Design of a large-scanning-range contact probe for nano-coordinate measurement machines

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1 Introduction
The increasing demands of industry for higher-accuracy measurements of microsystems have led to the development of the field of micro- and nanodimensional metrology. During the past decade, several micro- or nano-coordinate measuring machines (CMMs) that can measure meso- to micro-scaled parts with nanometer resolution have been developed. They are equipped with noncontact probes or contact probes. Although noncontact probes feature fast surface scanning, for any CMM, three-dimensional (3-D) contact probes are indispensable owing to their capability to measure most fundamental geometries, such as line, plane, circle, sphere, cone. A variety of contact probe systems have been designed for micro/nano-CMM, such as silicon-based, flexure structure-based, fiber Bragg grating type, boss membrane structures, suspension plate, and single fiber. A summary of some probe systems has been made by Weckenmann et al. Some of them are only touch trigger probes, and others possess a rather small scanning range, normally <10 μm.

Our group has developed a scanning tactile probe composed of a monolithic fiber stylus with a ball tip, a wire-suspended floating plate as the main mechanism, and some focus sensors. The measurement range of this probe is only several micrometers and, with four focus sensors embedded, its size is quite large.

A new contact probe having a large scanning range for micro/nano-CMM is presented in this paper. Its working requirements include (1) scanning range is ±20 μm in all axes, (2) resolution is 1 nm, (3) stiffness is equal in three dimensions, (4) to fit the CMM dimension, the probe head diameter should be <40 mm.

2 Design Principle
This scanning probe is composed of a fiber stylus with a ball tip, a mechanism with a wire-suspended floating plate, a two-dimensional (2-D) angle sensor, and a novel miniature Michelson linear interferometer. The stylus is attached to the floating plate. The wires experience elastic deformation when a contact force is applied, and then the mirrors mounted on the plate are displaced; the displacements can be detected by corresponding sensors. According to industrial demands, such as scanning range, resolution, equal stiffness, contact force, and probe size, several constrained conditions are established, and the optimal structure parameters of the probe are selected. Each component of the probe is designed, fabricated, and assembled in this research. Simulation and experimental results show that the probe can achieve uniform stiffness, ±20 μm scanning range, and 1-nm resolution in x, y, and z directions. The contact force is about 40 μN when the tip ball is displaced 20 μm. It can be used as a contact and scanning probe on a micro/nano-CMM. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.OE.51.8.081503]
measurement directions. The equal stiffness property is essential, since it ensures a constant correlation between the probing force and the tip displacement regardless of the contacting angle. Figure 2 presents a schematic illustration of the stylus suspension structure developed in this study. The stylus is inserted into the floating plate, which is suspended by four evenly distributed wires connected to the probe housing. The symmetrical design has the advantage of easy manufacturing and assembly, thereby reducing systematic errors. The contact force causes the floating plate to tilt and move as a rigid body motion while the wires experience elastic deformations. Plate motion caused by the \(x\)- or \(y\)-directional contact is detected by the 2-D angle sensor on the corresponding mirror mounted on the floating plate. The vertical motion of the plate is detected by the novel miniature Michelson interferometer with respect to the central mirror. Other redundant mirrors are used for the weight balance.

3 Sensor Design

3.1 Two-Dimensional Angle Sensor

The schematic illustration of the 2-D angle sensor employed in this probing system is shown in Fig. 3. In the present study, it is modified from a DVD pickup head (Hitachi HOP-1000), which is inexpensive but adequately accurate. The original objective lens and the voice coil motor of a DVD pickup head are removed so as to output with a collimated laser beam. The built-in four-quadrant photodiode (QPD) is used as the beam spot position detector. The collimated laser beam is projected onto the plane mirror. When the mirror normal is in line with the laser beam, the reflected laser beam is focused at the center of the QPD. A tilt of the plane mirror causes a corresponding lateral shift of the position of the focused light spot across the center of the QPD. The photo detector transforms the incident energy of the focused light spot into electrical current signals. Deviations of the focused light spot from the center of the photodiode result in a corresponding change in magnitudes of the electrical signals output by the QPD. By applying an appropriate resistance to these electrical current signals, voltage signals can be obtained. Changes in the magnitudes of these signals can then be used to determine the \(x\)- and \(y\)-coordinates of the position of the focused light spot on the photodiode in accordance with the following expressions:18

