Development of Nano-CMM and Parallel-CMM
— CMM in the 21th Century —

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Abstract
The Coordinate Measuring Machines (CMMs) are widely used for the three-dimensional measurements of workpieces. For solving the limits and the drawbacks of the traditional CMM, we have started developing novel systems and key technologies for 21th century CMMs. In this article, we introduce two of our developing projects; "Nano-CMM project" and "Parallel-CMM project." In the Nano-CMM project, our intention is developing the CMM with nanometer resolution to measure three dimensional positions, orientations and parameters of three dimensional features. And, in the Parallel-CMM project, we develop the CMM using parallel mechanisms to measure large machine parts quickly with high accuracy.

Keywords: CMM (coordinate measuring machine), nano meter measurement, parallel mechanism, optical sensor

1. Introduction

Coordinate Measuring Machines (CMMs) have been developed and widely used to measure quickly and complex shapes with high accuracy as improving precision of industrial workpieces. The system and the key technology of traditional CMMs come to maturity in this 10 years. However, the limits and the drawbacks of the traditional CMMs are clearly such as the limit of the accuracy, measuring range, measuring speed and so on.

Therefore, we have started developing novel systems and key technology for 21th century CMMs. In this article, we introduce two of our developing projects; "Nano-CMM project" and "Parallel-CMM project" carried out in the University of Tokyo.

1.1 Nano-CMM project

In the Nano-CMM project, our intention is developing the CMM with nanometer resolution to measure three dimensional positions, orientations and parameters of three-dimensional features. The targets of Nano-CMM project are as follows:

- Workpieces of Nano-CMM are micro machine parts, micro robots and optical components.
- Nano-CMM can be used under the normal constant temperature control.
- Nano-CMM has high stability against temperature and environmental conditions.

We introduce basic concept and prototype of Nano-CMM in section 2.

1.2 Parallel-CMM project

The traditional CMM is based on a serial mechanism; components from base unit to an end-effector i.e. a base unit, X-axis, Y-axis, Z-axis and a measuring probe are connected serially. However, some drawbacks of this mechanism are its weakness against external force and the accumulation of errors. Therefore, CMM tends to become large and heavy in order to avoid the influence of bending and twisting of its components and to decrease measurement errors. We developed for the following aims:

- Development of CMM using a parallel mechanism where a base unit and an end-effector are connected by many links in parallel.
- The advantages of this mechanism is its robustness against external force and error accumulation.
- We will be able to make a larger measuring machine that can measure quickly large objects like cars or industrial devices.

We introduce basic concepts and some prototypes of Parallel-CMM in section 3.

2. Development of Nano-CMM

2.1 Basic concept of Nano-CMM

Table 1 and Fig. 1 show our target specifications of Nano-CMM. Almost all specifications of Nano-CMM are 1/100 of the specifications of traditional CMMs. For developing Nano-CMM, we established the specifications and the key points of each factor, such as scales, actuators, tables and Nano-Probe (a probing system for Nano-CMM). Firstly, we decide that Nano-CMM has simple and the symmetric constructions made of single material for the stability of measurements. Therefore, a conventional scale system (optical glass scale) and double V groove mechanism are selected.

The main items of each factor of Nano-CMM are listed as follows:

- Scale: for absolute accuracy, large measuring range and high stability, an optical glass scale with 10 mm measuring range and 10 nm resolution is selected.
- Actuator: for large moving range, high resolution and feedback control by scale, a conventional screw drive system or a friction drive system is selected.
- Table: for stability, symmetric construction of sliders with a scale and an actuator, and a double V groove with PTFE (Teflon) thin films is selected.
- Materials: for single material, high thermal conduction rate and low thermal expansion rate, silicon, zerodure, aluminum or steal are considered.

Fig. 2 illustrates the basic construction of Nano-CMM. In this construction, the double V groove with precision cylinders are used between a X table, a Y table and a basement of Nano-CMM shown in Fig. 3.

Table 1 Specifications of traditional CMM and Nano-CMM.

