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VISION-BASED MEASUREMENT OF TWO-DIMENSIONAL POSITION ERRORS OF A MACHINE TOOL

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ABSTRACT

This research presents vision-based measurement of two-dimensional positioning errors of machine tools. In experiment, we attach a charge coupled device (CCD) camera to a spindle to view an artifact of the known form accuracy. The edge in the vision is detected by using the Sobel operator and the position of the camera with respect to the artifact is measured from it. In this paper, we use a grid evaporated on a glass plate as an artifact to measure straightness and squareness of the drive system. For comparison, we measure them with an eddy-current displacement sensor and a square edge. By using this measurement result, we evaluate the accuracy of this vision-based measurement.

1. INTRODUCTION

To improve the motion accuracy of positioning system, it is crucial to first measure it in an accurate, efficient manner. To measure straightness and squareness of drive system of machine tools, a measurement reference (for example, straight edge or square edge) and a displacement sensor are usually used. To measure the positioning accuracy for arbitrary reference points or trajectories, a cross grid encoder is often used. A cross grid encoder [1], or a two-dimensional digital scale, is a measurement device which uses a grid as a measurement reference to measure the position in two-dimensional orthogonal coordinate system by using the diffraction of light. It is commercially available from a couple of companies, including Dr. Johannes Heidenhain GmbH. Although it is accepted by many machine tool builders for the inspection of feed drive's motion accuracy, it has following inherent issues.

1. The gap between the grid plate and the measuring head must be set sufficiently small (for example, Heidenhain recommends to set the gap less than about 0.5 mm). The setup must be, therefore, done very carefully by an experienced operator.
2. We must accurately align the direction of the grid plate and head in order to obtain valid signal. It often requires significant setup time. Furthermore, we cannot use it when the head rotates with respect to grid plate; for example, a cross grid encoder cannot be used to measure the angular positioning accuracy of a rotary table.
3. It is extremely difficult to calibrate the measurement accuracy of cross grid encoder. To do so, geometric error of each grid line must be calibrated by comparison with the two dimensional position reference, which is in practice very difficult.
4. It is difficult to make large grid plate with accuracy (in case of Heidenhain's ones, the largest grid size is ϕ230).

Nowadays, many vision-based measurement systems are available in a variety of industries, due to technological advances in commercializing cameras of higher performance with lower cost. In fact, there are many on-machine measurement systems to measure the geometry of a part with visions. The objective of this paper is to present a vision-based measurement system of two-dimensional positioning errors of machine tools. The position of a spindle in relative to work table is measured by using a charge coupled device (CCD) camera attached to the spindle, viewing an artifact of the known form accuracy, identifying an edge in vision. Figure 1 illustrates experimental setup.

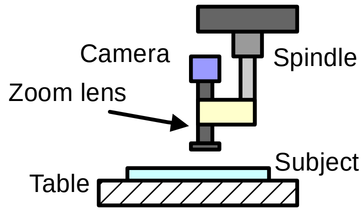


Figure 1: Experimental setup

Compared to a cross grid encoder, a vision-based measurement system has following potential advantages.

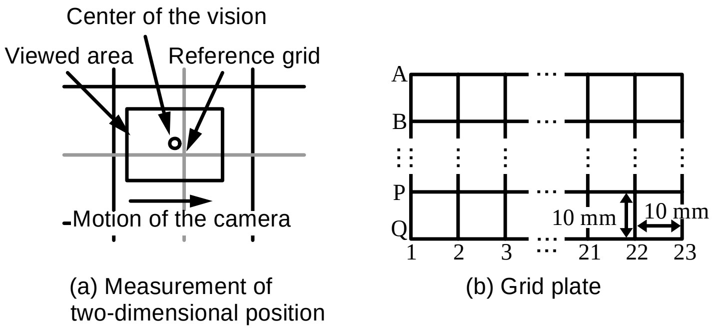
1. The distance between camera and object can be, depending on working distance of the lens, several tens of millimeters, which significantly facilitates the setup procedure.
2. The measurement can be performed even when the camera rotates with respect to the object. Consequently, the angular position of the artifact can be measured.
3. In this measurement system, the artifact can be selected arbitrarily, and it is relatively easy to calibrate the form accuracy of the artifact.

