High-precision Profile Projection System for On-machine Measurement of Workpiece Dimension

Takanori Yazawa[1], Kohei Hirota[2], Tatsuki Otsubo[3], Yukio Maeda[3], Yasuhiko OUGIYA[1], Tatsuhiro Kojima[1], Reiko Yamada[1]

[1]Division of System Science, Nagasaki University, Japan

[2]Graduate School of Science and Technology, Nagasaki University, (Now in Waida Mfg, Co.,Ltd.), Japan

[3]Depertment of Intelligent Systems Design Engineering, Toyama Prefectural University, Japan

E-mail: yazawa@nagasaki-u.ac.jp

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Abstract

In this research, a high-precision profile projection system for an On-machine measurement of workpiece dimension is proposed and investigated. Two methods, an APM and a parts projection method, are shown. The APM is used by spatial filtering and minimizes the effects of the image processing. The parts projection method measures the object size or workpiece dimension unaffected by their size. After the description of their principles, an optical design process for measurement system is shown and evaluation of this system is carried out. Finally, this is applied to measurement for rotation error of square end mill.

Keywords: Profile Projection, Parts Projection, Spatial Filtering, On-machine Measurement

1 INTRODUCTION

A profile projector accurately magnifies and projects a workpiece onto a screen, so that, in combination with a precision stage (or a precision scale) and image processing, the shape of the workpiece can be not only observed, but also measured. The measurement accuracy depends on the detection accuracy of the workpiece edge, the boundary between the workpiece shadow and the light on the screen. Now, the measurement accuracy without complicated image processing is about several microns.

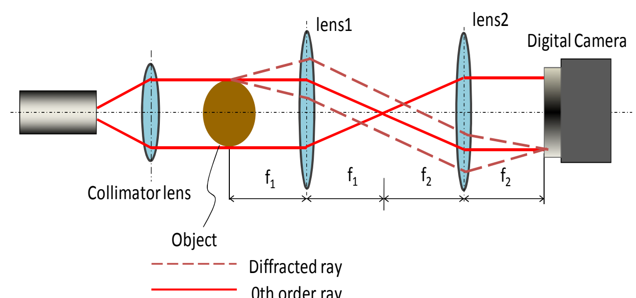
In a previous research [1][2], the authors proposed a new system for profile projection with sub-micron's accuracy using a spatial filtering system called the anti-pinhole method (APM). This is shown that the APM system has been shown to be independent of light intensity when projecting an object.

In this paper, the APM system is extended for on-machine measurement of workpiece dimension. The measurement resolution of workpiece dimension using this projection system is generally dependent on the tool diameter. Therefore, the authors propose to extract both side edges of a workpiece and to project them on a CCD camera. The principle and experimental results are described below.

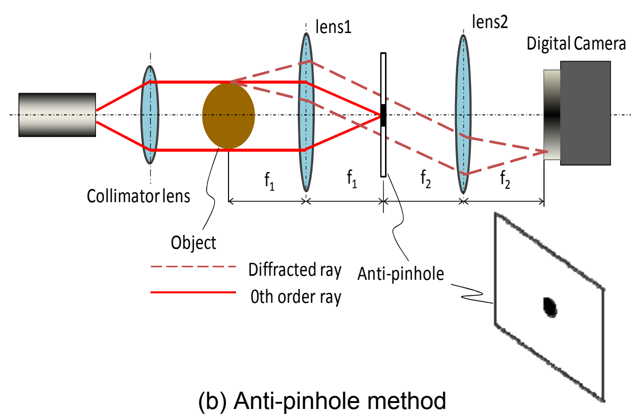
2 PRINCIPLE AND BASIC RESEARCH OF MEASUREMENT SYSTEMS

2.1 High-precision Edge Projection System using Spatial Filtering

Fig. 1 shows a comparison of projection systems using lasers, with (a) is the conventional method and (b) is the APM system. With the combination of two lenses on the right side of the object, the projecting magnification can be changed. The gradient of brightness near the boundary is the main cause of deteriorating accuracy in a general projector. The smaller the gradient, the wider is the boundary area between shadow and light. The width of the boundary area corresponds to the resolution of the edge detection on the screen. Edge detection is affected by the unevenness in the brightness of light on the digital camera, caused by interference from the diffracted ray generated at the object edge and through the ray, (i.e., 0th-order ray), near the object edge. In the APM, the 0th-order ray is only cut by a spatial filter through high frequency, called an anti- pinhole, at the Fourier transform