\[
x = k[(V_A + V_D) - (V_B + V_C)]
\]

and

\[
y = k[(V_A + V_B) - (V_C + V_D)].
\]

3.2 Michelson Interferometer

Figure 4 presents the schematic illustration of a miniature Michelson interferometer specially designed for this study. It is responsible for the sensing of the \(z\) motion of the ball tip. The laser beam is separated into an S-beam and a P-beam by the polarization beam splitter (PBS1) with equal intensity. The P-beam passes through PBS1 and the S-beam is reflected to the reference mirror. The P-beam is changed to a right-circularly polarizing beam by the quarter wave plate (Q1) and reflected by the object mirror. When it passes through Q1 for the second time it is changed to an S-beam. Similarly, the reflected S-beam is changed to a P-beam when it passes through Q2 twice. These two returned beams will not go back to the laser diode but propagate to
Q3, after which the P-beam changes to a right-circularly polarizing beam and the S-beam changes to a left-circularly polarizing beam. The NPBS splits both beams into two separate beams to PBS2 and PBS3 with equal intensity. These four beams are phase shifted into 0-90-180-270 deg by PBS2 and PBS3 (set fast axis to 45 deg) and interfere with each other. Analyzed by the Jones vector, the intensity of each photo detector can be expressed as

\[ IPD_1 = \frac{A}{2} \left[ 1 - \cos(2\Delta \omega \cdot t) \right], \]
\[ IPD_2 = \frac{A}{2} \left[ 1 + \cos(2\Delta \omega \cdot t) \right], \]
\[ IPD_3 = \frac{A}{2} \left[ 1 + \sin(2\Delta \omega \cdot t) \right], \]
\[ IPD_4 = \frac{A}{2} \left[ 1 - \sin(2\Delta \omega \cdot t) \right], \]

and

\[ \Delta \omega = 4\pi \cdot \frac{\Delta x}{\lambda}, \]

where \( \Delta x \) is the optical path difference between reference beam and object beam, which is to detect the \( z \) movement of the central mirror of the floating plate in the probe, and \( \lambda \) is the wavelength of the laser diode.

Regarding the signal processing, with the operation of \((IPD_1 - IPD_2)\) and \((IPD_3 - IPD_4)\), two orthogonal sinusoidal signals with \( \frac{\pi}{2} \) phase shift can be obtained, as shown in Fig. 5. With the pulse counting and the phase subdivision techniques, the \( z \)-motion of the object mirror can be resolved to nanometer resolution. The size of the probe head is restricted by the allowable space in the micro/nano-CMM; therefore, the physical dimension of this interferometer is specially made to only about 4 × 3 cm, being a useful miniature Michelson interferometer.

4 Optimization Design of the Structure Parameters

4.1 Contacting Model of the Probe

To analyze the response of the displacement to the contact force, we have to find the stiffness model of the probe. Figure 6 illustrates the structure of the floating mechanism. The wires are deformed when a horizontal or vertical force is applied to the ball tip, as shown in Fig. 7. From elasticity theory, the displacement-to-force relationship can be derived:

\[
\begin{bmatrix}
\delta_{X,\text{ball}} \\
\delta_{Y,\text{ball}} \\
\delta_{Z,\text{ball}}
\end{bmatrix}
= 
\begin{bmatrix}
C_1 & 0 & 0 \\
0 & C_1 & 0 \\
0 & 0 & C_2
\end{bmatrix}
\begin{bmatrix}
F_{X,\text{ball}} \\
F_{Y,\text{ball}} \\
F_{Z,\text{ball}}
\end{bmatrix},
\]

