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A Micro-CMM for Non-contact 3D Measurement in Meso Scale

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Abstract

A high precision Micro-CMM (Coordinate measuring machine) is under development at the School of Instrument, Hefei University of Technology, in collaboration with National Taiwan University. The expected measuring range is 25 x 25 x 10 mm and the resolution is about 10 nm. For the enhancement of machine accuracy, some new design concepts are introduced, such as the arch-bridge and the co-planar stage. The coarse and fine motions of each axis can be achieved by the piezo-ceramic linear motor. A linear diffraction grating interferometer is developed for the feedback of linear motion. In this report, the design principles of the developed Micro-CMM are described.

1. Introduction

Technology of ultra-precision 3-D profile measurement has received a great attention during the past decade [1]. Various types of nanometer probes were developed and successfully commercialized, such as STM, AFM, confocal probe, auto-focusing probe, etc. [2-5]. It was noted by Takamasu [6] that most researches in the past dedicated interests in the 1-D probe system only. An overall consideration in the 3-D system and its integration shouldn't be overlooked. Small sized CMMs have become a new topic of research, such as the Nano-CMM by Takamatsu [6], Small-CMM by NPL and [7], Miniature Probe System by Eindhoven Univ. [8] and PTB [9], Micro-CMM by Fan [10], etc. Small CMM requires higher accuracy and resolution. Scaling down the conventional CMM design principle is not a feasible way. Some new design concepts have to be introduced. This paper presents an innovative CMM design, including the arch-bridge, the coplanar precision XY-stage, the spindle, the motion actuator and feedback system, and the autofocusing probe. This Micro-CMM is designed for the measurement of mesoscale parts to the accuracy of nanometer range. It is aimed at achieving 10nm resolution within a measuring range of 20x20x10mm.

2. System Configuration of the Micro-CMM Structure

2.1 Concept of the arch-bridge structure [15]

Rectangular type of the bridge is always employed in the precision CMM structure for mounting the Z-axis probe, as shown in Fig. 1a. The deformation in the center of the bridge is very critical because of the concentrated load from the spindle. The maximum deflection at the center of the rectangular-bridge can be described as (P is the spindle load and R is the half span of the bridge):

$$\delta_{y\max} = 0.55\frac{PR^3}{EI} \qquad (1)$$

The research proposes a fixed arch-bridge structure, as shown in Fig. 1b. Under the same dimension and the same spindle load, the maximum deflection at the center of the arch-bridge can be reduced to (R is the radius of the semi-circle bridge):

$$\delta_{y\max} = 0.24\frac{PR^3}{EI} \qquad (2)$$

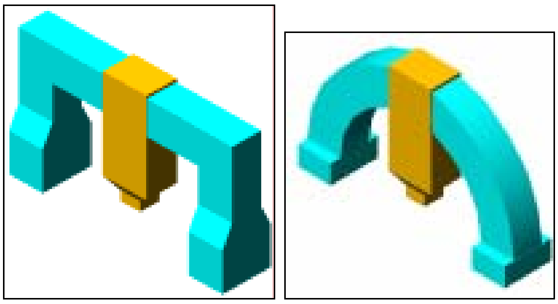

Figure 1: (a) the rectangular bridge, (b) arch-bridge.

Let the material be granite; the outer radius is 220mm and the inner is 150mm; the width is 60mm and the dimension of the supporting pad is 70mm╳100mm╳40mm. The total weight is about 40kg. Fig. 2 shows the deformed shapes of two bridges by finite element method. Table 1 lists the comparison between the analytical and FEM methods. It can be seen that the arch-bridge performs better static stiffness than the rectangular bridge.

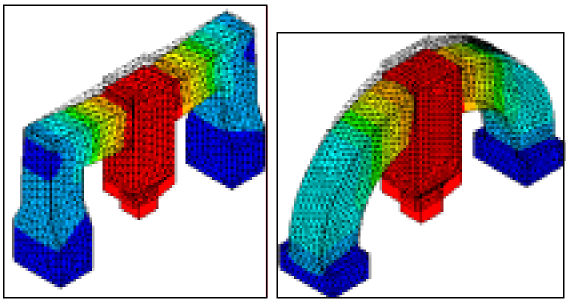

Figure 2: Deformed bridges by FEM analysis

Table 1: Comparison between Rectangular-bridge and Arch-bridge (μm)

Deflection	Analytical solution with spindle load	FEA	
		Spindle load	Self-weight
Rectangular	0.398	0.362	0.156
Arch-bridge	0.197	0.174	0.102

