COORDINATE MEASURING MACHINE USING PARALLEL MECHANISM

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Abstract: This study proposes a new coordinate measuring machine (CMM) based on a spatial 3DOF parallel mechanism. The use of this mechanism will potentially improve the stiffness, accuracy and efficiency. This paper describes the fundamentals and an experimental CMM. The influence of link layout on the measurement uncertainty, moreover, has been investigated analytically and experimentally. Obtained results show that the uncertainty has been decreased when the measuring point is in the extensional direction of the scale unit. Consequently, the Abbe's principle can be applied to proposed parallel mechanism.

Keywords: Coordinate Measuring Machine, Parallel Mechanism, Abbe's Principle.

1 INTRODUCTION

In recent years, coordinate measuring machines (CMMs) have been widely used for precision measurement in various fields. Such the conventional CMM employs an XYZ mechanism consisting of three mutually orthogonal slide mechanisms. It appears, however, the machine's accuracy and efficiency are already at their limit due to several of its characteristics: (1) violation of the Abbe's principle, which is the basis of precision measurement; (2) a weak (cantilever) beam structure in which deflection is often generated by minimal bending force; (3) accumulation of measurement errors led from each axis; and (4) low traverse speed due to a mass accumulation. In short, these problems, which limit the precision of the CMM, are inherent in its stacked architecture or serial mechanism.

This study has proposed a new CMM based on a parallel mechanism[1][2]. This mechanism consisting of closed-loop links will potentially improve the stiffness, accuracy and efficiency of the CMM. Moreover this mechanism enables to arrange the measuring point in directions of the scale units. This paper discusses the fundamentals, construction and performance of an experimental CMM, and the influence of measuring point location on the measurement uncertainty.

2 FUNDAMENTALS

Figure 1 depicts the proposed CMM. The touch trigger probe attached to the stage is connected to three prismatic joints (struts) through the revolutionary joints. Each prismatic joint is connected to the overhead base through three spherical joints and contains within it a prismatic joint, the length measuring instruments (scales) and actuators to expand and contract itself. Variations in the length of the three struts move the stage in three-dimensional space. When the probe touches the measuring object, the probe tip position can be derived absolutely from the strut lengths. The proposed CMM has a number of advantages over the conventional

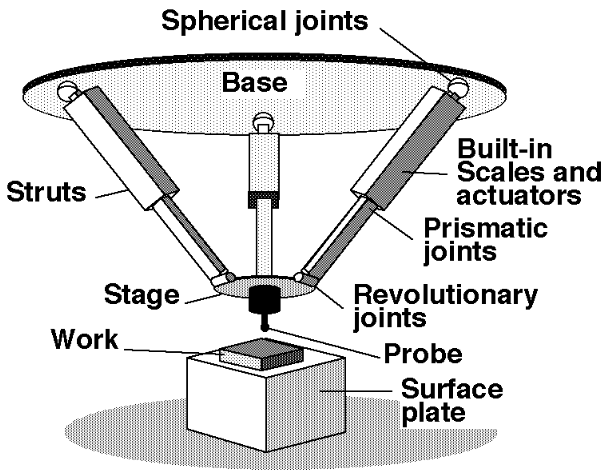

Figure 1. Proppsed CMM based on parallel mechanism

CMM; (1) the truss structure has a high stiffness because its members are subject to very few bending forces; (2) the systematic error produced by each of the scale units is averaged with the other two; (3) the small inertial mass enables high moving speed.

3 EXPERIMENTAL CMM

3.1 Outline

The experimental CMM with 3 DOF has been constructed as shown in figure 2 and 3. An octahedral truss frame and a granite surface plate are mounted on a vibration-isolation table. The frame supports three spherical joints connected three struts. The struts with the prismatic joints are expanded and contracted by three individual AC servomotors and ball screws. The prismatic joint is guided by four linear ball bearings. Each length variation of the struts is measured by three linear encoders with a nominal accuracy of $\pm 0.47\mu m_{p-p}$ and a resolution of 50nm (Sony, Laser scale). Figure 4 shows the detail view around the probe. The stage mounting the touch trigger probe (Renishaw TP200, Repeatability: 2s≤0.18μm) is connected to the strut ends through three rotational joints. A stroke of the struts is 220mm, then measurement work space is 120X120X120mm approximately.

