Special Feature: Nondestructive Testing and Evaluation Technology

Research Report

Three-dimensional Measuring Method for a Circular Hole

Toshihiko Tsukada, Keiichi Watanabe, Mitsuo Koide, Masahide Hirose, Yohei Horie and Yasunori Yamagishi

Report received on Nov. 8, 2013

ABSTRACT This paper describes a novel three-dimensional (3D) position measuring method for a circular hole in an object. In an automobile production process, circular holes are widely used as reference points for assembling the bodies and various parts of an automobile. In order to acquire information of the 3D position of the circular hole, we developed a method that measures the coordinates of four feature points on the circumference of the circular hole using the triangulation method. In this method, the feature points are extracted with high accuracy by combining two images that have a feature point near the circular hole. As a result, a measurement accuracy of ±0.05 mm or less (working distance: 200 mm) was obtained during our experiment. Moreover, it was confirmed that the developed sensor can be applied to the automobile assembly process.

KEYWORDS 3D Position Measurement, Circular Hole, Automobile Production Process, Triangulation Method

1. Introduction

In the automobile production process, numerous measurements and inspections are carried out to produce a high quality car. In particular, the precision of fitting the bodies and parts influence the appearance, quality, and size of the finished car. Therefore, circular holes are widely applied as reference points during assembly. Moreover, the information of the three-dimensional (3D) position of each circular hole is very useful when evaluating the ability of the production process. For these reasons, a technique that measures the 3D position of such circular holes is required.

Numerous methods have been developed to measure the 3D position of certain objects during the production process, such as the stereo camera method[1,2] and the light-section method.[3-5] However, problems arise when these methods are applied to the measurement of the 3D position of a circular hole during the production process. For example, since the stereo method is affected by the brightness variations of ambient light, the lighting of the environment needs to be controlled during the production process. On the other hand, the light-section method is less susceptible to the effect of the brightness variations of ambient light. However, since the method only uses the shape information of the projected light of a slit, as compared to the stereo method, the exact extraction of a feature point is more difficult.

Therefore, feature points were extracted from an image that was a combination of a light-section image and a two-dimensional image that contained the features of the circular hole, and a method was developed to measure the 3D coordinates.[6] This method utilizes a sensor that is simply composed of a TV camera, a white light source, and two laser slit light sources.

2. Principle of the Measurement Method

Figure 1 shows an example of the circular holes that exist in an automotive part. Circular holes are widely

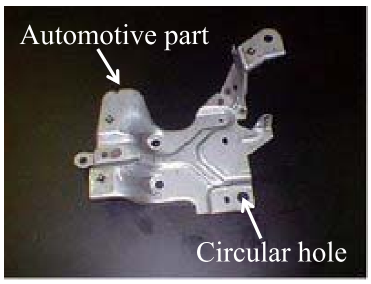

Fig. 1 Example of circular holes.

used for the assembly process and are also sometimes used as reference points. The purpose of this study is to automatically measure the 3D coordinates of such reference points. The circumference of such a circular hole may become tapered, and errors arise due to such tapering when using conventional 3D measurement technology. For this reason, we developed a novel measurement method as a practical solution to the problem mentioned above.

Figure 2 shows a schematic diagram of the proposed sensor. The sensor head is composed of a TV camera, two laser slit light sources, and a white light source located at the slanting upper area of the TV camera. The 3D coordinates of the circular hole can be measured by triangulation of the TV camera and the laser slit light sources. Since the two light sources are arranged so that the laser slit lights cross the circular hole crosswise, the four points of the laser slit lights that intersect with the circumference of the circular hole can be used as the feature points. The 3D coordinates of the four feature points are calculated by using the triangulation method. In addition, the equation of the circumference of the circular hole is acquired from the coordinates of the four feature points. Therefore, the 3D coordinates of the center of the circular hole, the normal vector, and the diameter of the circular hole are determined from the equation of the circumference of the circular hole. This 3D position was considered to be easily measurable as mentioned above, but an algorithm that accurately extracts each feature point from an image that only includes the shape of the projected slit light becomes very important when using conventional 3D measurement techniques. Therefore, in order to extract the feature points accurately, we propose a technique that analyzes an image that is a combination of two images of the different features of the circular hole.