where \( C_1 = \frac{L^3}{8EI} \cdot (3q^2 + 3qL + L^2) \), \( C_2 = \frac{L^3}{48EI} \), and \( I = \pi \cdot D^4 / 64 \).
The stiffness of the probe mechanism is the inverse of \( C \) in the corresponding direction. The parameters affecting the stiffness are wire length \( L \), wire diameter \( D \), stylus length \( l \), plate radius \( q \), the moment of inertia of the wire \( I \), and Young's modulus of the wire material \( E \).

### 4.2 Maximum Admissible Force

CMMs are designed to obtain highly precise measurements of a workpiece via a point-to-point measurement process. It is important that the magnitude of the probing force between the tip ball and the workpiece be less than the yield stress of either the tip ball or the material to ensure that permanent plastic deformation does not take place. The maximum admissible force \( F_y \) between the tip ball and the workpiece is given by

\[
F_y \approx 21.683 \frac{r^2 Y^3}{E^2} \quad (9)
\]

Assume that the workpiece is made of aluminum. Table 1 summarizes the mechanical parameters of the aluminum and the tip ball. To ensure that neither the workpiece nor the tip ball deforms plastically during the contact process, it is necessary to compute the maximum admissible force between them. Substituting the parameters into Eqs. (9) and (10), the maximum admissible force for the current probing system is found to be 1.4 mN. Given a large safety factor of 14, the maximum probing force is set to 0.1 mN.

### 4.3 Constrained Conditions

According to the design requirement for the probe, five constrained conditions to which the probe needs to conform are given as follows:

1. Uniform stiffness: from Eq. (8), set \( C_1 = C_2 \), so that

\[
6l^2 = 3q^2 + 3ql + L^2. \quad (11)
\]
(2) Maximum contacting force:

\[ F \leq 0.1 \text{ mN} \]  

(12)

(3) Measurement range:

\[ \delta_x = \delta_y = C_1 \cdot 0.1 \text{ mN} \geq 20 \mu \text{m} \]

\[ \delta_z = C_2 \cdot 0.1 \text{ mN} \geq 20 \mu \text{m} \]  

(13)

(4) Resolution of 1 nm:

\[ l \leq \sin \left( \frac{\varphi \cdot R_U}{U} \right)^{-1} \cdot 10^{-9} \]  

(14)

where \( \varphi \) is the angle measurement range of the angle sensor,

\( U \) is the maximum output voltage of the angle sensor,

and \( R_U \) is the resolution of the voltage.

(5) Cross-sectional size:

\[ q + L \leq 17 \text{ mm} \]  

(15)

### 4.4 Parameter Optimization

The optimized parameters calculated by the optimization method based on the above five constrained conditions are listed in Table 2.

From Table 2, we can see that the probe’s diameter \((2q + 2L)\) is 40 mm. The assembled probe conforming to these design parameters is shown in Fig. 8.

### 5 Compensation for Axes Alignment Error

The scanning probe has to work together with a CMM machine. In practice, the measured data of the workpiece is composed of the displacement of the machine and the displacement of the probe. We cannot directly add them together, since the orientations of these two coordinates may be different due to misalignment in installation. It is necessary to find a model to compensate for the cross-effect error.
5.1 Correction Model in Horizontal Plane

When the tip ball is moved in the $x$-axis of the CMM machine, both axes of the probe will output angle signals, shown in Fig. 9. This is due to the cross-axis effect. Because the coordinates of the CMM and the probe are located at two different coordinate systems, the cross-axis effect can be reduced by a coordinate transformation model. The schematic diagram of the two coordinate systems in the horizontal plane is shown in Fig. 10.