2.2 Concept of the Co-planar XY stage

Conventional XY stage is stacked up by two linear stages composing of many components, such as ball screw, bearing, linear slide, etc., as shown in Fig. 3. The Abbe' error of the lower stage is high and the components are made in micrometer accuracy ranges. More considerations should be taken into account when the XY stage is used to the micro/nano motion accuracy. An innovative co-planar stage is thus proposed in this study, shown in Fig. 4. The table is moved along the precision ground rod of the frame in the X-direction, and the frame is moved along the precision ground rod of the based. Four guiding rods are located in the same plane, as shown in Fig. 5. With such a design, the Abbe' error in vertical direction can be reduced. In addition, there are no more transmission components and the geometry is symmetrical, which ensures better static deformation under the same working conditions. Each axis motion is actuated by a motor from one side and its motion is detected by a scale from the other side. The whole stage is made of Invar steel so that the thermal deformation due to the driving heat can be significantly reduced. In order to minimize the moving weight, a modified structure is designed in the form of Fig. 6. From the Finite Element Analysis with ANSYS software it shows that at the table center the static deformation is about 0.13μm, and the thermal distortion is only 3.2nm assuming a 5 ℃ temperature rise at the driver.

2-3 The Driving system and feedback sensor

In order to remain high motion accuracy, the coplanar X-Y stage and the Z-stage are all driven by Piezo Ceramic Linear Motor (PCLM) made by Anorad Co. [11]. The PCLM system consists of the motor and a drive amplifier to excite the motor. These two components are combined to create the piezoelectric effect. This effect converts electrical field to a mechanical motion. The important role of operation is the 4 piezo elements PCLM (Type SP-4) motor. When the voltage is applying across the element in a precise sequence, the edge of the piezo element generates an elliptical motion. This elliptical motion then drives the stage by friction force to create linear motion, as shown in Fig. 7. The position feedback of linear motion in each axis is detected by the principle of linear diffraction grating interferometer (LDGI), as shown in Fig. 8, with a 1nm resolution [12].

