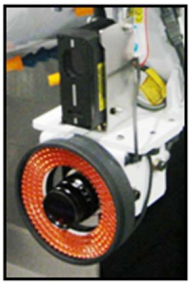
Improvement in Robustness of High-speed Hole Position Measurement System for Construction Machines

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When the boom of a construction machine is processed by an opposed horizontal boring machine, the hole position is measured using a touch sensor. However, this measuring time is a bottleneck in the enhancement of productivity and therefore the improvement of the measurement speed is desirable. Mitsubishi Heavy Industries, Ltd. (MHI) developed a contactless hole position measurement system and realized the enhancement of productivity through a reduction of the process time. This measurement system offers an optimum processing algorithm for workpieces that have various disturbance factors at customer machining sites to realize high robustness. This paper presents specific issues in improving the robustness of a contactless measurement system and their solutions, as well as the automatic hole position offset function that can eliminate manual intervention.

1. Introduction

In recent years, demand for construction machines is drastically increasing in emerging countries, and needs for opposed horizontal boring machines used for processing construction machine components are expanding significantly. Accordingly, MHI faces a pressing need to differentiate its opposed horizontal boring machines by providing high-value-added functions in order to increase their market share. We focused on the enhancement of productivity through a reduction of the cycle time as one of the high-value-added functions. Construction machine components as shown in **Figure 1** are assembled by welding the parts that are made by sheet metal working and casting, and then machined. The hole boring position needs to be measured before the machining process because of welding distortion and errors in mounting the support tools, and a touch sensor is typically used for this measurement. The time required for this measurement can account for as much as one third of the entire process time, and a reduction of measuring time is sought after. MHI developed a contactless hole position measurement system using cameras and laser length-measuring devices as a function for the reduction of measuring time.

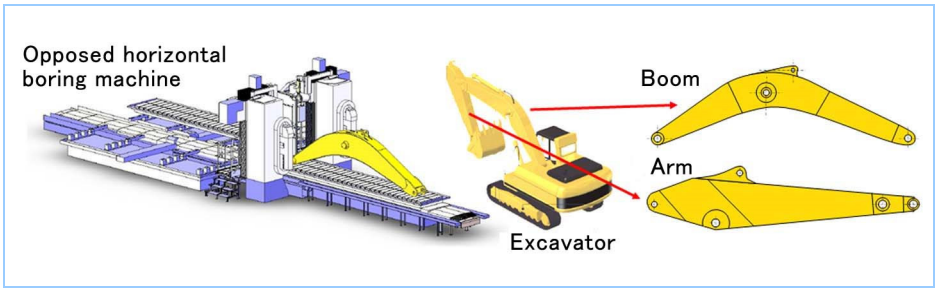

Figure 1 Opposed horizontal boring machine and example of construction machine components

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2. Summary of contactless measurement system

This measurement system is mounted on the saddle of an opposed horizontal boring machine equipped with two columns. **Figure 2** shows the configuration of this system. The system consists of cameras for the measurement of the hole center position and laser length-measuring devices for the measurement of the hole height. The system measures the hole position of a workpiece on the table from both sides.