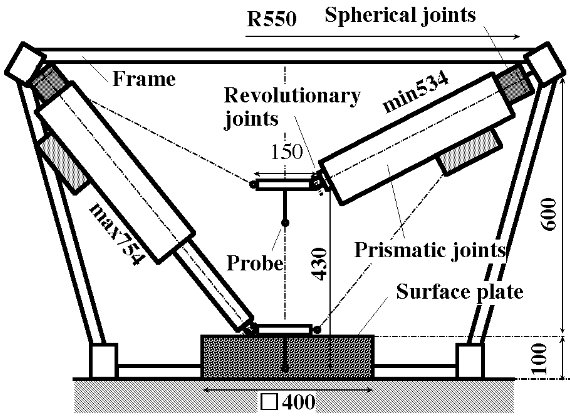

Figure 2. Scheme of experimental CMM

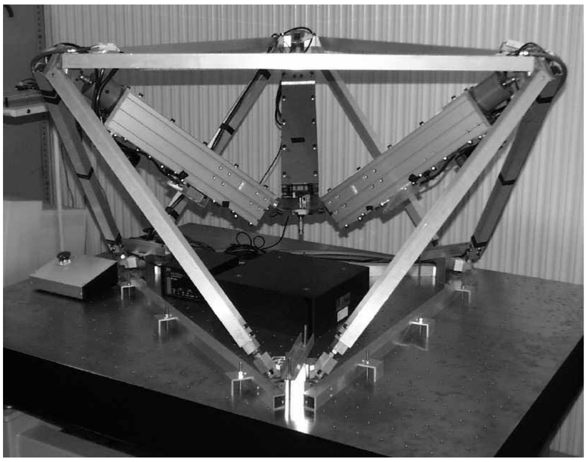

Figure 3. General view of the CMM

3.2 Joints

This CMM needs the spherical joints and rotational joints with high rotating accuracy within 1 μm. The spherical joint and the rotational joint employ 1” and 1/4” steel balls for ball bearing (nominal sphericity: 0.5μm). 1” balls were friction-welded together shank. After welding, measured sphericity of the ball was less than 0.75μm.

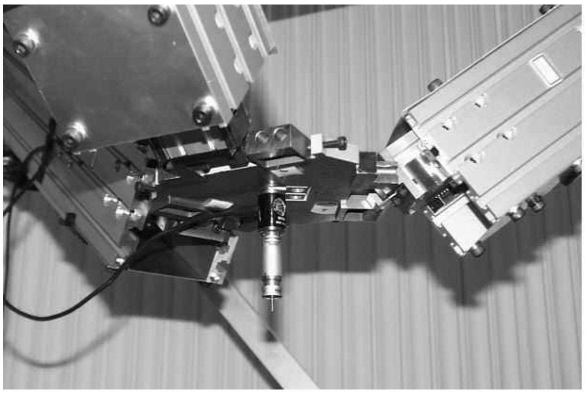

Figure 4. Detail view around the probe

3.3 Software for measurement

A personal computer holds and reads the scale values when the touch probe contacts the workpiece. The computer, moreover, calculates XYZ coordinates of the probe tip by solving the simultaneous nonlinear equations. Furthermore, the alignment program defines a work coordinate system in the machine coordinate system when the workpiece is located for any position and any attitude on the surface plate.

4 RESULTS OF ACCURACY TEST

The accuracy tests has been performed by measuring the length of the block gauges with several sizes before and after calibration. Figure 5 shows deflections and standard deviations of measured values in Z direction before the calibration. The deflections increase in proportion to the gauge sizes because of the measurement space distortion caused by the disagreement before calibration. The standard deviations of the measured value, however, are less than 0.15μm. This