	Traditional CMM	Nano-CMM
Size of machine	$(2000\ \text{mm})^3$	$(200\ \text{mm})^3$
Mass of machine	1000 kg	10 kg
Measuring range	$1\ \text{m}^3$	$(10\ \text{mm})^3$
Resolution	1 μm	10 nm
Accuracy	5 μm	50 nm
Diameter of probe	5 mm	50 μm
Measuring force	10^{-1} N	10^{-3} N
Accuracy of scale	5 μm	50 nm

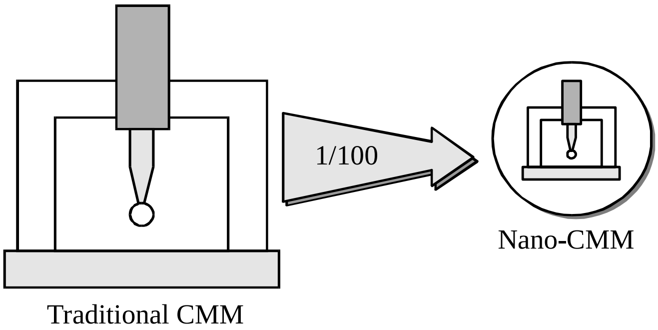


Fig. 1 From traditional CMM to Nano-CMM.

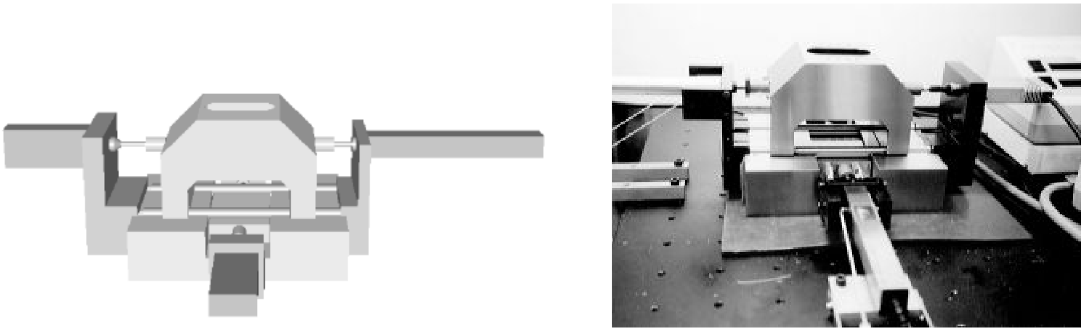
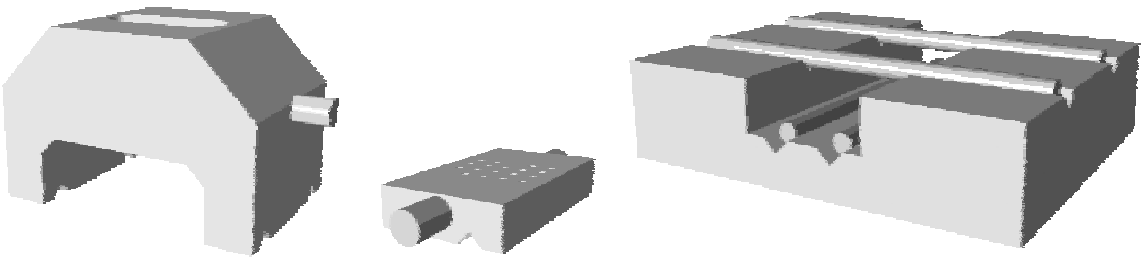


Fig. 2 Basic construction and photograph of Nano-CMM



(a) X table (b) Y table (c) Basement

Fig. 3 X table, Y table and basement of Nano-CMM

2.2 Friction drive system for Nano-CMM

As the actuator of the Nano-CMM, the conventional screw system was used for the first prototype. However, the rotational moment of the screw system influenced the straightness of the stages. Therefore, the friction drive system has been adopted for the second prototype. Fig. 4 displays the friction drive system of X stage of Nano-CMM. A capstan roller is rotated by a DC serve motor with a Harmonic Drive (1/100 reduction) and the 1 kgf pre-load is obtained to the capstan rollers by two idle rollers with a spring.

The straightness of X-stage and Y-stage of the prototype are evaluated using the measurements on a surface of a gauge block by a contact type sensor. Fig. 5 shows the profiles of 10 measurements of the gauge block over 10 mm. From these evaluations, the straightness of a X-stage and a Y-stage are approximately 50 nm and the repeatability of these stages are approximately 20 nm (see Table 2).