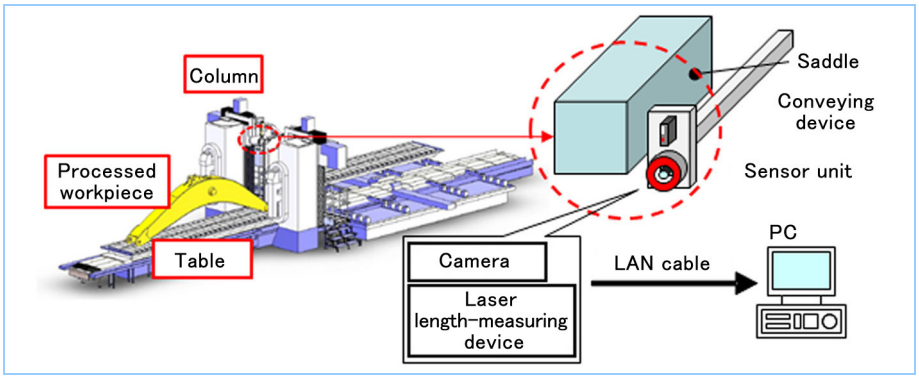

Figure 2 Configuration of measurement system

Figure 3 compares the conventional method and the developed system. The conventional method uses a touch sensor to measure the center of a hole and requires the sensor to contact the measurement point at a very slow speed, and therefore approaching time is required. On the other hand, the developed measurement system performs contactless measurement and can reduce measuring time significantly as a result. Overviews of the hole center position measurement and the hole height measurement are described below.

(1) Hole center position measurement

For hole center position measurement, the camera is moved to the hole position to take a picture. Then the edge of the hole is detected by image processing and the hole center position is pinpointed by calculating the circular shape.

(2) Hole height measurement

The hole height is calculated based on the measurement of the two edge points on the end face of the cylindrical article, and the machining allowance in the Z axis direction and the error in setup change are checked.

Actual workpiece measurement is affected by various noise factors and the edge detection accuracy for the hole center position measurement deteriorates as a result. For this reason, it is difficult to ensure accuracy just through standard image processing. Issues in image processing of an actual workpiece and their solutions are described in the next section.

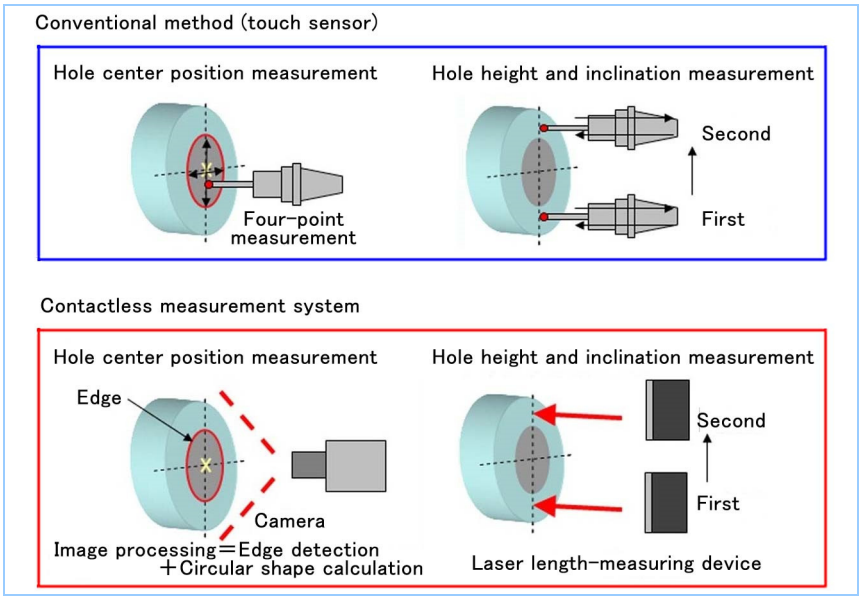

Figure 3 Comparison of measurement methods

3. Efforts to ensure high robustness

3.1 Characteristics of workpiece to be measured

Figure 4 shows example conditions of workpiece end faces to be measured. Although the measurement of a workpiece is performed on a single workpiece, it has high-brightness milled sections with a high-reflectance and low-brightness cast surface sections with a low reflectance. Accordingly, the brightness of acquired images varies significantly even when the images are taken under the same conditions. In addition, some holes have a pattern or markings on their end face and others have a tapered or rounded angle between the end face and the inner cylinder. As a result, to achieve the targeted result, it is necessary to correctly capture the characteristics of images and perform image processing accordingly. The specific efforts we made for this improvement of robustness are described below in chapters 3.2 and 3.3.

