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3D MEASUREMENT OF THE INNER SHAPE OF A CAVITY

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Abstract − We strive to develop a 3D coordinate measuring machine, which can measure the inner shape of a cavity with a complex shape. Currently, the ILC (International Linear Collider) project is progressing through international collaboration. The major goal of ILC is to produce and investigate Higgs bosons. ILC consists of two linear accelerators facing each other, and will hurl some 10 billion electrons and positrons toward each other at nearly the speed of light [1]. The cavity is an important component to accelerate particles to near light speed. A cavity's inner 3D shape influences the accelerating performance. Therefore, it is important to measure the inner 3D shape of a cavity. However, it is difficult to measure the inner shape of cavities with complex shapes like a bellows. We are developing a highly accurate, inner shape measuring machine using triangulation and a measuring method.

Keywords: 3D Measurement, Inner Shape Measurement, Non-contact Measurement

1. INTRODUCTION

A cyclotron is a conventional high power accelerator with a circle structure. Particles are accelerated while turning in a cyclotron. However, bent electrons and positrons lose energy due to synchrotron radiation. Hence, a cyclotron cannot accelerate electrons and positrons up to 500 GeV. Therefore, ILC has adopted a linear accelerator (Fig. 1). A linear collider requires a high accelerated gradient because the length of the accelerating path is shorter than a cyclotron.

An accelerating cavity is used to accelerate particles (Fig. 2). Each cavity consists of nine cells, and is made of niobium. The cell-shape design has yet to be completed. Hence, we assume that the diameter of a cavity varies from ϕ80 mm to ϕ210 mm and the length is shorter than 1300 mm. Our goal is to measure the inner shapes of the cavities.

Traditional processing of cavities involves welding half cells. However, we are developing seamless cavities by deforming Nb pipes into cavities by necking and hydroforming (Fig. 3). Seamless cavities are cheaper and improve reliability. Currently, the inner shape of a welded or seamless cavity is impossible to measure.

The followings are target specifications of our system.

1. Without contact
2. 3D measurement
3. Radial measuring range: ϕ80 mm to ϕ210 mm
4. Axial measuring range: 1300 mm
5. Accuracy: 0.1 mm
6. Measuring unit size: less than ϕ80 mm

The main challenges are downsizing, improving accuracy, and calibration.

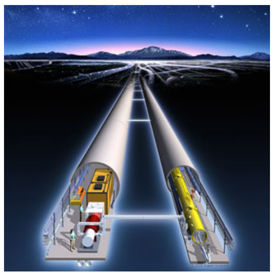

Fig. 1. Image of the International Linear Collider.

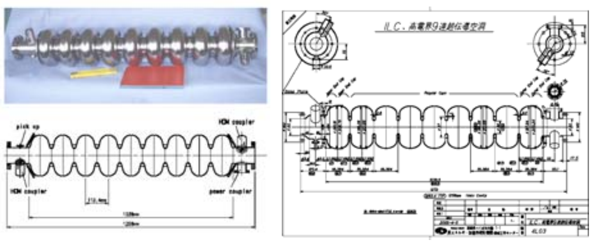

Fig. 2. Accelerating Cavities (welded, nine-cells).

Fig. 3. Seamless three-cell cavities made by necking and hydroforming (test modules made of copper).

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2. PRINCIPLE

The measuring system consists of two components, a measuring head to determine the distance to the surface of an object and a scanning system to drive the measuring head (Fig. 4).

The measuring head gauges the distance to the inner surface of a cavity by the triangulation method. It has a diode laser unit and a camera (or cameras). The camera captures an image of a laser spot. The measured distance is calculated from the position of the laser spot on the camera image.

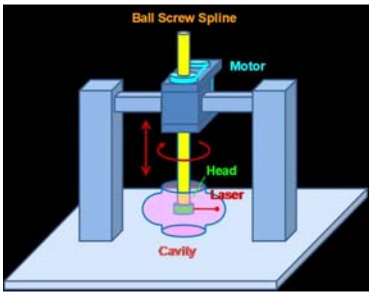

Fig. 4. Inner Shape Measurement System (for a one-cell cavity).

Below is an outline of our development approach (Fig. 5).

