The Structure Design and Analysis of a Parallel Kinematic Mechanism Based on Abbe's Principle

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Abstract. The purpose of this study is to design and analysis of a parallel kinematic mechanism based on Abbe's principle can be applied to the 3D-coordinate measuring machine. In this study is the design and analysis of the parallel kinematic mechanism, which includes the mechanism design of linear drive rod mechanism and displacement sensing position coaxial, and the intersection of the three linear drive rod mechanisms are located at the contact probe. Therefore, the design of this study improves the displacement of the linear drive rod and Abbe error resulted from the angle variation of the displacement sensor. Furthermore, the mechanism performance has been verified experimentally. Through precision tests of the machine by a laser Doppler interferometer, the linear drive rod mechanism positioning precisions are within 1μm.

1. Introduction
Coordinate Measuring Machines (CMMs) are extensively used throughout the industry to measure the geometries, dimensions and profiles of a wide range of components. With advances in micro-electro-mechanical systems (MEMS) and ultra-precision manufacturing technologies in recent decades, the characteristic scale of many devices has reduced to the micro- or even nanometer level. Consequently, a requirement exists for CMMs with commensurate measurement capabilities. Leach et al. [1] described three instruments developed at the National Physical Laboratory in the UK for facilitating accurate and traceable measurements at the nanometer scale, namely (1) an atomic force microscope (AFM) / surface texture measuring instrument; (2) an optical / X-ray interferometer calibration system, and (3) a CMM with a working volume of (50 mm)3 and a volumetric accuracy of 50 nm. Fan et al. [2] presented a high-precision, low-cost micro-CMM featuring an arch-shaped bridge designed to provide an improved stiffness and thermal accuracy and a co-planar stage designed to reduce the Abbe error. The experimental results indicated that each axis had a positioning resolution of 1 nm, while the overall working area had dimensions of 25 × 25 × 10 mm3. Fan et al. [3] presented design considerations of a precision micro-CMM system and its mechatronic modules. The basic design concept is to meet the requirements of high stiffness, force balance, thermal balance, Abbe principle, metrology frame and vibration-free. Based on these criteria, a novel bridge of pagoda shape was designed and analyzed by optimization to verify its superior stiffness with force balance and thermal balance structure due to its symmetrical geometry, moreover, the co-planar XY stage, the ram and the nano-scale encoder. The experimental results indicated that each axis had a positioning accuracy of ±10 nm, while the overall working area had dimensions of 20 × 20 × 10 mm3. Brand et al. [4] modified a commercial CMM through the addition of high resolution scales and optimized air bearings to enable the dimensional metrology of micro system components with a measurement uncertainty of less than 1 nm. The proposed system incorporated two sensing systems, namely an opto-tactile 3D-sensor and a tactile touch trigger sensor, respectively, and incorporated a metrology frame comprising three miniaturized plane mirror laser interferometers which enabled the simultaneous measurement of both the displacement and the angle of the object of interest. Looking at the literature of many research units in the market or abroad, the results of CMM [5-12], most of their designs are serial-type CMM, so this study will design a parallel kinematic mechanism based on Abbe's principle can be applied to the 3D-coordinate measuring machine.
2. Design of the parallel kinematic mechanism

The mechanism is designed with three linear drive rods mounted on the three universal joints of the top casting. The other end of each drive rod is directly connected to the probe stage to form a three-degree-of-freedom parallel kinematic mechanism, as shown in Figure 1. The optical linear encoder provides instant feedback to the system when the drive rod moves. This design method creates to the driveshaft and the optical linear encoder to be positioned coaxially, and the intersection point of the three drive shafts is at the contact probe sphere, as shown in Figure 2. This design improves the Abbe error caused by the difference between the displacement of the drive rod and the angle of the optical linear encoder, improve the accuracy of the machine. In addition, the mechanism has a working volume of XY axes is Ø200 mm and Z-axis is 200 mm.

Figure 1. Schematic diagram of the parallel kinematic mechanism.

Figure 2. Three-view diagram of the parallel kinematic mechanism.
3. **Design of the linear drive rod mechanism**

   The linear drive rod mechanism has been adopted for the actuator of the parallel kinematic mechanism. Figure 3 displays the basic construction of the linear drive rod mechanism of the parallel kinematic mechanism. A capstan roller is rotated by a servo motor with a Harmonic Drive. And the pre-load is obtained to the capstan roller by two idle rollers with a pre-load spring.

![linear drive rod mechanism](image)

**Figure 3. Photograph of the linear drive rod mechanism.**

4. **Experimental set-up and measurement results**

   The optical linear encoders in the parallel kinematic mechanism were to measure the displacements of the micro-positioning stages during the mechanism motion procedure. To confirm the precision of the optical encoders, a series of positioning tests were performed in which the displacement measurements obtained from the optical encoders were compared with those obtained using a laser Doppler interferometer. The experimental configuration is shown in Figure 4.

![experimental set-up](image)

**Figure 4. Schematic diagram of the experimental set-up.**

In the experiments, the linear drive rod was driven through a total distance of 200mm in incremental steps of 10mm and was then returned to its starting point again in the same incremental steps. The experiment was repeated seven times for each stationary position of the mechanism. Figure 4 plot the differences between the seven times positioning precision measurements and the corresponding Doppler measurement at each stationary position. From inspection, it was determined that the displacement measurements of the encoder deviated from those of the laser interferometer by no more than 1μm. If the influence of the environment was isolated, the positioning precision of the linear drive rod could be further improved.
5. Conclusion
This study successfully developed a parallel kinematic mechanism that can be applied to CMM, and its characteristics are as follows:

1. In order to reduce the influence of Abbe error on the parallel kinematic mechanism. Therefore, this study uses the design of the linear drive rod and displacement sensing position coaxial, and the intersection of the three linear drive rod mechanisms are located at the contact probe. The design of this study improves the displacement of the linear drive rod and Abbe error resulted from the angle variation of the optical linear encoder, and improves the accuracy of the machine. In addition, the mechanism has a working volume of XY axes is Ø200 mm and Z-axis is 200 mm.

2. In order to improve the positioning accuracy of the CMM machine, this study designed a linear drive rod mechanism to drive the parallel kinematic mechanism to achieve the purpose of 3-DOF motion. The experimental results have shown that the mechanism has a positioning accuracy of 1μm.

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6. References
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