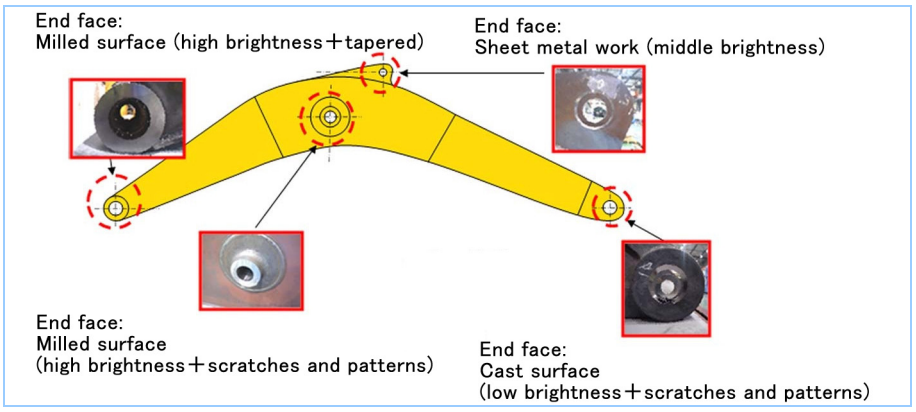

Figure 4 Example conditions of workpiece end faces to be measured

3.2 Clamp filtering

Figure 5 summarizes issues to be resolved in this section. Normally the boundary between the end face and the inner cylinder is detected as the edge. In cases where the hole to be measured has a tapered part and the end face is a high-brightness milled surface, however, the boundary between the end face and the tapered part may be partially detected as the edge, and the accuracy deteriorates as a result.

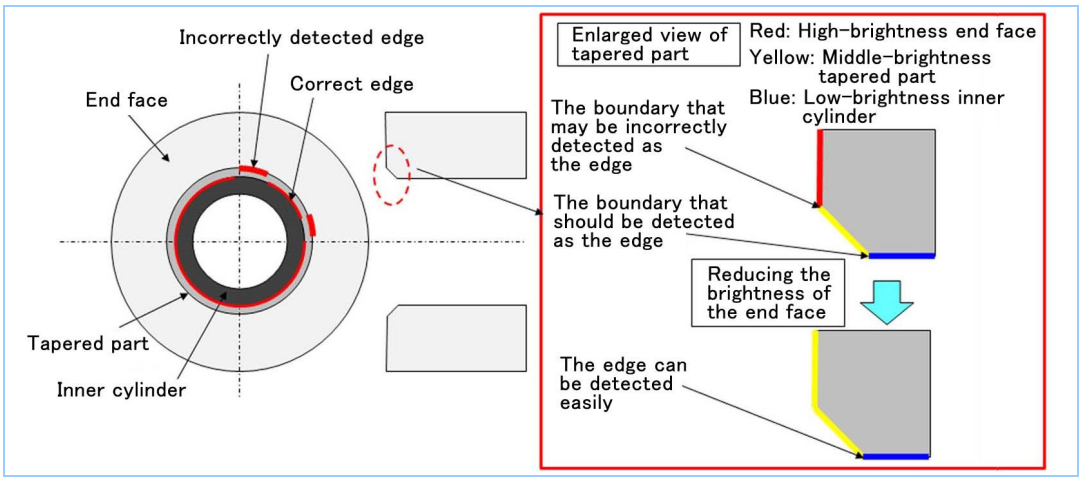

Figure 5 Example workpiece of issue 1

To resolve this issue, a threshold process that adjusts the brightness of an end face to the optimum value (hereinafter referred to as clamp filtering) was developed. Clamp filtering classifies an image into three forms and then determines the optimum end face brightness adjusting method respectively. In the case of the image example in Figure 4, "End face: Milled surface (high brightness + tapered)" is classified as form 1, "End face: Milled surface (high brightness + scratches and patterns)" is classified as form 2, and "End face: Sheet metal work (middle brightness)" and "End face: Cast surface (low brightness + scratches and patterns)" are classified as form 3.