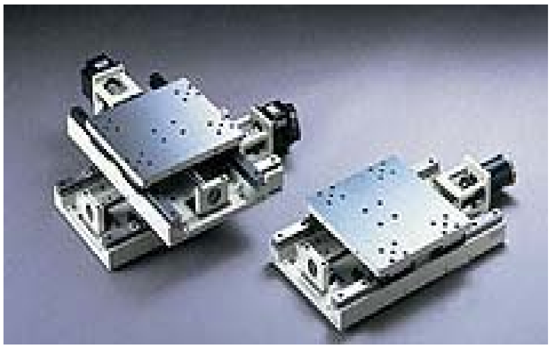

Figure 3: Conventional XY-stage

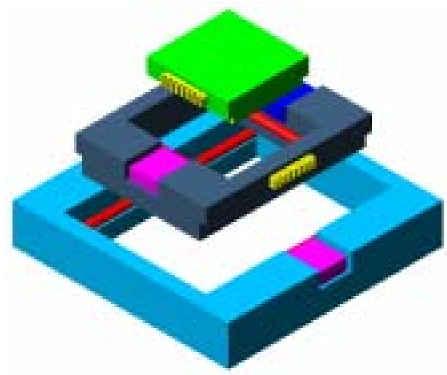

Figure 4: Proposed co-planar XY-stage

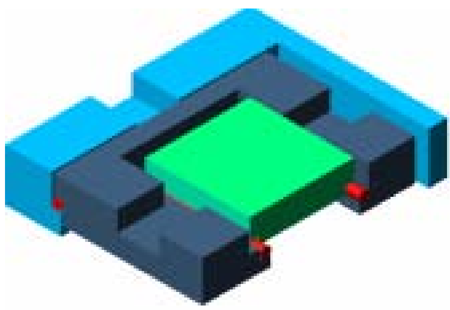

Figure 5: Sectioning view showing the guiding rods

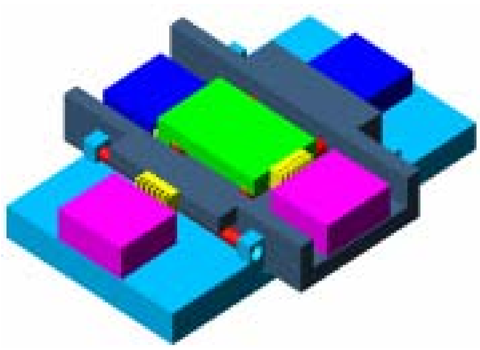

Figure 6: Final stage in minimum weight

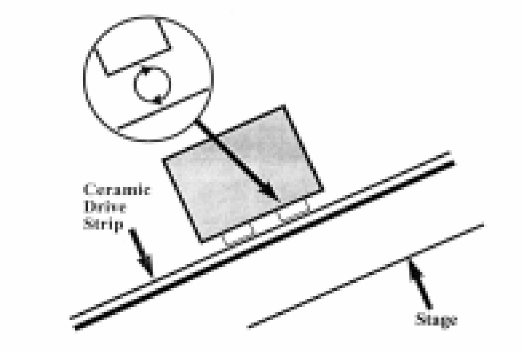

Figure 7: Motion principle of the PCLM

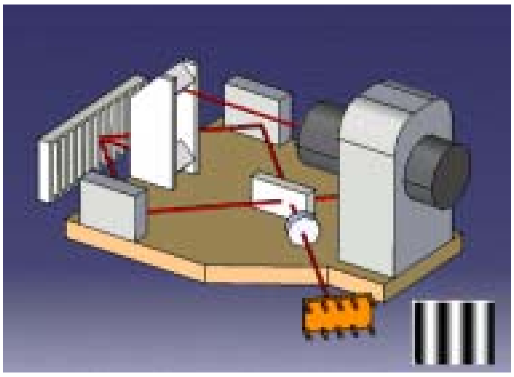

Figure 8: Position feedback principle of the LDGI

2-4 Spindle head design

The spindle that carries the probe is moved along a short linear stage, which is driven by a PCLM and its motion is detected by a LDGI, as shown in Fig. 9. The grating scale is in line with the spindle so that there is no Abbe' error. A counterweight is applied to balance the total mass center during the spindle motion. The whole structure of the developed Micro-CMM is shown in Fig. 10.

The overall design specifications of this Micro-CMM are summarized in Table 2.

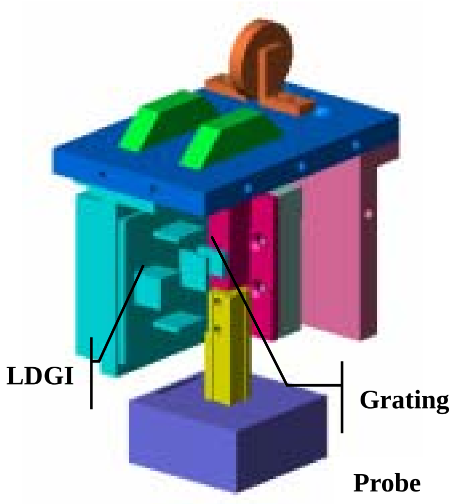

Fig. 9: The spindle head design

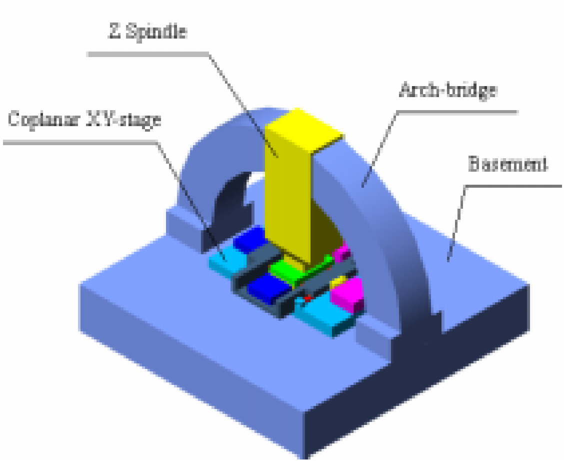

Figure 10: The innovated Micro-CMM

Table 2: Specifications of the Micro-CMM

Size of machine, mm^3	300x300x300
Weight of machine, Kg	40
Measuring range, mm^3	25x25x10
Resolution, nm	1
Accuracy, nm	30

3. Development of an Auto-focusing probe

This research aims at development of a low cost optical probe [13] with the measurement capability in the sub-micron range. The pickup head of the commercial DVD player was adopted based on its principle of focus error. With the proper modification on its signal processing unit, this head can be converted to a profile probe with sub-micron accuracy.