(a) Conventional projection system



(b) Anti-pinhole method

Figure 1: Comparison of edge projection system using laser.

plane. The action of lens 1 is Fourier transform of the rays. The diffracted ray without the 0th order through the anti-pinhole goes through the reverse Fourier transform lens (lens 2), and focuses on the screen. Therefore, the gradient of brightness is enlarged. Here, note that the Fourier transform lens also works as a low -pass filter because its diameter is finite. Table 1 compares projection images with and without anti-pinhole.

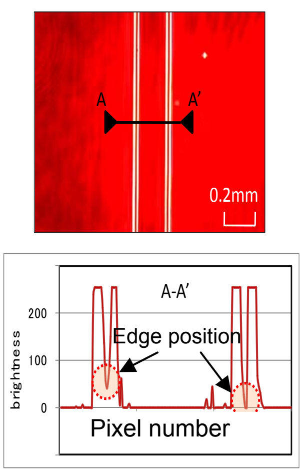
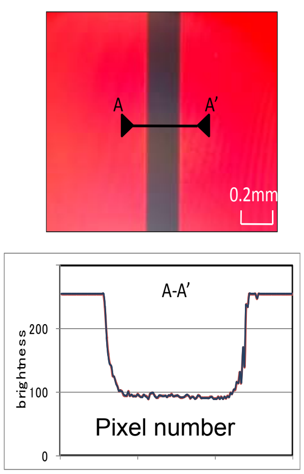
Some simulations and experiments are carried out confirming the effectiveness of this system based on the aforementioned principle. Their results show that

1) The edge position on the screen coincides with the position of minimum brightness (drawn in table 1) .
2) The projection accuracy is under the pixel size of the CCD camera used with the screen.
3) At about 500 times projection, the difference in edge position is less than or equal to sub-micron without image processing.

2.2 Parts Projection Method for Size Measurement

In this paper, the APM system is extended for on-machine measurement of workpiece dimension. Fig. 2 and Table 2 show the principle of the extended APM system. In the conventional method of image projection, measurement resolution is dependent on the object size. Therefore, an optical prisms system is included in the optical system to adapt to the changing object size, as shown in Fig. 2.

Table 1: Comparison pin-gage image with / without anti-pinhole.

With anti-pinhole	Without anti-pinhole
	

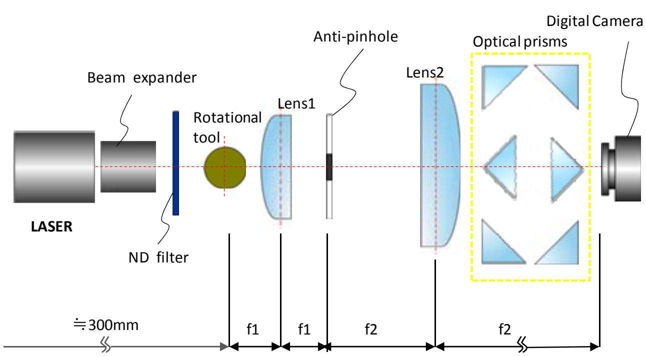


Figure 2: Configuration of optical system (Top View).