Figure 6 shows the details of this clamp filtering. For the image of form 1, a process that performs thresholding of the end face so that the boundary between the end face and the tapered part is not detected as the edge is effective. For the image of form 2, a process that performs thresholding so that the brightness of the end face is reduced to the extent where the scratches and patterns disappear is effective. If the same thresholding as that for form 1 is performed, the boundary between the end face and the inner cylinder cannot be detected as the edge and a change of the circular shape results, which is inappropriate. For the image of form 3 in which the brightness difference between the end face and the inner cylinder is small and the same thresholding as that for form 1 or form 2 cannot determine the boundary between the end face and the inner cylinder as the edge, a process for reducing only the brightness of a high-brightness picture element that is manifestly believed to be noise is effective. As stated above, the edges on a workpiece with various surface characteristics can be detected correctly by proper preprocessing.

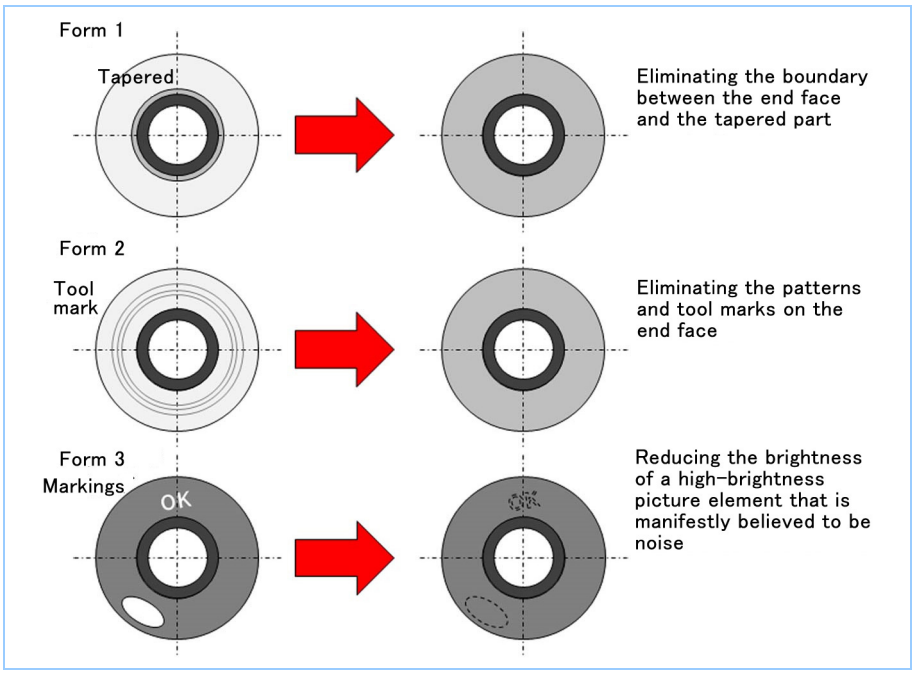

Figure 6 Details of clamp filtering

3.3 Donut filtering

Figure 7 summarizes the issues to be resolved in this section. When the difference in brightness between the end face and the inner cylinder is small and therefore the image is not clear, or the angle between the end face and the inner cylinder is rounded, it is necessary to detect a weak edge with a small brightness change on the boundary between the end face and the inner cylinder. In this case, however, there is the problem where a large amount of irrelevant noise existing on the end face and the inner cylinder is detected as an edge. In particular, when a tool mark or a scratch exists on the end face or the inner cylinder, it is susceptible to being detected as an edge and therefore the correct circular shape cannot be detected.