A commercial DVD player pickup head was used for this experiment. In principle, the pickup head essentially is an auto-focusing laser probe, as shown in Fig. 11. A 780 nm wavelength light source generated from a laser diode is primarily polarized by a grating plate. By passing through a beam splitter and a quarter wave plate the light beam is focused by an objective lens onto a 2 mm away object surface with a spot size approximately 1 μm in diameter. The reflected beam signal is imaged onto a four-quadrant photo detector by means of the quarter wave plate. The photodiode outputs are combined to give a focus error signal (FES) which is used for feedback control the position of the movable lens suspended by the voice coil motor within the sensor such that the focal spot of the beam remains coincident with the object surface. In this system, the focusing signal is detected by the Astigmatic method. At the focal plane, the spot is a pure circle. While away from the focal plane, the spot appears an elliptical shape in different orientations with inside or outside the focal planes. The corresponding FES is detected by a photodiode, which provides an S-curve signal proportional to the distance, as shown in Fig. 12. This motion control strategy is implemented by a DSP (TI Co, 32-bit) with some surrounding circuits as shown in Fig. 13. Fig. 14 shows the control principle of moving the lens in steps according to the height change of the surface in order to lock the focal point all the time. The linear range can be extended to over 1mm.

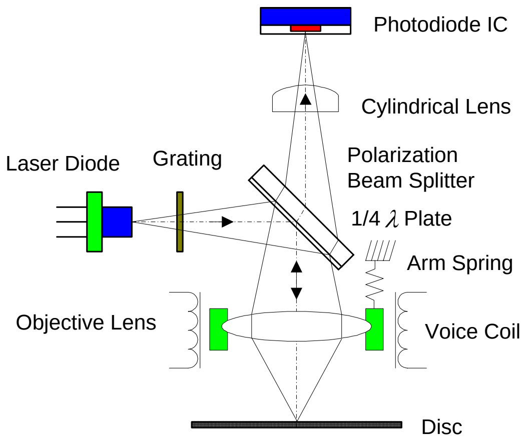

Fig.11: Principle of autofocusing probe

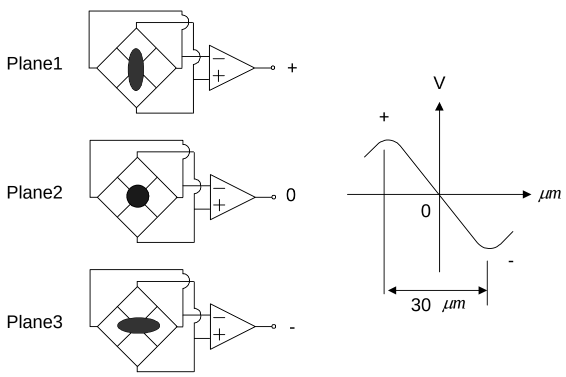

Fig. 12: The variation of the spot shape with the S-curve.

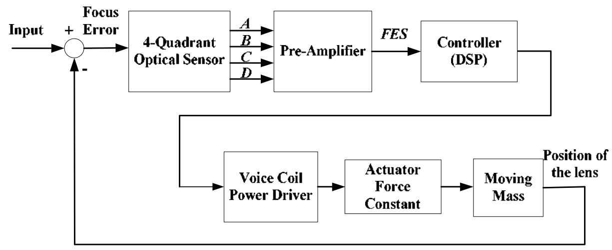

Figure13: System control loop of the probe

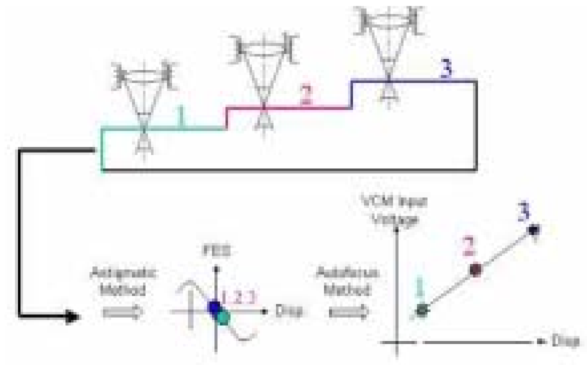

Figure 14: Autofocusing principle

4. Experimental Tests

The developed Micro-CMM has been fabricated in components and integrated into a prototype machine, as shown in Fig. 15. Some performance tests have been carried out.

4-1 Positioning accuracy tests

The motion of each axis can be calibrated using a laser interferometer in a temperature and humidity controlled room. For the long stroke test, the positioning accuracy is about 0.9μm (±3σ) over 25mm, as shown in Fig. 16. For the short range test (fine motion) with only 0.3μm travel the averaged maximum positioning error is only 20nm. This performance can meet our original requirement of 30nm.