The framework of the above proposed method is shown in **Fig. 3**, and the procedure of the method is as follows. At first, two laser slit lights are projected onto an object and an image, defined as a slit light image, is captured. Then, the white light source is used to illuminate the object without the use of the laser slit lights and an image, defined as a circular hole image, is captured. As results of this procedure, the slit line image shows clear reflected light lines that outline the shape of the object and circular hole, and the circular hole image shows the clear contrast of the object surface and circular hole. Section 3 describes, in detail, the image processing that was applied to these images, and the notable features of this method are further discussed. Since these images are acquired with the same TV camera, they can be overlaid to create a combined image. If this is done, the feature points can be defined as the intersection points of the central lines of the slit lights and the circumference of the circular hole. Four feature points were extracted accurately by the procedure mentioned above. However, if the

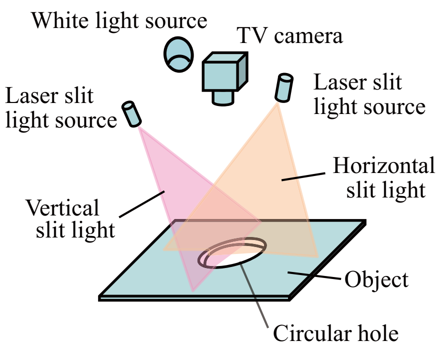

Fig. 2 Schematic diagram of the proposed sensor.

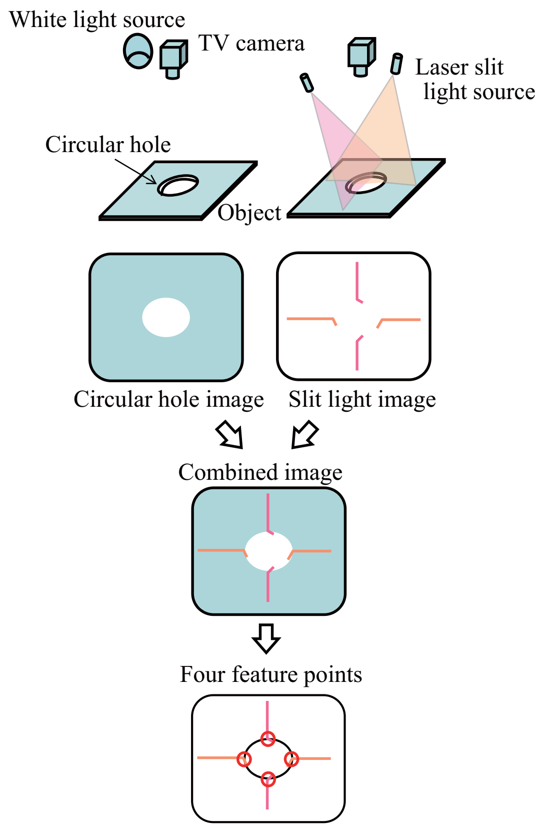

Fig. 3 Framework of the proposed method.

elliptical approximation is applied to extract the circumference of the circular hole, the line that shifted from the actual circumference line can be extracted as shown in **Fig. 4**. As compared to Fig. 4(a), in which the circumference line was extracted without error, the extracted circumference line of Fig. 4(b) shifted from the actual circumference line. This shift is caused by an inclination of the object or a distortion of the camera image pickup system mainly according to an optical lens. In order to deal with this shift, it is necessary to increase the reference point and to compute an elliptical approximation with a high-dimensional function. However, an increase in the processing time may become a problem. Therefore, as shown in **Fig. 5**, a curvilinear approximation was applied to each of the four partial circumference segments extracted from the actual circular hole image, and the intersections of the approximated curved lines and the central lines of the slit lights were extracted as the feature points.