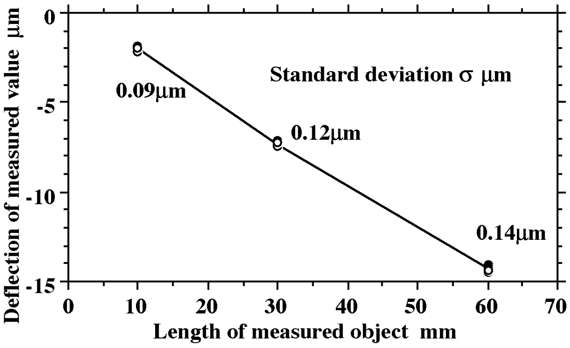

Figure 5. Deflection and standard deviation of measured data in Z direction before calibration

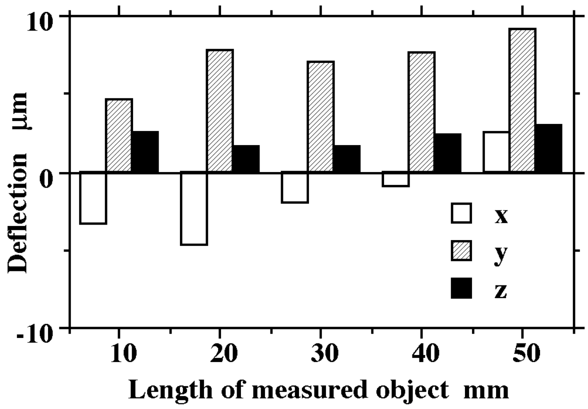

Figure 6. Deflection of measured data in XYZ directions after simple calibration

results show that this CMM has high repeatabillity of the mechanism. Figure 6 shows deflections measured in XYZ directions after simple calibraion. The deflections are independent of the gauge block size, and are less than 10µm in XYZ directions. In the near future, exact calibration will improve the measurement accuracy of the CMM.

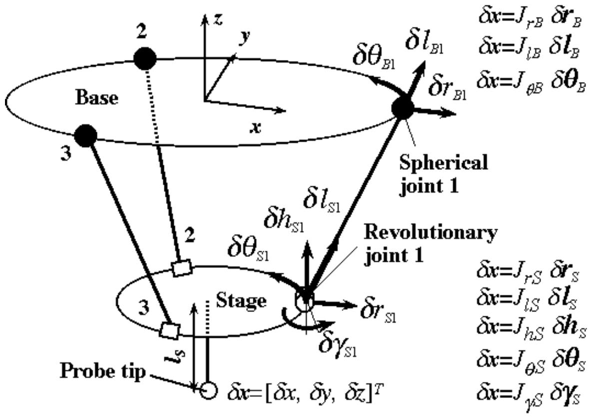

Figure 7. Motion errors of joints and probe tip

5 ERROR ANALYSIS

It is expected that joint motion errors or runouts have a strong effect on the mechanism motion error or the measurement uncertainty. In particular, in conventional CMM, the motion error of each prismatic joint causes on the measurement error because the measuring point isn't in sensitive directions of the scales. However, it is too difficult that the measuring point is located in each scale direction.
Contrarily, the parallel mechanism enables that arrangement. In this chapter, error analysis has been performed by using a singular value decomposition to obtain the relationship between the link layout and the influence of joint runouts on the measurement error.

5.1 Effect of joint motion error

Figure 7 shows coordinate system of proposed CMM and components of joint motion errors in various directions. For instance, when the revolutionary joints on the stage have radial motion errors $\delta \boldsymbol{r}_S$, displacement of the probe tip $\delta \boldsymbol{x}_S$ are shown in following equation provided quantities of them are very small:

$$\delta \boldsymbol{x} = J_{rS}\delta \boldsymbol{r}_S, \tag{1}$$

where J_{rS} is Jacobian matrix, and is numerically derived from the forward kinematics. Because this Jacobian represents the relationship between the joint radial motion error and the probe motion error, singular values of the Jacobian show magnitude of that effect. In the same way as the radial error, effects of the other error components are obtained. In calculation, the base radius and the stage radius have been set to 550 mm and 100 mm, respectively. The position of probe tip, moreover, has been fixed at the isotropic point at which the measurement resolution in XYZ directions becomes equal.

5.2 Calculated results

Figure 8 shows the singular values related to the motion error of the joints on the stage. When probe length is 70.7mm, the measuring point is in the extensional direction of three scale units. Circular and square symbols in the figure represent translational motion of the joints, and triangles represent angular motion. Thus, the angular motion of the joint has little effect on measurement error when the measuring point is in the scale directions. The results of the base joints are identical to above.