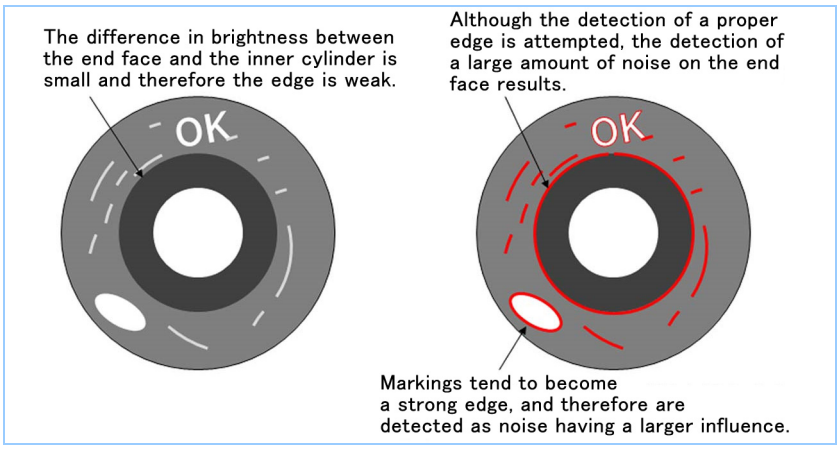

Figure 7 Example workpiece of issue 2

For the reduction of such noise, we devised a process that defines a donut-shaped range in the calculating operation and uses repeated calculation for limiting the range where edge detection is performed (hereinafter referred to as donut filtering). This process narrows down the periphery of the boundary between the end face and the inner cylinder where a proper edge exists. For the purpose of noise reduction, it is favorable to make the donut width narrower, but the boundary between the end face and the inner cylinder may fall outside the donut filter range if the width is too narrow. Thus, repeated calculation is used to gradually make the donut narrower.

Figure 8 shows the specific processes of donut filtering. An edge is detected only in the edge detection range defined by the donut filter, and the radius and the center position of a circle acquired based on the detected edge are calculated. Then a donut filter narrower than the previous one is defined based on the calculated radius and center position, and an edge is detected again. By performing this repeated operation, an edge can be detected only from the periphery of the boundary between the end face and the inner cylinder even when the image contains a large amount of noise components.