1st. 1D Measurement
- Develop a sufficiently small, but highly accurate distance measuring system

2nd. 2D Measurement
- Unitization of the measuring system to a measuring head
- Measure 2D shape by rotating the measuring head

3rd. 3D Measurement
- Measure 3D shape by linear and rotating motion of the measuring head
- Measuring Targets are one-cell cavities and nine-cell cavities

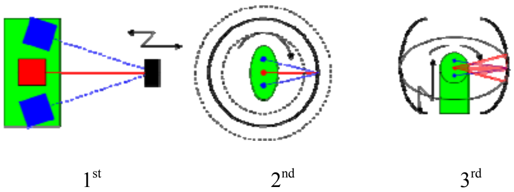

Fig. 5. Development Plan (Red: laser, Blue: camera)

3. 1D MEASUREMENT

3.1. Principle for measurement

Distance is measured via the laser triangular method. The accuracy of triangulation depends on two factors.
- Accuracy of the detecting position of the laser spot on the image
- Length of the baseline (from the camera to the laser unit)

A measuring system with a longer baseline can more accurately measure distance. However, the baseline is limited because the measuring head must be inserted into the cavity. We assumed that the aperture diameter is 80 mm. Therefore, we must enhance the accuracy of point detection. Hence, we employed sub-pixel processing to push the limit due to the pixel size of CCD.

3.2. Error cancellation by a multi-camera system

The position error of the laser spot causes a distance error, and the influence of this error increases with a shorter baseline. Thus, the influence of the position error of the laser spot must be reduced. We used two cameras, and aligned one right of the laser unit and the other left of the laser unit. The position errors caused by texture or irregularity of the laser spots occur on the opposite side. Therefore, the errors are cancelled by summing these outputs.

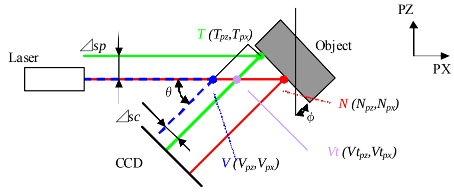

Fig. 6. Influence of position error: Δs_c is the position of the laser spot. ***V*** is a miss-detected point and ***N*** is a true point.

3.3. Experiment

Figure 7 shows the experimental setup. The measuring system consisted of two cameras and a laser diode unit. The target was an aluminium plate with a quasi-mirror surface on a linear stage. The target could move along the laser axis so that the distance from the measuring unit to the target varied from 30 mm to 230 mm. Figure 8 shows the result of the experiment when the measurement distance is between 130 mm and 131 mm, which is the farthest area in an actual measurement and has the lowest triangulation accuracy. The accuracy of the left and right cameras was 0.13 mm and 0.16 mm, respectively, and the accuracy of the combined output was 0.064 mm. The error of the sum output was smaller than root-mean-square of errors, indicating that the errors of the right and left cameras are dependent, and effectively cancel each other.

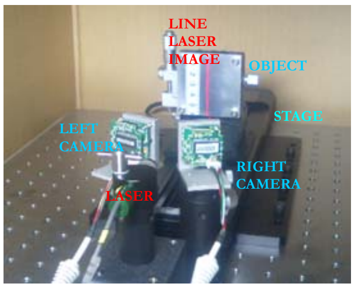

Fig. 7. Experimental setup.

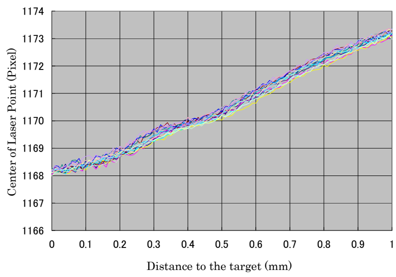

Fig. 8. Experimental result.

4. 2D MEASUREMENT

4.1. Calibration for the 2D Measurement

The 2D shape is given by rotating the distance measurement system. If the equipment is ideal, an accurate 3D position is easily obtained from the measured distance and setting angle. However, the original point of the measuring head differed from the axis of rotation. Therefore, to obtain an accurate point, a vector from the axis to the original position is necessary. Hence, the system was calibrated using a cylindrical artefact, which must be measured by CMM and have a known diameter. We solved the vector from the measurement results of the artefact without aligning the artefact.