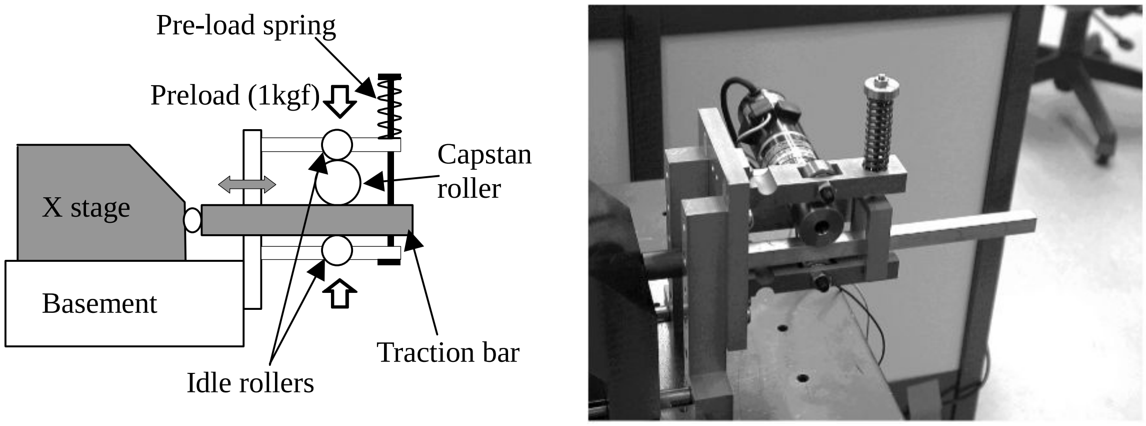


Fig. 4 Basic construction and photograph of the friction drive system

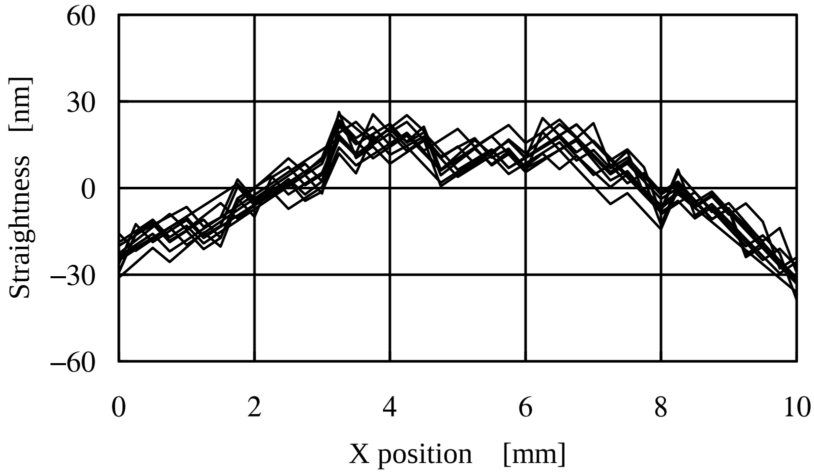


Fig. 5 Straightness of X table: horizontal displacements of X table in 10 times over 10 mm

Table 2 Straightness and repeatability of X table and Y table

	straightness	Repeatability
X table forward	40 nm	20 nm
X table backward	60 nm	20 nm
Y table forward	40 nm	20 nm
Y table backward	50 nm	20 nm

2.3 Nano-Probe system

We developed an optical sensing system to measure 2D position of a spherical target to better than 10 nm on each axis using optical collimation. We have developed a new probe system using this optical sensing system. The requirements of Nano-Probing system for Nano-CMM as follows:

- small in size,
- without thermal source,
- with nanometer resolution and
- 2 or 3 dimensional sensing.

Fig. 6 shows an optical setup of the sensing system to detect a reflecting image point. In the sensing system, a laser beam from a laser tube and a beam expander focused by an objective lens through a PBS (Polarized Beam Splitter) on a target sphere. Then, a reflecting beam changes its path at the PBS and focuses by an image lens on a photo detector such as QPD (Quadrant Photo Diode.) The 2D displacement of the reflecting beam is measured using the output voltages from 4 photo diodes of QPD.