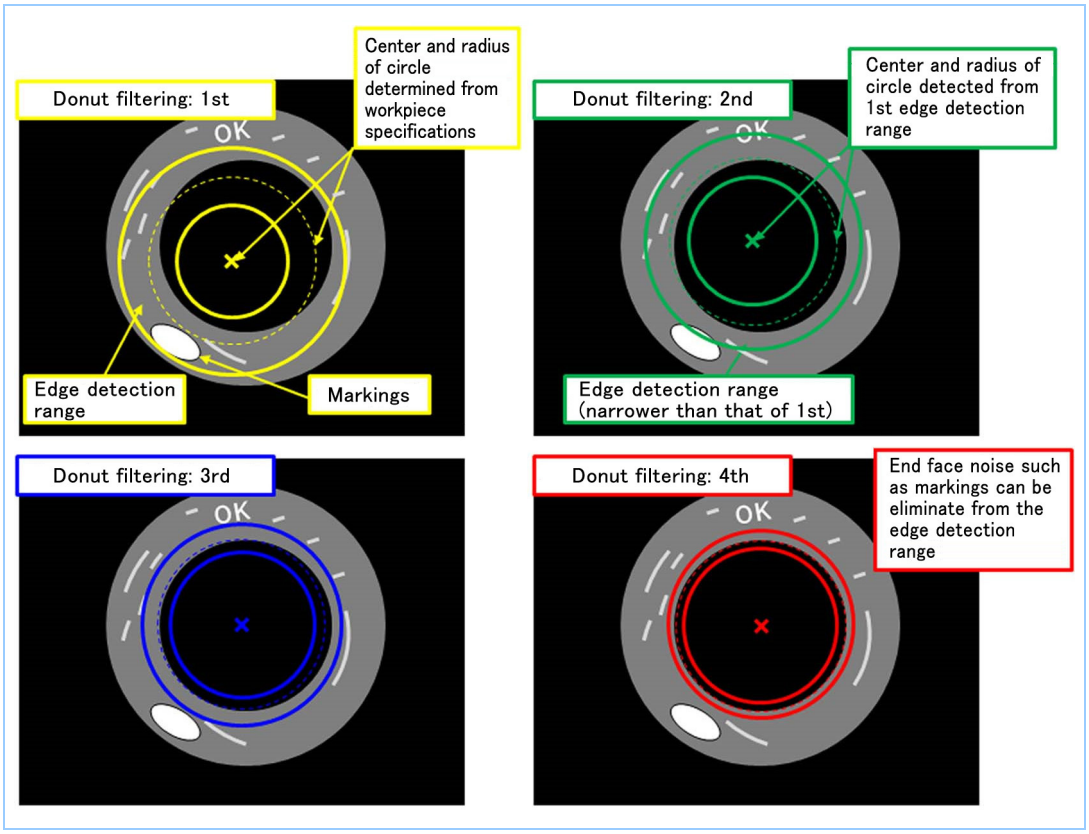

Figure 8 Details of donut filtering

4. Automatic hole position offset function

4.1 Function overview

If the distance between the centers of holes for which the positions have been measured deviates from the prescribed value, machining without any countermeasures will result in a defective product. For this reason, the machining position was typically offset manually while ensuring the machining allowance of the holes. To handle this, we developed a function that performs automatic offset to the optimum machining position based on the hole measurement results, the hole positions prescribed by the drawing, and the allowable distance between centers. Thus, manual intervention can be eliminated, and as a result, the time is shortened and the risk of human error is significantly reduced.

Figure 9 shows an example of the automatic hole position offset function. It presents a case where the measurement of a workpiece as shown in Figure 9 results in the distance between centers AD of 6005 mm, which deviates from the prescribed value of 6000 +/-3 mm. In this case, offsetting the machining positions of the A boss and the B boss inwards by 1 mm can result in a distance between centers of 6003 mm, which means that the workpiece is acceptable. If multiple

permissible errors are exceeded simultaneously, however, no local optimization should be performed. To eliminate the need for thickness deviation processing, it is desirable to make the offset value as small as possible. The details of the automatic offset function are described in the next section.