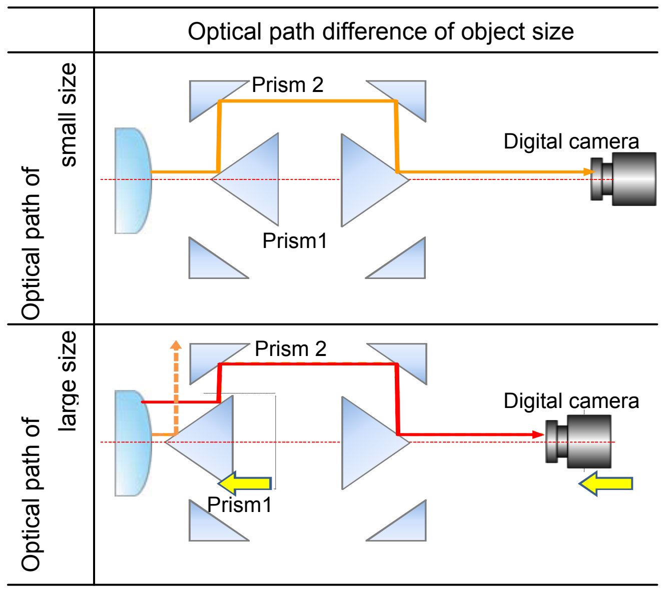
Table 2 shows the principle of the parts projection system. In the case of one -to -one projection, if the object is smaller than the imaging element, the image of the object edges is focused on the image area of the digital camera. However, if the object is larger than the imaging element, the object edges cannot be in focus. Hence, at each position, prism 1 and the digital camera move the same distance toward lens 2. Because the paraxial rays do not arrive at prism 2, the central area of the object is not focused on, but the image of the object edges is in focus. Hence, the distance between the object edges is unaffected by the size of the object. In other words, this system can project the object edges at high magnification and can measure the workpiece dimension at high precision.

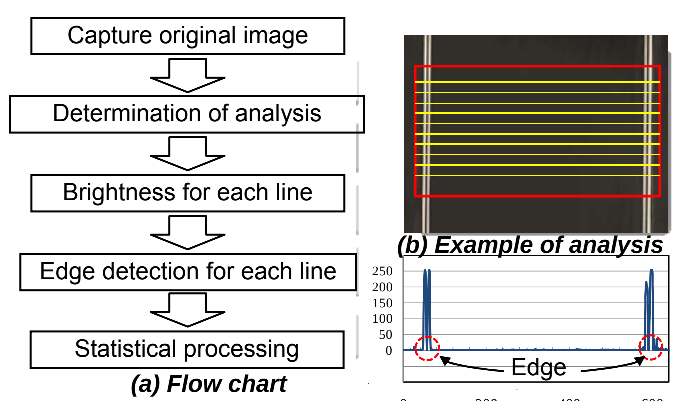
2.3 Image Processing Flow

Image processing flow is shown in Fig. 3. First, the analysis area is determined after capturing to the original image. Second, the brightness is analyzed for each line and the edges are detected by a sub-pixel process, as shown in Fig.4. The steps to define each edge in this process are as follows:.

1) Choose three threshold lines.

Table 2: Principle of parts projection method





(a) Flow chart *(b) Example of analysis* *(c)Example line data of*

Figure3: Image processing flow

2) Determine six intersection points.

3) Calculate two lines by least squares using each three points.

4) The intersection of two lines is an edge position.

Finally, statistical processing is performed on all edge position data.

3 OPTICAL DESIGN AND EXPERIMENTAL CONDITIONS

Requirements for a prototypical optical system were established as follows for on-machine measurement:

1) The optical path length is less than 1 m.

2) The measuring object diameter is 0.2-2.0 mm.

3) The measurement resolution for the 2.0-mm-diameter object is less than or equals to 1 µm.

The measurement resolution is determined by Eq. (1) and the measurable object size is calculated by Eq. (2):

$$R = D_p / M \quad (1)$$

$$D_I > Md \quad (2)$$

where R is resolution, D_p is pixel size of the digital camera, M is magnification of the lenses, and D_I is imaging area size of the digital camera and d is diameter of the object. D_p and D_I are dependent on the digital camera used. Fig.5 shows the relationship between magnification, resolution, and measurable object size with the digital camera used, whose specifications are shown in Table 3 (D_p = 2.8 mm and D_I = 3.58 mm). It has been determined that magnification should be larger than 2.4 times to satisfy the requirement. The magnification was selected as to 5 times considering the margin of resolution and the easy combination of lenses. Because this figure also shows that the measurable object size is less than 1 mm, it is necessary to determine the minimum size and minimum movement of the prism. The relationship between minimum prism size and object size is determined by Eq.(3), and the relationship between the minimum prism movement and the object determined by Eq.(4):.