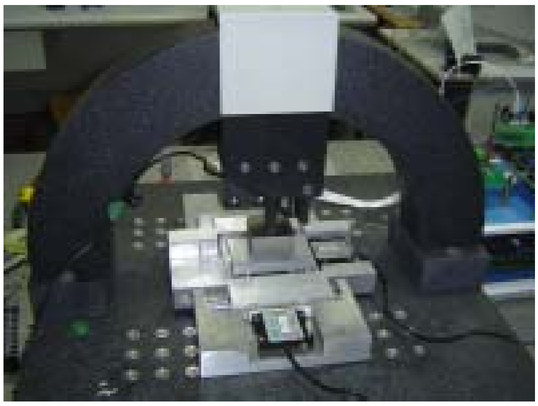

Figure 15: The prototype Micro-CMM

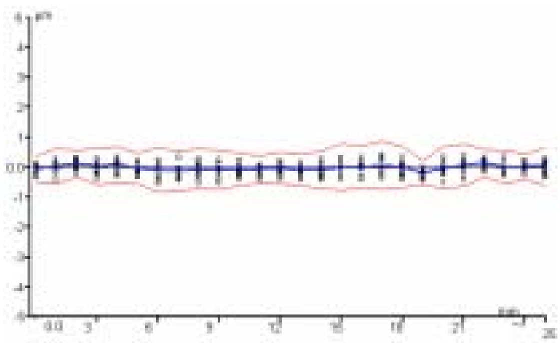

Figure 16: Long stroke positioning accuracy of one axis

4-2 Autofocusing probe tests

The focus error signal (FES) test was carried out by mounting the probe on a linear stage. The stage motion was measured by a laser interferometer. Fig. 17 shows the tested results with respect to different materials. Good S-curve means the material has good reflection surface [14].

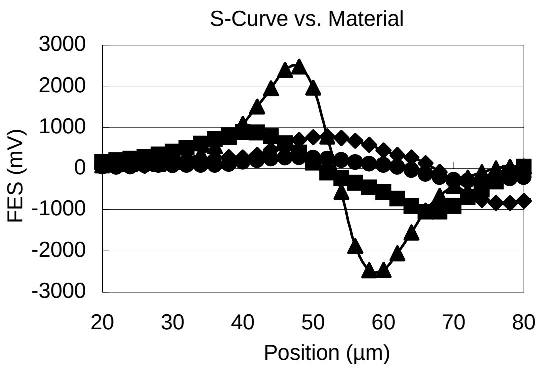

Figure 17: S-curves for various materials

In the experiments of autofocusing motion, the objective lens will be moved by the VCM along with the surface variation in order to lock the zero voltage of the 4-Q detector output. Fig. 18 shows the result that a 1.5 mm linear range of the servo controlled displacement of the voice coil motor with respect to the FES was found [13]. Having calibrated, the probe can reach to around 0.1µm accuracy for autofocusing (Servo-FES) function and 30nm accuracy for focusing (FES) function.

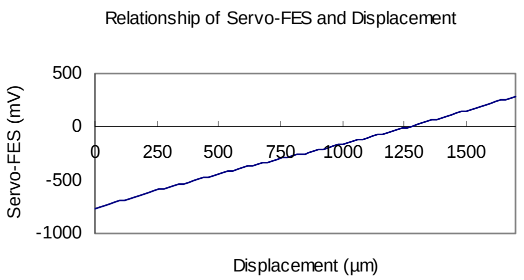

Figure 18: Relationship between the motion of the objective lens and the FES.

4-3 System integration

The whole software system of this prototype Micro-CMM is developed in the LabView environment. Current work has not completed the system integration and tuning processes. Moreover, the volumetric errors of the CMM have to be calibrated and compensated in order to achieve higher accuracy. Ambient conditions are also sensitive to its accuracy. An environmental controlled chamber is under developing to shed this machine.

5. Concluding Remarks

This article states the current progress on the development of a Micro-CMM. Design considerations and preliminary results are described. With the particular consideration in the structural accuracy, the innovative arch-bridge and the co-planar stage are proposed. Equipped with the PCLM actuator and the LDGI feed back position sensor the motions in three directions can be achieved to nanometer resolution and 30nm accuracy after calibration. The autofocusing probe is integrated into the system to form a prototype micro-CMM. Experimental tests have shown the feasibility of the current system. Future tasks will implement the performance tests volumetric error compensation to further enhance the system accuracy. In addition, the miniature contact probe will be studied..

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