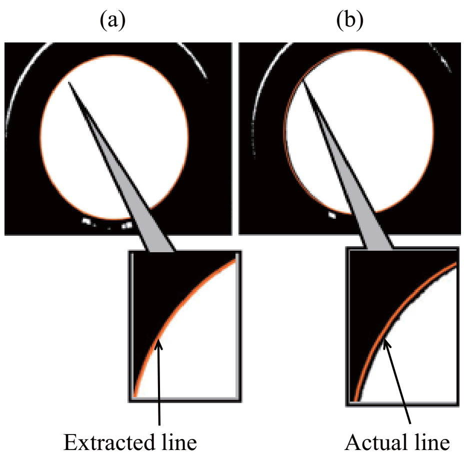

Fig. 4 Example of the circumference extraction results by elliptical approximation, (a) result of normal extraction and (b) result of having shifted.

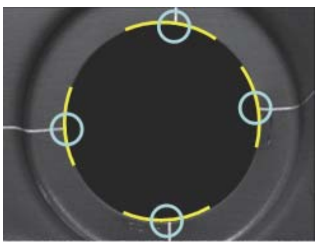

Fig. 5 Example of the extracted four feature points.

3. Measurement System

3. 1 Structure of the System

Figure 6 shows a schematic diagram of the developed prototype measurement system. This system is composed of a host computer, a control unit for the two laser slit light sources, and the sensor head described in Section 2. In this system, the two laser slit light sources of the sensor are located at the upper and side regions of the TV camera. The TV camera is equipped with XGA (eXtended Graphics Array) CCD (1024 × 768 pixels) and its frame rate is 30 frames per second. The wavelength of each laser light source is 650 nm, and the beam is extended to the shape of a slit by the lens system. The horizontal slit light is projected from the upper light source, and the vertical slit light is projected from the side light source. In this state, the directions of the two laser sources can be adjusted so that the two slit beams intersect along the optical axis of the TV camera.

Figure 7 shows two photographs of the developed sensor head. The specifications of the developed prototype sensor are summarized in **Table 1**. The system is arranged so that the baseline length between the TV camera and each laser slit light source is 170 mm and the working distance is 200 mm. The measurement range is set to ±10 mm from the reference position in the XYZ direction so that the system could respond to position change of an object in a factory line. Since the field-of-view of the TV camera is approximately 66 mm × 50 mm, the pixel resolution is 0.65 mm.

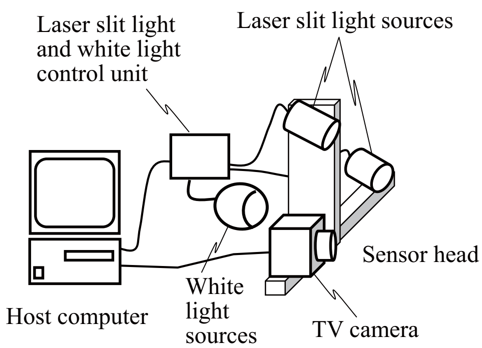

Fig. 6 Schematic diagram of the prototype measuring system.

3. 2 Measurement Procedure

Figure 8 shows the procedures for the 3D measurement of the position of the circular hole. First, as described in Section 2, a slit light image and a circular hole image are obtained by the TV camera. The region of the circular hole is extracted by threshold processing of the circular hole image (procedure #2 in Fig. 8). After that, as shown in procedure #3 in Fig. 8, the approximated curved lines of the circumference are generated the four segments based on the outer line of the circular hole extracted by the conventional edge processing method. In contrast, the center lines of the projected slit lights are extracted by thinning the slit light image (procedure #5 in Fig. 8). The two extracted images of the line segments are overlaid to create a combined image (procedure #6 in Fig. 8). The intersection points of the approximated curved lines of the circumference and the center lines of the slit lights are extracted as feature points (procedure #7 in Fig. 8). Then, the 3D coordinates of the feature points are calculated by using the coordinate transformation formula, which should be proofread in advance. Finally, the diameter of the circular hole is calculated by using the equation of a circle, which passes along the 3D coordinate of the four feature points.