$$L_p > (1/2)^{1/2} Md \quad (3)$$

$$X_p = (1/2)^{1/2} L_p \quad (4)$$

where L_p is the minimum prism size and X_p is the minimum distance the prism is moved. Fig. 6 shows the effect of object size on prism size, and Fig. 7 shows the effect of object size on the distance of prism movement. These results show that the minimum prism size is 7.07 and the minimum distance the prism is moved is 5.0 for 5 times magnification and a 2.0-mm-diameter object. Hence, a 25 mm size prism and a 13 mm travel stage for moving the prism were used. Other experimental conditions are shown in Table 3.

4 EVALUATION OF THE PROJECTION SYSTEM

The influence of the threshold level on edge distance without special image processing, (e.g., edge extraction processing,) is shown in Fig. 8. The figure reveals that

1) In the conventional method (without anti-pinhole), the edge distance is strongly dependent on threshold.

2) In the proposed method (with anti-pinhole), the edge distance is constant.

A serious issue is that small changes in threshold affect changes in edge distance for on-machine measurements. Because the threshold level mainly causes a gradient of brightness near the boundary between light and shadow

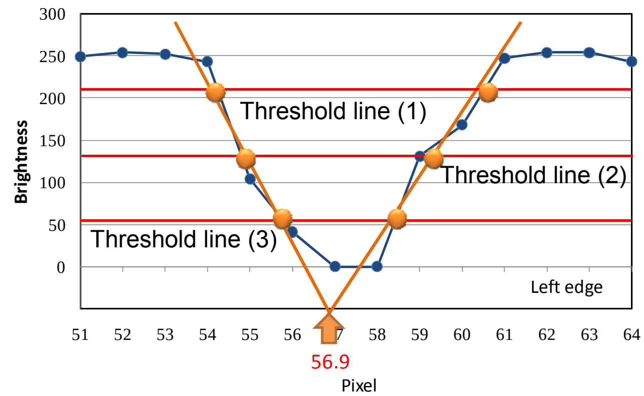


Figure 4: Example of edge detection process

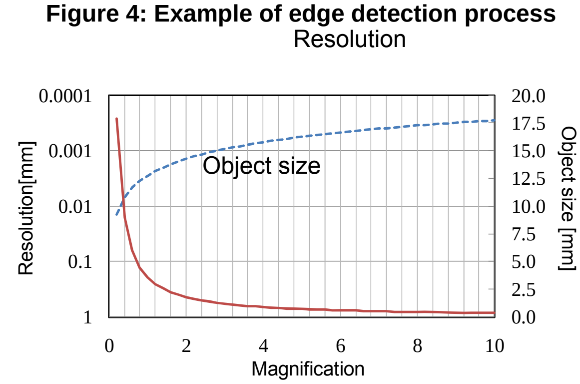


Figure 5: Relationship between magnification, resolution, and measurable object size

Table 3 Experimental conditions

Light source (He-Ne Laser)	Beam diameter [mm]	ϕ1.1
	Wave length [nm]	632.8
	Power [mW]	10
Beam Splitter	Size [mm]	ϕ 17
Filter	ND [%]	0.01 - 50
Workpiece	Pingage [mm]	ϕ0.3-30
Lens1	Concave [mm]	D=20, f=20,60
Lens2	Concave[mm]	D=50, f=300
Prism	Size [mm]	a=b=c=30
Knife-edge-prism	Size[mm]	a=b=c=35
Digital camera (E!Kit-CAM-USB)	Image sensor	1/4"CMOSColor
	Connection method	USB2.0
	Resolution (H) x (V)	1024 x1280
	Pixel size [µm]	2.8 x 2.8
Stage	Max storke[mm]	13

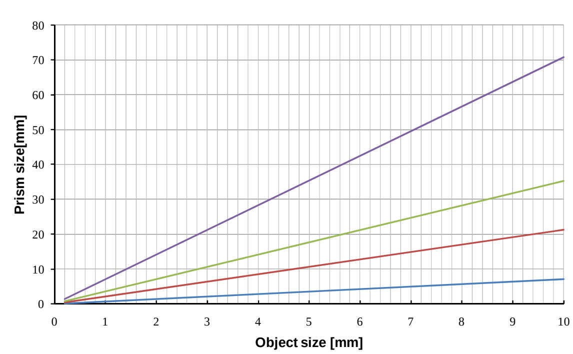


Figure 6: Effect of object size on prism size

on the digital camera, these results show the effectiveness of the proposed method, (i.e., the APM).