Figure 9 shows the parameters to be considered. The vector from the rotation axis to the original point of the measuring unit is (a_x, a_y), while the vector from the center of the observed circle to the rotation axis is (s_x, s_y). Both vectors are unknown, but the radius of circle R and rotation angle θ are known. The observed distance is l. The relationship between the unknown parameters and observed values is:

$$\left| \begin{pmatrix} a_x \\ a_y \end{pmatrix} + \begin{pmatrix} s_x \\ s_y \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} + l \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \right| = R \qquad [1]$$

We calculated the parameters by solving the following equation:

$$\boldsymbol{p} = \mathbf{A}\boldsymbol{d}. \qquad [2]$$

Parameter vector $\boldsymbol{p}$, Jacobin matrix $\mathbf{A}$, and observation vector $\boldsymbol{d}$ are defined below:

$$p = \begin{pmatrix} a_x \\ a_y \\ s_x \\ s_y \end{pmatrix}, \qquad [3]$$

$$A = \begin{pmatrix} -p_{x1}/r_1 & -p_{y1}/r_1 & (p_{x1}\cos\theta_1 + p_{y1}\sin\theta_1)/r_1 & -(p_{x1}\sin\theta_1 + p_{y1}\cos\theta_1)r_1 \\ \vdots & & & \vdots \\ -p_{xn}/r_n & -p_{yn}/r_n & (p_{xn}\cos\theta_n + p_{yn}\sin\theta_n)/r_n & -(p_{xn}\sin\theta_n + p_{yn}\cos\theta_n)r_n \end{pmatrix}, \qquad [4]$$

$$d = \begin{pmatrix} r_1 - R \\ \\ r_n - R \end{pmatrix}, \qquad [5]$$

$$\begin{aligned} p_{xi} &= (a_x + s_x\cos\theta_i - s_y\sin\theta_i + l_i\cos\theta_i) \\ p_{yi} &= (a_y + s_x\sin\theta_i - s_y\cos\theta_i + l_i\sin\theta_i) \\ r_i &= \sqrt{p_{xi}^{\,2} + p_{yi}^{\,2}} \end{aligned} \qquad [6]$$

The parameter vector was calculated by the nonlinear least square method using the Gauss-Newton method. We performed a simulation, and confirmed that the parameters are solved correctly [2].

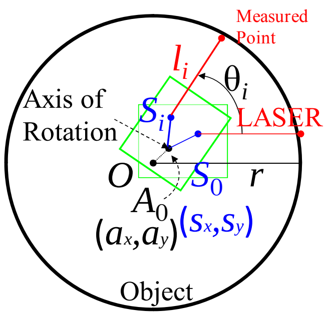

Fig. 9. Parameters to be considered.

4.2. Experiment

Figure 10 shows the cylindrical artefacts and experimental setup. A ϕ150 mm artefact was used for the calibration, and a ϕ100 mm one was used for the measurement. Each artefact was 200 mm high.

Figure 11 shows the results of the calibration data (right: raw data, left: reconstructed). The raw data was deformed by parameters a_x, a_y, s_x, s_y. However, the parameters were determined by solving equations. The parameters were solved by only three loops of calculations, and were (a_x, a_y, s_x, s_y) = (-12.74, 17.93, 45.54,-0.10). The data reconstructed from the parameters had circular shape.

Figure 12 shows the measurement results for the ϕ100 mm artefact. The measured radius was 49.9 mm. Thus, this system can determine the radius of the artefact.

Fig. 10. Cylindrical artefacts and experimental setup.

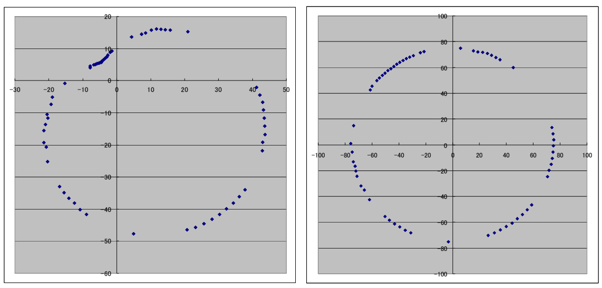

Fig. 11. Calibration Result: Raw data (Left) and reconstructed data (Right).