In this paper, we show at first a definition of an edge and a scheme to measure the camera position from edge locations. Then, the two experiments are presented. The experiment 1 shows identification of an edge in vision under small motion for the distance smaller than one pixel size. The experiment 2 shows the measurement of two-dimensional position errors of machine tools.

2. MEASUREMENT SYSTEM

2.1. VISION-BASED MEASUREMENT OF POSITION

In measurement of two-dimensional position, we view a grid, as shown in Fig.2 (a), which is composed of horizontal and vertical lines with certain distance. We define the coordinate system as follows: the horizontal line is X axis, the vertical line is Y axis, and the intersection point is the coordinate origin in vision. We calculate the position of the certain point (for example, a center of the vision) as the two-dimensional position of camera. Fig.2 (b) illustrates the grid plate used in experiments presented in this paper.



(a) Measurement of two-dimensional position (b) Grid plate

Figure 2:Measurement of one-dimensional and two dimensional position of the camera by using reference grid

2.2. DEFINITION AND IDENTIFICATION OF EDGE

On a certain line in a captured image, the location of the pixel where the first derivative of its brightness is locally maximized is defined as an edge point. An edge point is searched on all lines over the entire image. A set of edge points is defined as an edge.

We calculate the first derivative of pixel brightness in horizontal and vertical directions by using the Sobel operator and combine them to calculate the edge intensity [2].

To identify the edge location in a resolution smaller than the pixel size, the edge intensity is computed at each pixel, and its local maximum is found by interpolating it in a resolution of one tenth of pixel size. The detailed description of the algorithm of sub-pixel edge recognition is presented in [2] and omitted in this page.

3. MEASUREMENT OF ONE DIMENSIONAL POSITION BY USING EDGE

3.1. EXPERIMENT 1: MEASUREMENT OF POSITION IN A RESOLUTION SMALLER THAN THE PIXEL SIZE

The work table is moved for a distance smaller than camera's pixel size, and then its displacement is measured by using edge identification. A square edge (its straightness and squareness errors are smaller than 1μm in all sides) is fixed on the table of a machine tool, and it is positioned for every 1 μm step toward the X direction for six times (total 6 μm). Its position is statically measured by vision. Fig. 3 illustrates the setup. The specification of experimental devices is shown in Tables 1 to 3.

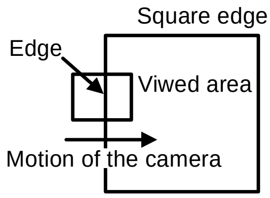


Figure 3: Procedure of experiment 1

Table 1 Specifications of machine tool

Travel	X：610 mm Y：510 mm Z：460 mm
Drive type	Servo motor ＋ Ball screw
Guide way	Roller guideway
Positioning resolution (X, Y, Z)	1 μm