Fig. 7 (a) displays a photograph of a prototype of Nano-Probe system that consists of the sensing system and a stylus of the probe. Fig. 7 (b) shows a photograph of the stylus that consists of a small ball, a thin pipe and an objective lens. When the small ball touches a workpiece to be measured, the ball shifts and the displacement of the ball can be detected by the sensing system through the thin pipe to QPD.

For the prototype of the Nano-Probe system, the inner and the outer diameter of the stylus is 3 mm and 4 mm, respectively, and a focal length of the objective lens is 10 mm and the diameter of the ball is 5mm. From the experiments, we reached that the Nano-Probe system is small and simple to fit to use for Nano-CMM. Fig. 8 shows the relationship between the output voltage from QPD and the shift of ball, when the ball moved by a piezo electric device at the range of 650 nm. These results show that Nano-Probe system has up to 10 nm resolution.

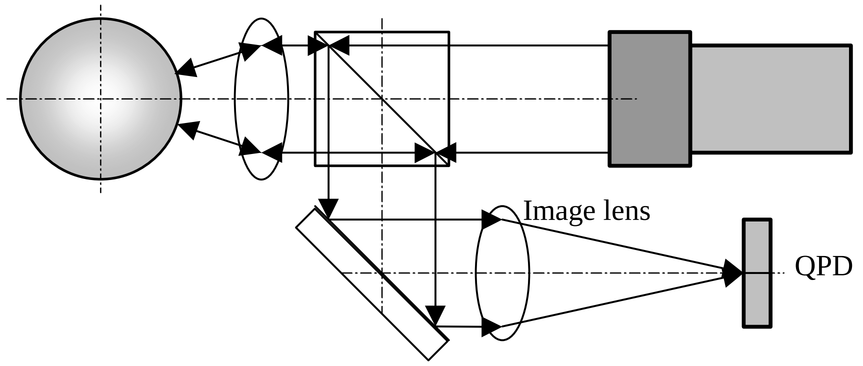
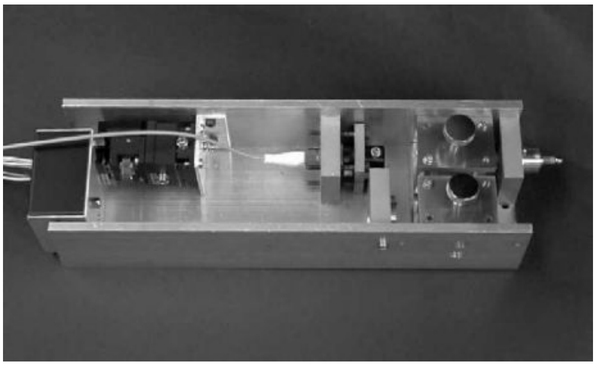
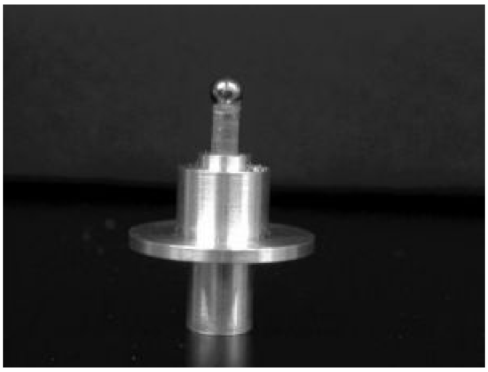


