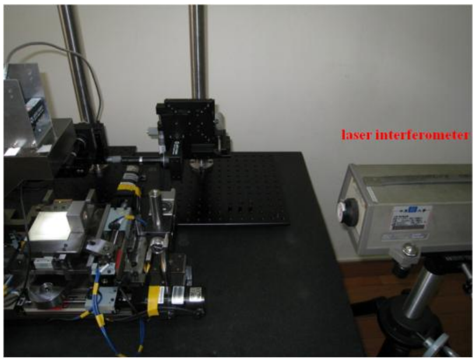

Fig. 7 Positioning accuracy assessment setup

4.2 Verification of Error Compensation

A 0.2mm-dia. Micro cutter was used to cut Graphite in this experiment. Cutting parameters are listed in Table 2. Nine 0.2mm-dia micro holes (Fig. 8) were machined. The location accuracy of the center of the first hole was checked.

In the experiment, the system measured the positioning error of thecutter, and generated a NC program to offset the cutter for precision machining. Table 3 shows the initial positioning errors of the cutter. The x-dir. Positioning error was -0.002mm, and the y-dir. Positioning error was -0.025 mm. After compensation, the y-dir. Positioning error was reduced to 0.001 mm. The total distance error (from the center of the hole to the machining origin) was reduced from -0.02mm to

-0.001mm. Figure 9 (a) shows the cutter deviated from the machining origin. The cutter was moved to the origin after error compensation (Fig. 9(b)). The machined workpiece was shown in Fig. 10.

Unit(μm)	1st		2nd		3rd		4th	
Laser	Vision	Error	Vision	Error	Vision	Error	Vision	Error
0	0	0	0	0	0	0	0	0
10	10.14	0.14	10.58	0.58	10.58	0.58	10.58	0.58
20	19.4	-0.6	19.4	-0.6	20.29	0.29	19.85	-0.15
30	29.55	-0.45	29.99	-0.01	29.99	-0.01	30.43	0.43
40	40.13	0.13	40.57	0.57	40.57	0.57	39.25	-0.75
50	49.39	-0.61	50.27	0.27	50.72	0.72	50.27	0.27
60	59.54	-0.47	59.54	-0.47	60.86	0.86	60.86	0.86
70	70.12	0.12	70.56	0.56	70.56	0.56	70.12	0.12
80	79.38	-0.62	79.82	-0.18	80.7	0.7	80.26	0.26
90	89.52	-0.48	89.96	-0.04	90.85	0.85	90.41	0.41
100	99.23	-0.78	100.11	0.11	100.55	0.55	100.55	0.55
R.M.S			0.48μm					
Max.			0.85μm					

Table 1 Experimental results

Machine: Toggle-Micro Machine tool

Cutter dia.: 0.1 *mm*

Feedrate: 100 *mm/min*

Spindle speed: *150,000* r.p.m.

Material:Graphite

	Pixel resolution	Canny edge parameter: T1/σ
Camera1	441 *nm/pixel*	0.5 / 10
Camera2	441 *nm/pixel*	0.5 / 10

Table 2 Experiment conditions

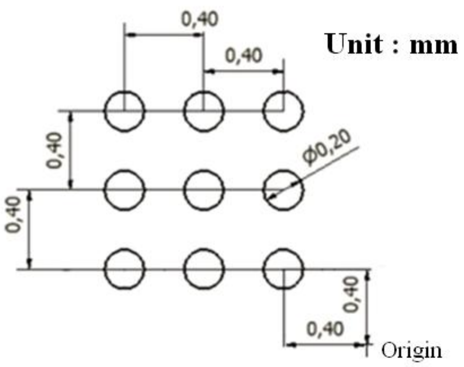

Fig. 8 Micro machining drawing

5. Conclusions

Utilizing machine vision technology and NC code based error compensation technology, an on-machine micro tool positioning error measurement and compensation system was developed. In the measurement method, was first used to enhance the image taken by a CCD. Canny Edge Method, image projection method and Power Law Method were integrated to ensure the accurate measurement. In addition, an auto NC-code editing system was developed for auto error compensation. The experimental results have shown that the positioning error can be improved by 95%.

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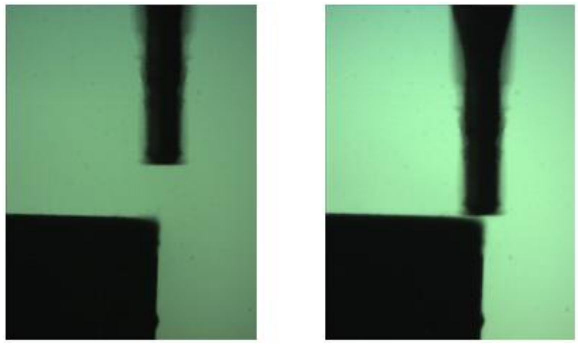

Fig. 9 Images of micro cutter positioning in y-dir. And z-dir.

Fig. 10 The micro machined workpiece

	x-dir. (mm)	*y*-dir. (mm)	From orign (mm)
Theo. dist	0.4	0.4	0.565685
Act.dist	0.398255	0.374861	0.546925
Error	-0.001745	-0.025139	-0.018759

Table 3 Non-compensated positioning

	x-dir. (mm)	*y*-dir. (mm)	From orign (mm)
Theo. dist	0.4	0.4	0.565685
Act.dist	0.397935	0.401265	0.565124
Error	-0.002065	0.001265	-0.000561

Table 4 Compensated positioning

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