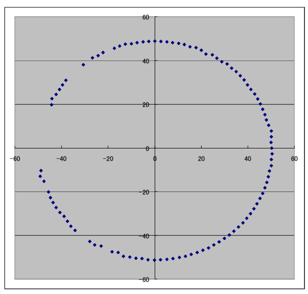

Fig. 12. Measurement result for the measurement.

5. 3D MEASUREMENT

5.1. Constitution of the 3D measuring machine

Our ultimate goal is to measure a nine-cell cavity. Because our research is conducted in stages, we have developed a one-cell measuring system.

Figure 13 shows the 3D measuring machine for a one-cell cavity. The main shaft is a splined ball-screw driven by two pulse-motors, and has linear and rotating motion. The working distance along the z-axis is 160 mm, while the rotating angle is 360 degrees. A measuring head is located at the end of the shaft.

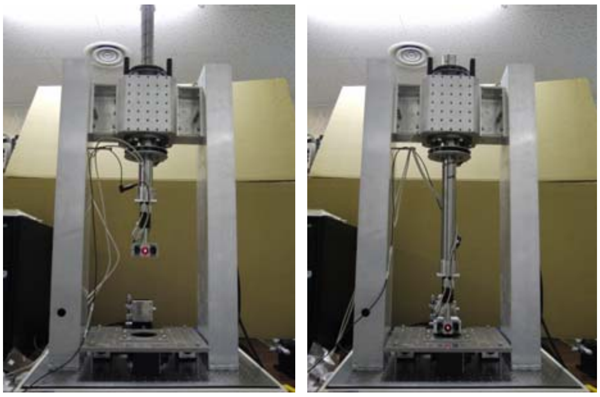

Fig. 13. One-cell measuring machine (Left: highest end, Right: lowest end).

Figure 14 shows the measuring head used in the experiment. The body is made from aluminium, and consists of two cameras, a diode laser unit, and ND filters. The diameter is ϕ72 mm and height is 35mm.

Fig. 14. Measuring Head (Left: bare, Right: with ND filter and light shielding cover).

5.2. Experiment

Figure 15 depicts the experimental setup. Initially we set a cylindrical artefact on the table, and measured the 2D shape in four sections. We displaced the artefact by approximately 1 mm in the direction of the X-axis, and remeasured its shape in same sections.

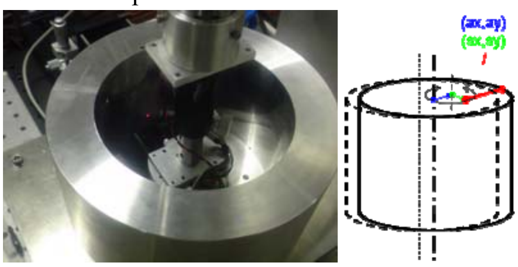

Fig. 15. Experimental setup.

Table 1 shows the experimental results. The displacement vector of the cylindrical artefact and radius coincide in each cut plane. It indicates that this machine is capable of measuring the radius and center position with an accuracy of 0.01 mm.

Table 1. Experimental Results.

	z (mm)	a_x (mm)	a_y (mm)	r (mm)
1st	0	-0.184	-0.596	75.090
	20	-0.157	-0.542	75.074
	40	-0.121	-0.496	75.097
	60	-0.107	-0.457	75.086
2nd	0	0.802	-0.428	75.093
	20	0.833	-0.379	75.080
	40	0.864	-0.338	75.105
	60	0.885	-0.290	75.077
Difference (2^{nd}-1^{st})	0	-0.986	-0.167	-0.004
	20	-0.990	-0.163	-0.004
	40	-0.985	-0.158	-0.007
	60	-0.992	-0.167	0.009

6. CONCLUSIONS

We strive to develop a highly accurate system capable of measuring inside cavities with complex shapes. For this purpose, we have developed a multi-camera error reduction system and calibration system using a cylindrical artefact. We constructed a one-cell measuring machine, and confirmed that this system is capable of measuring the inner 3D shape. In this paper, we measured an artefact, which had simple shape, with an accuracy of 0.01 mm. In the future, we will measure cavities, which have complex shapes, with an accuracy of 0.1 mm to achieve our ultimate goal, which is to measure the inner shape of nine-cell cavities.

7. ACKNOWLEDGEMENT

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