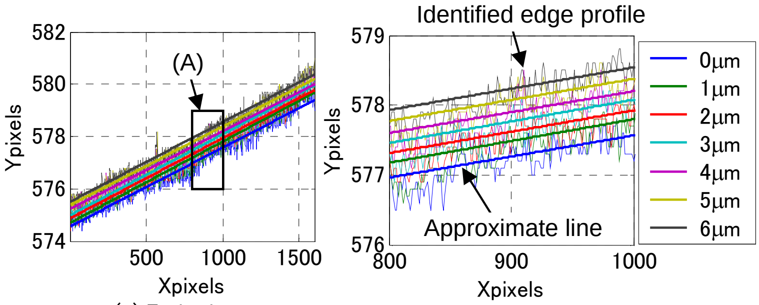
Table 2 Specifications of lens

Magnification	0.75 ×～4.5 ×
Working distance	90 mm
Resolution	11.6 μm～4.9 μm

Table 3 Specifications of camera

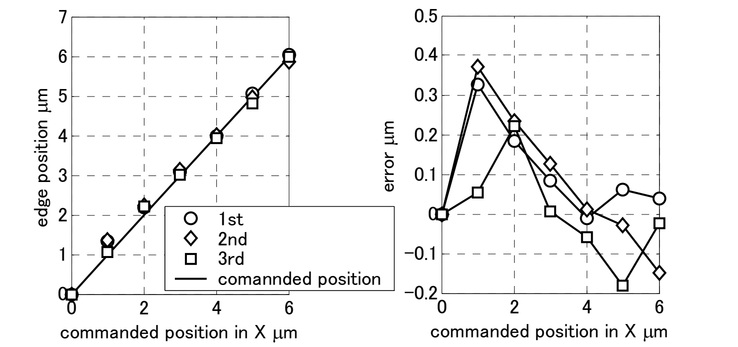
Sensor type	CCD (black-and-white)
Number of valid pixels	1628(H)×1236(V) (About two million pixels)
Area of valid pixels	7.16 mm(H)×5.40 mm(V)
Pixel size	4.4 μm(H)×4.4 μm(V)

Figure 4 shows edges identified from visions and approximate lines by least square fit. In this experiment, one pixel approximately corresponds to the area 6.6 μm×6.6 μm (pixel size of camera, multiplied by magnification by lens (1/0.75)). This means that, to recognize the motion for the distance 1 μm, the edge location must be identified in resolution of about 1/6 of the pixel size. Figure 5 shows measured displacement in X by vision under motion toward X direction (under 1 μm step motion). Edge positions are defined as the average value of identified edge positions in the feed direction. In Fig.5 (b), the average difference of commanded position and edge position is smaller than 0.4 μm. This suggests that the measurement resolution of 1 μm is secured with the uncertainly less than 0.4 μm by using sub-pixel edge recognition.



(a) Entire image (b) Magnified in the region (A)

Figure 4: Edges identified from visions under 1μm step motion toward X. (straight lines indicate approximate line by least square fit)



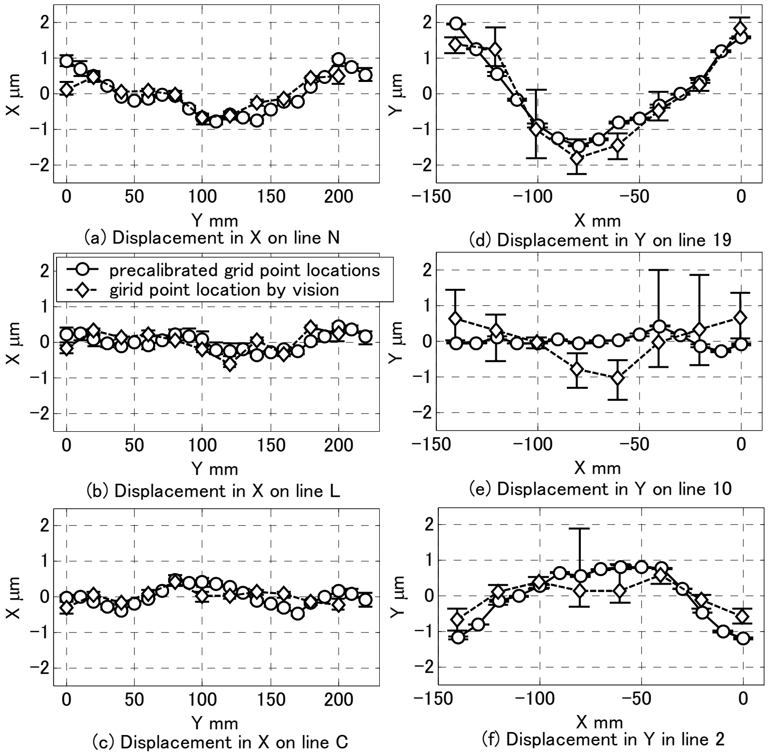
(a) Commanded position and edge position (b) Difference between commanded position and edge position in (a)

Figure 5: Measured displacement in X by vision under motion toward X direction (under 1 μm step motion)

3.2. MEASUREMENT OF TWO-DIMENSIONAL POSITION ERRORS

We measure two-dimensional positioning errors of a machine tool at a set of given reference locations by viewing a grid of the known form accuracy. For comparison, we measure them with an eddy-current sensor and a square edge. Figure 2 (b) illustrates the grid plate used in experiment. This grid plate is a glass plate on which the grid pattern is produced by vacuum-depositing chrome. Each line width is about 8 μm. In the experimental setup, lines A, B, … Q are aligned in X axis of drive system and lines 1, 2, … 23 are aligned in Y axis. Then we view grid points on a certain line at 20 mm intervals with stopping the drive system by using the CCD camera attached to the spindle. In this experiment, the camera captured an image at every point on lines N, L, C, 19, 10, and 2. Measurement was conducted five times per one line. The straightness and squareness errors of the grid itself are corrected as follows: the position of each grid point is calibrated by using a vision-based coordinate measuring machine of the calibrated measurement uncertainty, Smart scope VANTAGA 600 by ODP, and it is used as reference location.