Moreover, analysis of the singular values related to the scale direction component of the joint motion error (J_l) and related to two direction components at a right angle to the scale direction (J_n and J_t) has been performed. As shown in figure 9, the joint motion error in the scale direction strongly affects the measurement error. Effect of the motion errors except the scale direction are negligible when the measuring point is in the scale direction.

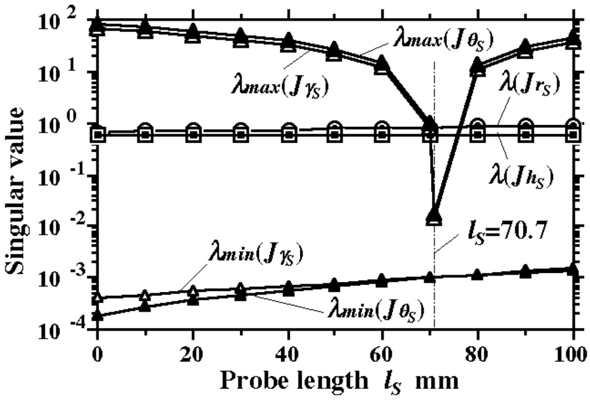

Figure 8. Influence of link layout on singular value related to stage joints

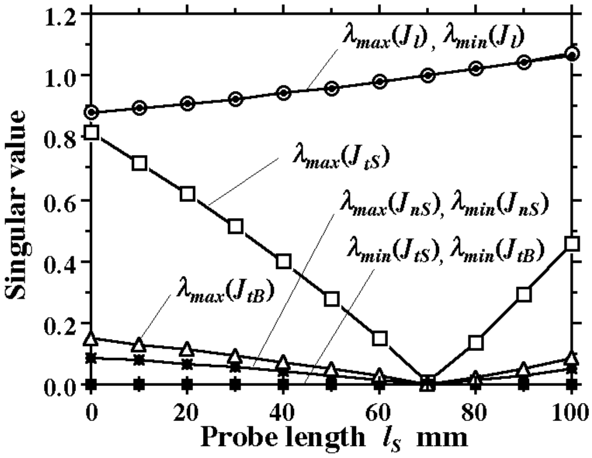

Figure 9. Effect of joint motion errors in scale direction and its orthogonal directions

6. EXPERIMENT

Length measurement using the block gauge has been performed in various probe extension. In this repetitive measurement, considerable plays (0.5-1mm) have been given to the joints purposely in order to increase the effect of joint motion errors. Figure 10 shows the influence of the measuring point location on the standard deviation of measured values. Meshed zone in the figure represents the link layout at which the measuring point is in the scale directions. The dispersion of the measured values in XYZ directions decreases in above link layout.

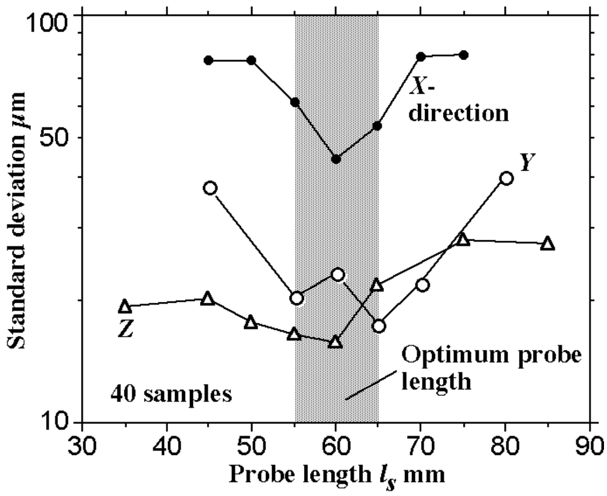

Figure 10. Influence of measuring point location on dispersion of measured value

7. CONCLUSION

New CMM based on a parallel mechanism instead of XYZ mechanism has been proposed. Fundamentals and an experimental CMM have been described. Moreover, the influence of the link layout on the measurement uncertainty has been discussed. In conclusion, the Abbe's principle can be applied in proposed parallel mechanism.

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