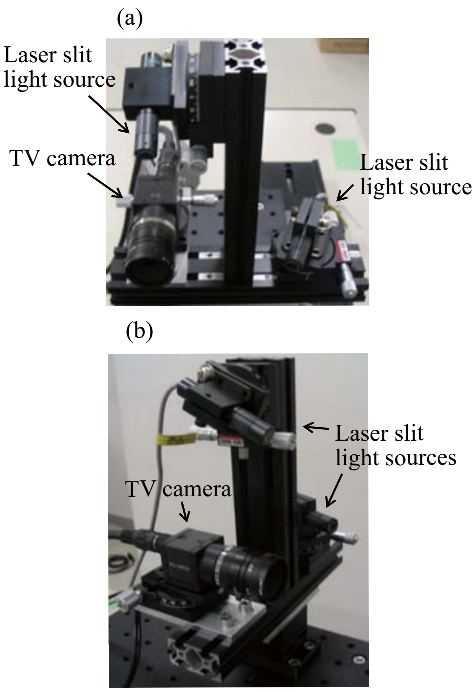

Fig. 7 Photographs of the prototype sensor head, (a) front view and (b) side view.

Table 1 Specs of the developed prototype sensor.

Working distance	200 mm
Measuring range	±10 mm
Image size	1024(h) × 768(v) (pixel)
Pixel resolution	0.65 mm/pixel
Wavelength	650 nm

4. Experiments and Results

To confirm the validity of the developed measurement method, an experiment using a target board and an XYZ coordinate system, as shown in

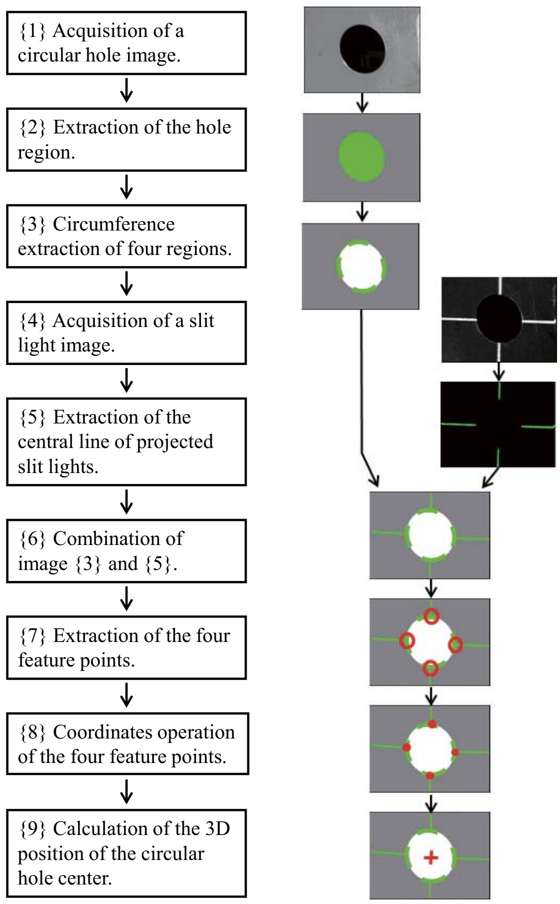

Fig. 8 Proposed procedure of the 3D position measurement for the circular hole.

Fig. 9, was carried out. In the triangulation by light-section method using a TV camera and a laser slit light, it is necessary to obtain the relation between the 3D position coordinate of the target and the pixel position of the slit light acquired with the TV camera before actual measurement. Therefore, a calibration board with which a circle with exact size was drawn was used as a target board prior to the experiment. Since the movement of the XYZ coordinate system is exact, even if it moves the calibration board, the 3D position of the drawn circle is known. The formula which acquires the spatial relationship of this known 3D position of the circle and the image captured with the TV camera was obtained, and the coordinate system of the TV camera was proofread.