Figure 6 compares the measured grid point location by vision on the experimental machine tool (○ marks) and pre-calibrated grid point locations (◇ marks). In Fig.6, the coordinate system is defined to make the average of the displacement zero. ○ and ◇ marks represent the average value at each commanded position and error bars (⌶) represent the variation in five measurements. The difference in measured and calibrated grid point locations represents the positioning error of the experimental machine tool.



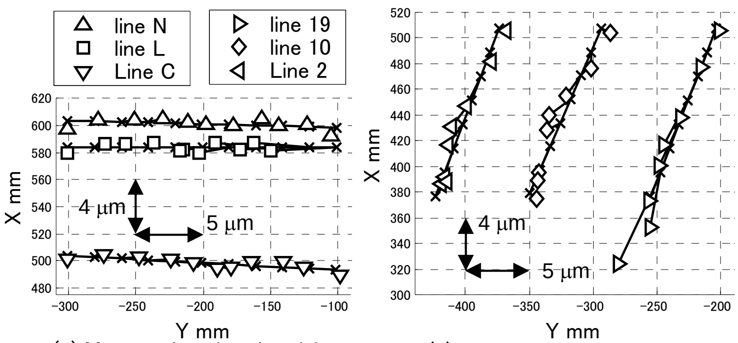
(a) Displacement in X on line N (d) Displacement in Y on line 19

(b) Displacement in X on line L (e) Displacement in Y on line 10

(c) Displacement in X on line C (f) Displacement in Y in line 2

Figure 6: Measured and pre-calibrated of grid position

By comparing measured and calibrated grid positions, the machine's two-dimensional positioning error for each reference location of grid point is given as shown in Fig.7. Errors are magnified by a factor 10,000 in Fig.7. Both coordinate systems are defined to make average the approximate line of the displacement measured by viewing along line L horizontal. × marks represent reference locations.



(a) Measured positon by vision (Feed toward Y) (b) Measured positon by vision (Feed toward X)

Figure 7: Errors map (Errors are magnified by 10,000)

Figure 8 shows comparison of measured displacements in X by vision and those measured using a displacement sensor and a square edge when driving toward the Y direction (corresponding to Line L in Fig.7 (a)). Note that the coordinate system is defined such that the mean of displacement in X on this line (L) becomes zero. The difference is, in driving toward Y, 1.0 μm in average and 2.6 μm in maximum.

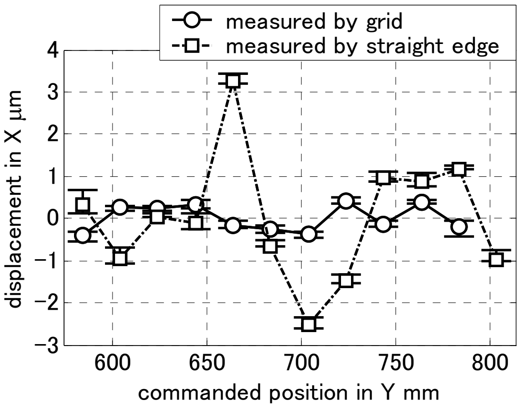


Figure 8: Measured displacement in the direction normal to the feed direction (straightness error)

Figure 9 shows measured displacement in Y under the motion toward X direction. Figure 9 (b) shows the displacement in the Y direction when the table moves in the X direction on the line 19, measured by vision. Figure 9 (c) and (d) similarly show the displacement measured by vision on lines 10 and 2. Only on Line 19, the positioning displacement in Y direction is measured by using a displacement sensor and a square edge for comparison. The approximate lines in this figure represent squareness errors of X and Y axes of the machine to be measured. The value of squareness errors are -5.9 μm / 140 mm (viewed along line 19), -6.5 μm / 140 mm (along line 10), -5.7 μm / 140 mm (along line 2). In Fig.9 (a) shows the displacement in the Y direction when the table moves in the X direction on the line 19 measured by using a displacement sensor and a square edge. Comparing Fig. 9 (a) and (b), the deference between the measurement along line 19 and with a displacement sensor is 0.3 μm / 140 mm.