Fig. 9 shows the relationship between pin-gage size and measurement resolution, and reveals that

1) In the conventional method, resolution is dependent on pin-gage size.

2) In the proposed method, resolution is independent of pin-gage size.

The numbers in the figure are maximum magnifications of the optical system for measuring the pin-gage size, (i.e., object size). Therefore, a 3.0mm object can be measured to 0.4μm accuracy by combining the anti-pinhole method and the parts projection method. These results show that measurement resolution can be maintained by using the parts projection system. The parts projection method is proposed and its effectiveness is confirmed.

Fig.10 shows the influence of prism size and object size on limiting measurable resolution. From this figure, the minimum prism size can be easily determined from the object size and the required measurement resolution. For example, if the object size is 10mm and the required measurement resolution is 1μm, then the minimum prism size L_p is 20mm.

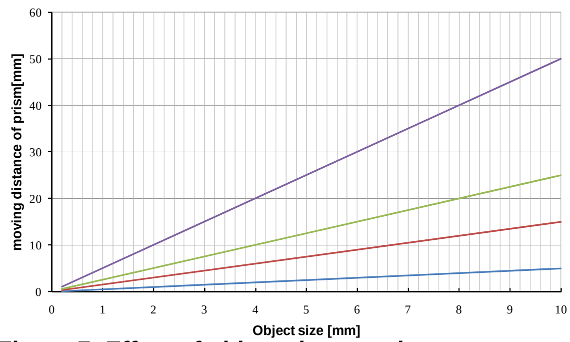


Figure 7: Effect of object size on prism movement

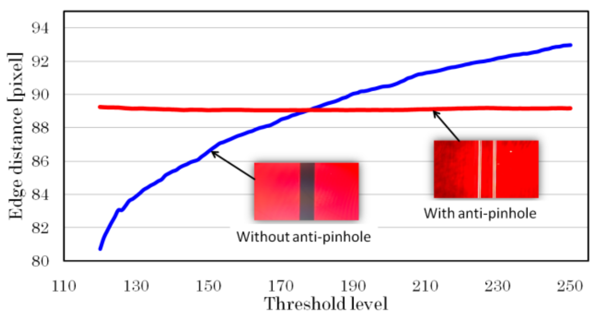


Figure 8: Influence of threshold level on edge distance

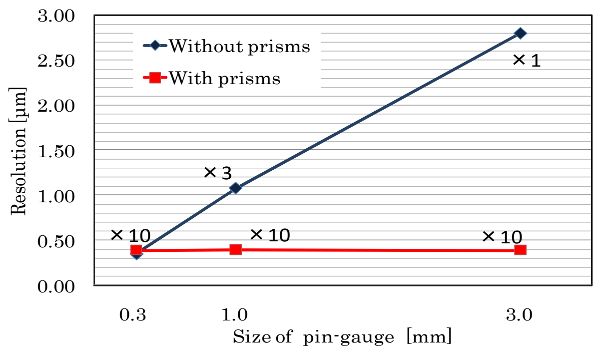


Figure 9: Comparison of resolution

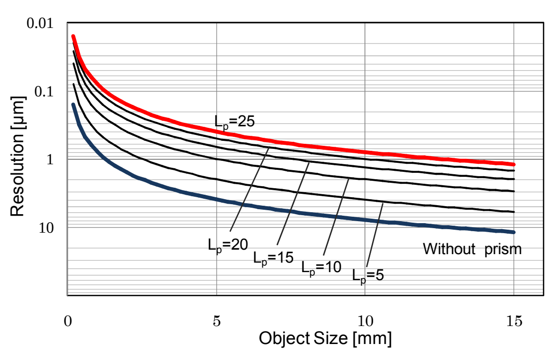
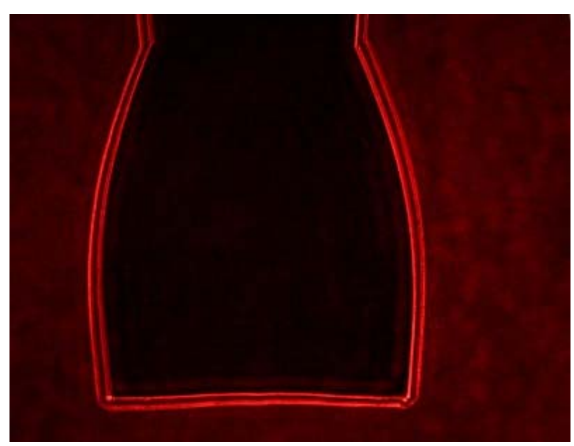


Figure 10: Resolution and size range of prisms

5 EXAMPLE OF MEASUREMENT FOR ROTATION ERROR OF END MILL

The prototype system was used to measure the quasi-static rotational error of a tool. The rotation tool was a square end mill of 2mm diameter, as shown in Fig.11 (a). Fig.11 (b) shows an example of a projection image of the end mill. In the figure, the black line, which is at minimum