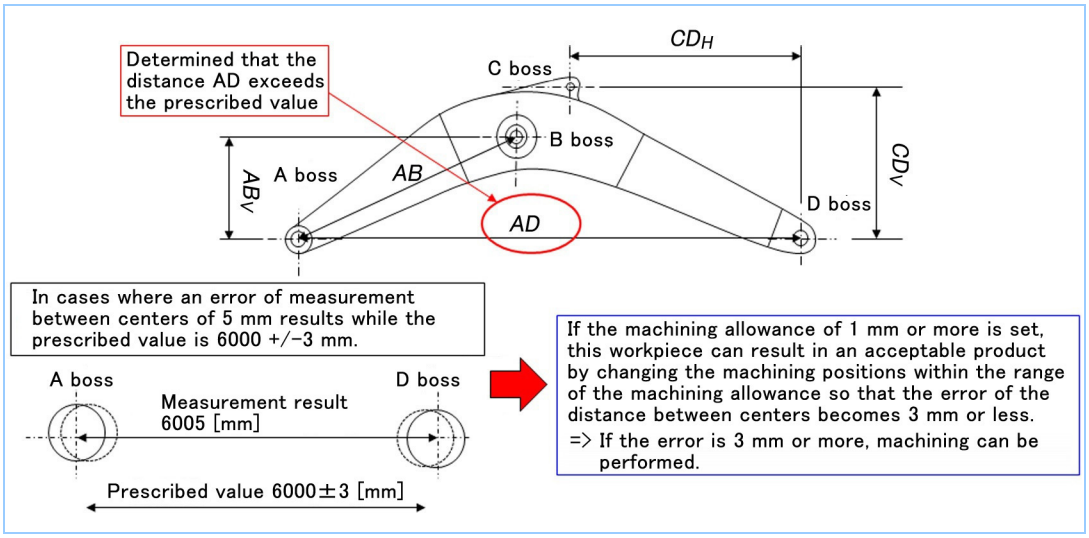

Figure 9 Automatic hole position offset function

4.2 Function details

This system calculates the hole center positions ($0X_a$, $0Y_a$), ($0X_b$, $0Y_b$), ($0X_c$, $0Y_c$), and ($0X_d$, $0Y_d$) where the error of the distance between centers is within the prescribed value and the offset amount is minimized by performing a repeated calculation using a weighting coefficient and solving the minimization problem of the multivariable function. The following paragraphs describe the example of a workpiece with four holes shown in Figure 9.

For the distance between centers to be managed, the error amounts of distance between centers (ΔAB, ΔAB_V, ΔAD, ΔCD_H, ΔCD_V) are defined based on the offset hole center positions. Then the offset amounts ($\Delta\emptyset A \sim \Delta\emptyset D$) are defined based on the measurement results and the offset hole center positions. The evaluation amount S is the sum total of each of the squared error amounts and squared offset amounts multiplied by the respective weighting coefficient. S allows simultaneous adjustment of the error of the distance between centers and the offset amount.

$$S = (W_1 * \Delta AD^2) + (W_2 * \Delta AB^2) + (W_3 * \Delta AB_V{}^2) + (W_4 * \Delta CD_H{}^2) + (W_5 * \Delta CD_V{}^2)$$
$$+ (W_A * \Delta\phi A^2) + (W_B * \Delta\phi B^2) + (W_C * \Delta\phi C^2) + (W_D * \Delta\phi D^2)$$

$W_1 \sim W_5$: Weighting coefficient of error of distance between centers
$W_A \sim W_D$: Weighting coefficient of offset amount

When the minimization problem is solved with the weighting coefficient of a certain term of S increased, the term becomes dominant in comparison to the amount of S and therefore a solution that reduces the term results. This time, the purpose is to obtain a solution with which the error of the distance between centers is within the prescribed value and the offset amount is minimized, and therefore the weighting coefficient is set so that the offset amount becomes dominant in comparison to S. That is to say, the repeated calculation is started with the initial value of the weighting coefficient set to 0 (zero) for the error of distance between centers and 1 (one) for the offset amount. When the minimization problem is solved with the weighting coefficients set as above, the result indicates that it is unnecessary to move the position from the measured position because S becomes minimized when all of ΔØA~ΔØD are zero. In cases where there is a section that deviates from the allowable value, solving the minimization problem of S with the weighting coefficient of the corresponding term increased from the above initial value results in the contribution of the term to the amount of S, and therefore a solution with which the error of the distance between centers in the section decreases and the offset amount of the hole that configures the section changes accordingly can be obtained.

In this way, the offset amount can be adjusted gradually so that the error of the distance between centers becomes smaller by repeating calculation of the minimization problem of the evaluation amount S while increasing the weighting coefficient little by little, and a solution with which the error of the distance between centers is within the prescribed value and the offset amount is minimized can eventually be obtained.

5. Conclusion

As described in this paper, as a method to reduce the cycle time and enhance productivity, MHI developed a contactless hole position measurement system using cameras and laser length measuring devices that reduces the measuring time significantly from twelve minutes in the conventional method to two minutes and thirty seconds. In addition, we resolved specific issues for higher added value and then established a high-robustness algorithm. We also researched the needs of our customers and developed an automatic hole position offset function that can eliminate manual intervention and developed a further high-value-added measurement system. We will work hard to gain the top share in the global large machine tool market by not only understanding customer needs directly from processing sites, but also by offering high-value-added systems for the enhancement of customer productivity.