In the experiment, the surface of the target board was diffused by shot blast processing, and a circular hole with a diameter of 20 mm was cut at the center of the board for evaluation. The target board was moved within the range of ±7 mm at a step of 1 mm from the reference position. The 3D coordinates of the circular hole that were measured for every position in the XYZ coordinate system were recorded. The differences between the displaced distances in the XYZ coordinate system and the changes in the distances of the obtained position of the center of the circular hole were defined as errors. The values of these errors were evaluated to determine the accuracy of the measurements.

Figure 10 shows the variations in the error values with respect to their measurement positions. In the figure, the upper, middle, and lower panels show results for the X, Y, and Z directions, respectively. As compared to the results of the X and Y directions, the reason for the small values of error in the Z direction is considered to be as follows. During the calculation of the position of the X direction, the extraction error of the feature points which are the intersection points at the left and right side influences the precision of the measurement greatly. For the Y direction, the extraction error of the feature points at the top and bottom intersections have a similar influence. On the other hand, for the Z direction, since the influences of the extraction errors for the four feature points are similar, the influence of the extraction errors on the precision of the measurements is small. Although the errors for the measurement are different for the X, Y, and Z directions, the experimental results for all the measurement locations show that the error values are ±0.05 mm or less. This range can be considered small, since the pixel resolution is 0.65 mm, which verifies that the proposed 3D measurement method is accurate. Moreover, the constructed prototype sensor can measure one circular hole within 1 second. Because the basic performance of the sensor was confirmed, the sensor was installed in a factory line

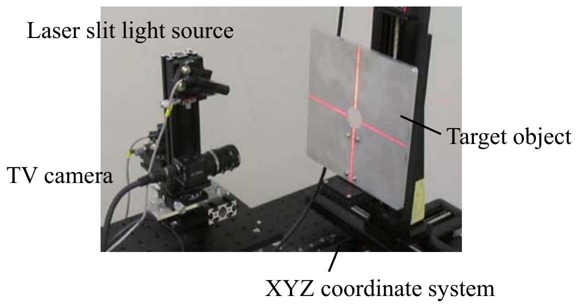

Fig. 9 Experiment setup for the 3D position measurement of the circular hole.

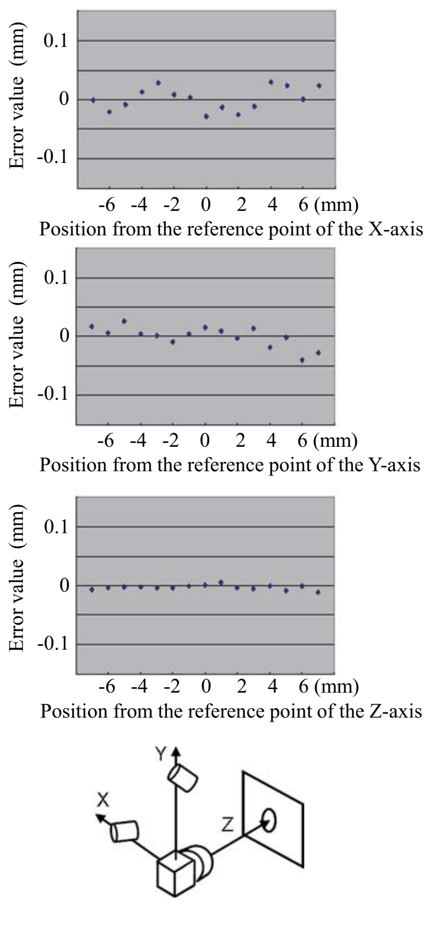

Fig. 10 Measuring results of the error value over position change.

and its applicability was evaluated, as shown in **Fig. 11**. In the figure, the upper left image is a photograph of an automotive body and the lower image is a photograph of the sensor projecting two slit lights onto a circular hole located on the automotive body. The 3D coordinates of 3800 circular holes were measured. The installed sensor operated without malfunction in the factory line, and its applicability to an in-line inspection was confirmed. The sensor is currently being continuously evaluated in the automobile production line in order to finalize the structure of a practical sensor system.