(a) Square endmill image (ϕ = 2.0 mm)



(b) Edge projection image using APS

Figure 11: Image of square endmill and projection image of endmill

brightness and appears as the feature in the APM image, can be observed along the entire tool edge. Two images shifted by 180 degrees are captured, as shown in Fig. 12. Feature points (dotted circles in the figure) are extracted from each picture. The tool axis is calculated from them, and the axis gap ΔX is visible from the line passing through the image center and parallel to the tool axis in each picture. Rotational error Δ is calculated from ΔX_0 and ΔX_{180}., that is, Δ = 957 μm in this figure.

6 CONCLUSIONS

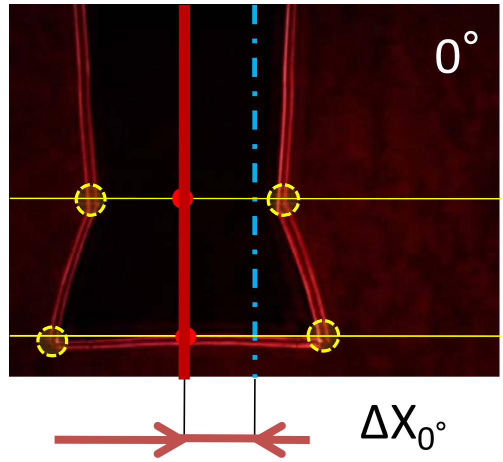
The aim of this research was to build a high-precision profile projection system for on-machine measurement of workpiece dimension. In summary,

1) The parts projection method was proposed and its effectiveness was confirmed.

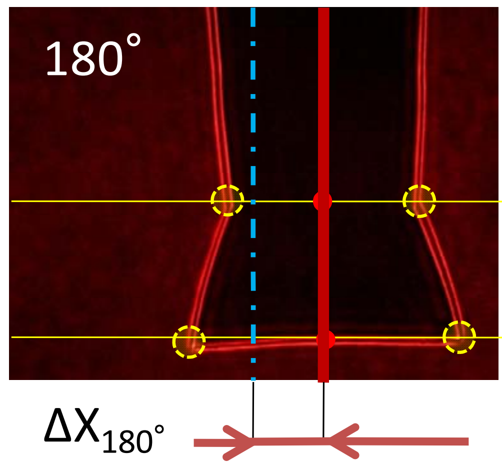
2) The dimension of a 3.0mm object was measured to an accuracy of 0.4μm by combining the anti-pinhole method and the parts projection method.

3) The relationship between the minimum prism size and limits on measurable resolution for a particular object size was clarified, and guidelines for optical design were established.

4) This method was adapted for the measurement of workpiece dimension, and its effectiveness was confirmed.



(a) 0 dgree image of endmill



(b) 180 dgree image of endmill

Figure 12: Measurement of eccentricity for endmill using APS

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