4. CONCLUSIONS

The first experiment shows that it is possible to measure 1 μm displacement in resolution of smaller than one pixel by detecting edge and measuring one-dimensional position. The comparison in squareness and straightness measurements clarifies that the deference between these two measurements is smaller than 3 μm / 140 mm in straightness and 0.3 μm / 140 mm in squareness.

ACKNOWLEDGEMENT

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[1] Sangyo Gjutsu Service Center, 2008 “Encyclopedia of precise positioning technology”, pp.558, (in Japanese)
[2] LinX Corporation, 2004 “Quality use of HALCON” pp.76 (in Japanese)

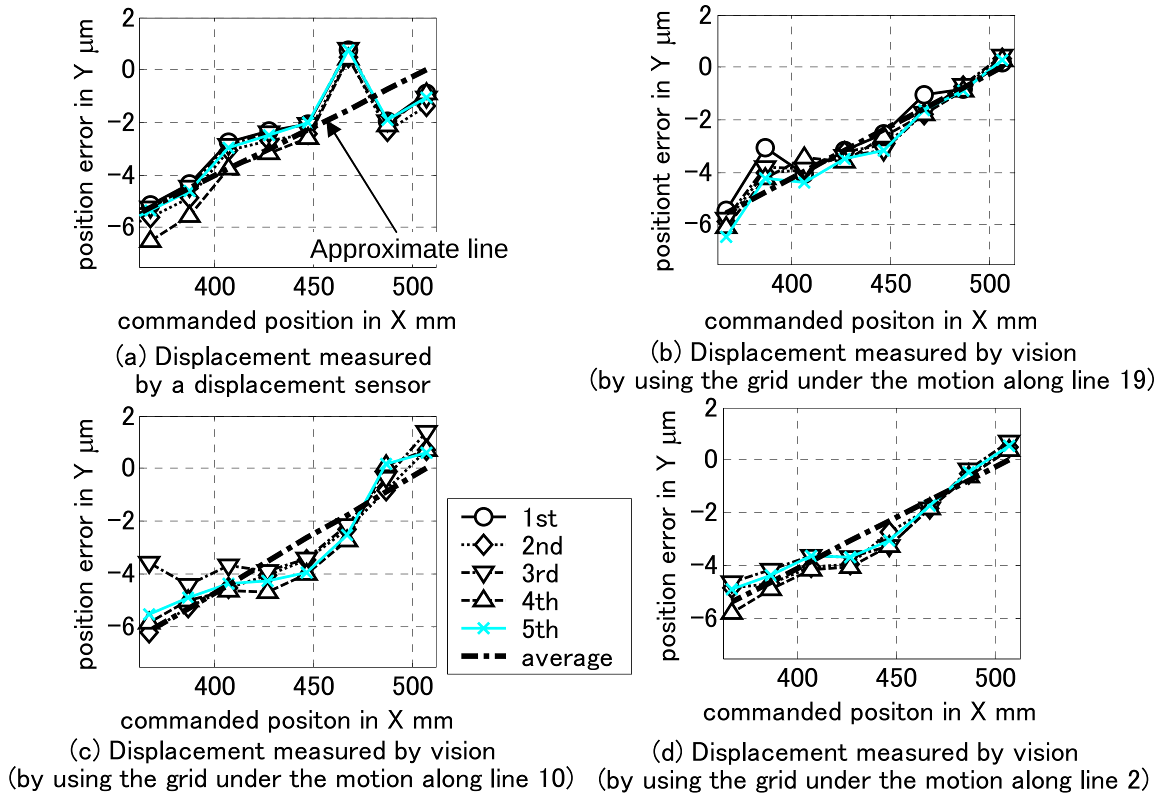

Fig. 9: Measured displacement in Y under the motion toward X direction (squareness error)