Fig. 6 Optical setup of Nano-Probe system



(a) Prototype of Nano-Probe system



(b) Stylus of Nano-Probe

Fig. 7 Photograph of Nano-Probe system

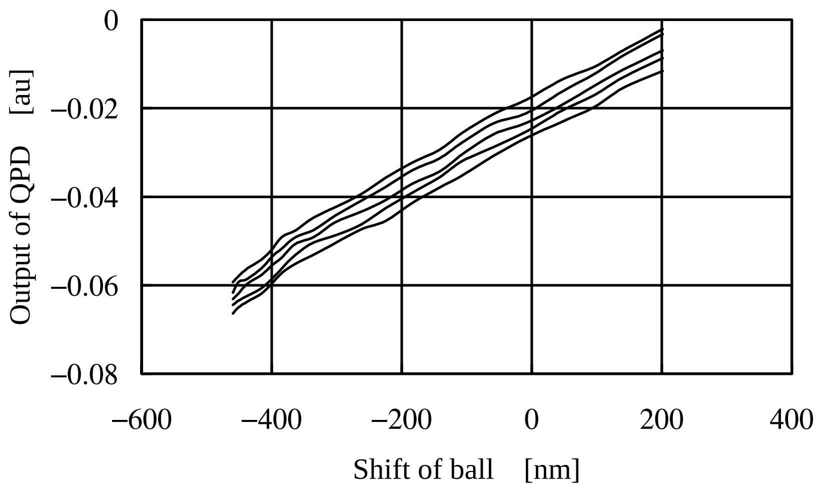


Fig. 8 Relationship between the normalized output of QPD and the shift of ball

2.5 Future works for Nano-CMM

From the development of the first prototype of Nano-CMM, the series of measurements show the following future works:

- Development of Z stage of Nano-CMM.
- Establishment of calibration method of Nano-CMM.
- Miniaturization of Nano-Probe system.

3. Development of Parallel-CMM

3.1 Basic concept of Parallel-CMM

The position errors of joints in a serial mechanism are accumulated, in the other hand, they are averaged for a parallel mechanism because an end-effector is connected with a base unit in parallel. For the same reason, the parallel mechanism has higher rigidity and accuracy. In serial mechanism, the dimensions of components depend on their positions: a part close to the base has to be stronger and thus heavier. However, we can use lighter components that have small inertia in the parallel mechanism because of its structure. So, the probe fixed on end-effector can move quickly and the measurement time becomes shorter.

In parallel mechanism, solving forward kinematics is difficult and this problem is a drawback for measurement. But some structures are known for an easy solving of forward kinematics. Therefore, we adopted the novel 3-DOF parallel mechanism like DELTA mechanism is one of the structures which forward kinematics can be solved analytically.

Fig. 9 and Fig. 10 shows basic concepts of 3-DOF Parallel-CMM developed us for the purpose of measuring experiment. This mechanism consists of DC motors, linear mechanisms that transform rotational movements of motors into the linear movement using a ball screw and a ball nut, rotational joints or ball joints, connecting rods and an end-effector. All heavy components that are the DC motors and the linear mechanisms are fixed on the base unit at the intervals of 120 degree, so the upper part of this mechanism is very light and can move quickly. The end-effector can move only X, Y and Z-axis and does not rotate, because the rotational joints or ball joints and the pair of rods make a parallel crank mechanism.