5. Summary

A method for measuring the 3D position of a circular hole was developed. A measurement accuracy of ±0.05 mm or less (working distance: 200 mm) was obtained when using the prototype sensor. Moreover, since it was confirmed that the developed sensor can be applied to the automobile assembly process, the validity of the sensor is currently being evaluated in a factory line.

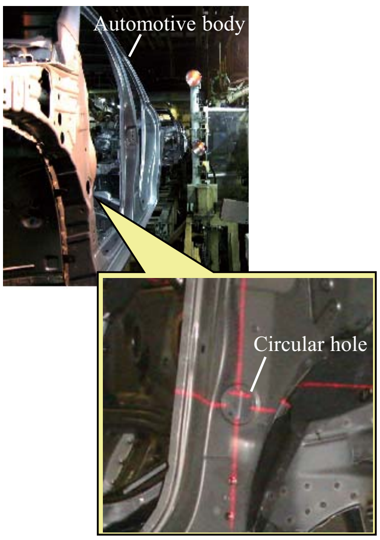

Fig. 11 Experiment scenery in the automotive production line.

References

(1) Onda, T., Igura, H. and Niwakawa, M., "A Handling System for Randomly Placed Casting Parts Using the Plane Fitting Technique", *Proc. of IEEE/RSJ IROS*, Vol. 3 (1995), pp. 435-440, IEEE.
(2) Sablatning R. and Kampel, M., "Model-based Registration of Front and Back Views of Rotationally Symmetric Objects", *Computer Vision and Image Understanding*, Vol. 87 (2002), pp. 90-103.
(3) Bolles, R. C. and Horaud, P., "3DPO: A Three-dimensional Part Orientation System", *Int. J. of Robotics Research*, Vol. 5, No. 3 (1986), pp. 3-26.
(4) Yokoya, N. and Levine, M. D., "Volumetric Description of Solids of Revolution in Range Image", *Proc. of the 10th Int. Conf. of Pattern Recognition* (1990), pp. 303-308, IAPR.
(5) Tsukada, T., Nakano, T., Yamamoto, S., Matsuo, H. and Iwata, A., "A Measurement Method for the 3-D Shape of Objects Having Uneven Reflection Surfaces", *Proc. of the 4th Int. Conf. on Quality Control by Artificial Vision* (1998), pp. 280-286, IEEE.
(6) Tsukada, T., Watanabe, K., Koide, M., Hirose, M., Horie, Y. and Yamagishi, Y., "Development of a 3-D Position Measurement Method for a Round Hole", *Proc. of the 2011 IEEE Int. Conf. on Mechatronics and Automation* (2011), pp. 624-629, IEEE.

Toshihiko Tsukada
Research Field:
- Optical Sensing System

Academic Degree: Dr.Eng.
Academic Societies:
- The Institute of Electronics, Information and Communication Engineers
- The Institute of Electrical Engineers of Japan

Awards:
- Japan Welding Society Committee of Micro Joining Excellent Research Award, 1996
- R&D 100 Award, 2003

Keiichi Watanabe
Research Fields:
- Optical Shape Measurement System
- Optical Inspection System

Academic Societies:
- The Japan Society for Precision Engineering
- The Society of Instrument and Control Engineers

Mitsuo Koide
Research Fields:
- Robotics
- Control System

Academic Societies:
- The Society of Instrument and Control Engineers
- Robotics Society of Japan

Yohei Horie*
Research Fields:
- Automotive Engineering
- Energy Managament

Academic Society:
- Society of Automotive Engineers of Japan

Masahide Hirose*
Research Fields:
- Introduction of Universal Hand Device
- Development of General-purpose Chemical Drop Lifting Device

Yasunori Yamagishi*
Research Field:
- Development of Manufacturing Technique

* Toyota Motor East Japan, Inc.