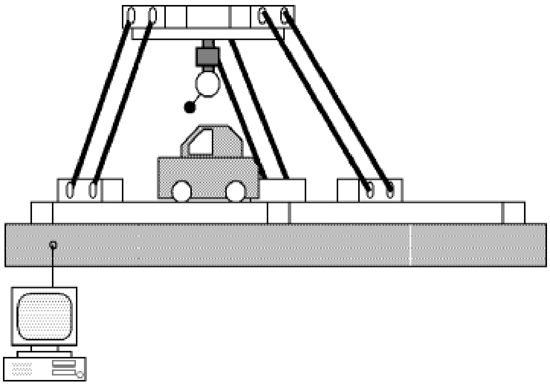


Fig. 9 Basic concept of 3-DOF Parallel-CMM

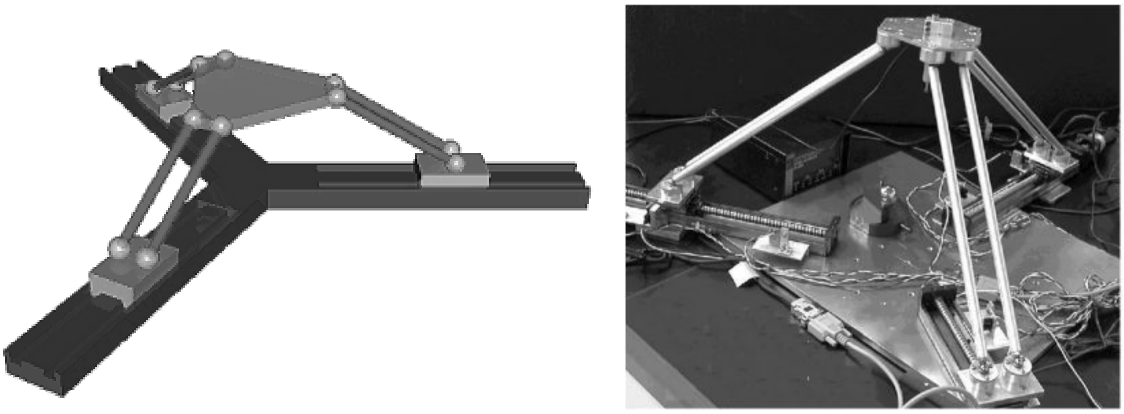


Fig. 10 Basic construction and photograph of the prototype of 3-DOF Parallel-CMM

3.2 Magnet ball joint

In the prototype of Parallel-CMM, the key unit is the rotational joint and the ball joint. The repeatability and the moving range of the joints decide the accuracy and the measuring range of Parallel-CMM. For the first prototype, we use normal rotary bearings as the rotational joints (see Fig. 12). The first prototype moves rickety and has not good repeatability, because the rotational joints have low stiffness. Therefore, we developed the magnet ball joint which consists of a steel ball, a triangle hole plate and a strong magnet for the second prototype of Parallel-CMM. Fig. 11 shows the construction and the photograph of the magnet ball joints. The repeatability of the magnet ball joint is depend on the sphericity of the ball, so we expect the magnet ball joints have high repeatability.

Fig. 11 Construction and photograph of the magnet ball joints

3.3 Repeatability of Parallel-CMM

Fig. 12 displays the repeatability test of the first and the second prototype of Parallel-CMM using a touch trigger probe and a gauge block. Table 3 shows the result of repeatability of Parallel-CMM. We conclude that the magnet ball joints has good repeatability.

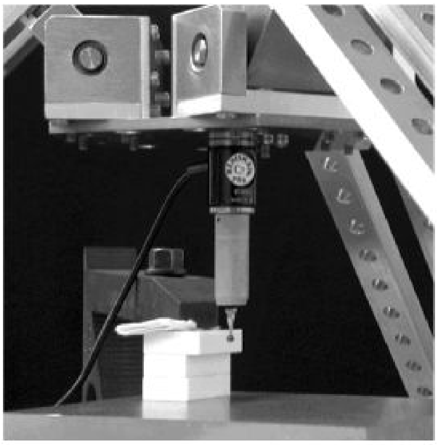


Fig. 12 Repeatability test of Parallel-CMM

Table 3 Repeatability of Parallel-CMM

Measuring direction	X	Y	Z
Rotary bearing	6.0 μm	5.9 μm	3.0 μm
Magnetic ball joint	1.4 μm	2.9 μm	2.9 μm

3.4 Future works for Parallel-CMM

We made two prototypes of 3-DOF Parallel-CMM which have the rotary joints or the magnetic ball joints. From the development of 3-DOF Parallel-CMM, we pointed out the following future works:

- Development of the control system of Parallel-CMM.
- Establishment of calibration method of Parallel-CMM
- Development of the large and high speed Parallel-CMM.

4. Conclusion

We pointed out that the limits and the drawbacks of the traditional CMMs are clearly such as the limit of the accuracy, measuring range, measuring speed and so on. Therefore, we have started developing novel systems and key technologies for 21th century CMMs. In this article, we introduced two of our developing projects; “Nano-CMM project” and “Parallel-CMM project” carried out in the University of Tokyo.

We reached the following conclusions from the developments and the series of experiments of Nano-CMM:

- The thermal conditions is most important for Nano-CMM.
- The friction drive system works good for Nano-CMM.
- Straightness of the prototype is approximately 50 nm and the repeatability is approximately 20nm.

- Nano-Probe system which consists of the optical sensing system and the stylus is made and tested.
- The resolution of Nano-Probe system is up to 10 nm.

We constructed 3-DOF Parallel-CMM and reached the following conclusions:

- For our 3-DOF Parallel-CMM, the forward kinematics can be solved analytically.
- The magnetic ball joint are made and tested. It has good repeatability and fit the rotational joint of Parallel-CMM.
- The repeatability of Parallel-CMM is up to 3 μm.

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