$X0Y$ is the coordinate system of the $XY$ stage of the CMM, $x0y$ is the coordinate system of the scanning probe, $\beta$ is the misalignment angle between these two coordinate systems, and $a$ and $b$ are the offsets between the origins of the two coordinate systems in the $x$ direction and $y$ direction, respectively. Point $C$ is an arbitrary point, whose coordinate is $(X, Y)$ in $X0Y$. Here, we take a reasonable assumption that the two coordinate planes are parallel, since only a 1-nm error happens when the angle between the two planes is 0.5 deg. We can make sure that the angle is $\leq 0.5$ deg by adjusting the probe.

The coordinate of point $C$ in $x0y$ can be expressed by the following equation:

$$
\begin{bmatrix}
  x \\
  y
\end{bmatrix} =
\begin{bmatrix}
  \cos \beta & -\sin \beta \\
  \sin \beta & \cos \beta
\end{bmatrix}
\begin{bmatrix}
  X \\
  Y
\end{bmatrix} +
\begin{bmatrix}
  a \\
  b
\end{bmatrix}.
$$

(16)

The two voltage signals $(u_1, u_2)$ from the angle sensor are linear to $x$ and $y$, respectively:

$$
\begin{bmatrix}
  x \\
  y
\end{bmatrix} = k
\begin{bmatrix}
  u_1 \\
  u_2
\end{bmatrix}.
$$

(17)

Therefore, the coordinate of point $C$ in $X0Y$ can be transformed into $x0y$ by the following equation:

$$
\begin{bmatrix}
  u_1 \\
  u_2
\end{bmatrix} =
\begin{bmatrix}
  \cos \beta & -\sin \beta \\
  \sin \beta & \cos \beta
\end{bmatrix}
\begin{bmatrix}
  X \\
  Y
\end{bmatrix} +
\begin{bmatrix}
  a \\
  b
\end{bmatrix}.
$$

(18)

The four unknown parameters $(k, \beta, a, b)$ can be obtained by the least-squares method from experiments. We can obtain the tip ball’s displacement in $X0Y$ by the following equation:

$$
\begin{bmatrix}
  X \\
  Y
\end{bmatrix} =
\begin{bmatrix}
  \cos \beta & \sin \beta \\
  \sin \beta & \cos \beta
\end{bmatrix}
\begin{bmatrix}
  ku_1 - a \\
  ku_2 - b
\end{bmatrix}.
$$

(19)

5.2 Correction Model in Vertical Direction

The transformation model in $z$ direction is simple:

$$
Z = z \cdot \cos \gamma + c,
$$

(20)

where $Z$ is the vertical displacement in $XYZ$, $z$ is the vertical displacement in $xyz$, $c$ is the deviation between the two zero points, and $\gamma$ is the angle between $Z$ and $z$ axes.

6 Analysis of the Contact Force

6.1 Analytical Solution

Applying the parameters given in Table 2 to $I$, $C_1$, and $C_2$ in Eq. (7), we can get $C_1 = 0.51$ m/N and $C_2 = 0.5$ m/N.
When $\delta_x = \delta_y = \delta_z = 20 \mu m$ in Eq. (12), the computed contact forces in X, Y, and Z directions are $F_{X,ball} = F_{Y,ball} = 39.2 \mu N$ and $F_{Z,ball} = 40.0 \mu N$. Similarly, we found that the computed contact forces in an arbitrary angle in XOY plane, XOZ plane, and YOZ plane are also 40 $\mu N$ when the tip ball is displaced by 20 $\mu m$. Therefore, the present probe has equal stiffness in three dimensions.

6.2 Simulation

To validate the correctness, the designed probe was simulated by a commercial software ANSYS. The tip’s displacement is shown in Fig. 11 when it is applied a 40-$\mu N$ force in horizontal (a) and vertical (b) directions. The calculated linearity of the probe within the measurement range is shown in Fig. 12. We can see that the probe has nearly equal stiffness in all three dimensions. The contact force is $<40 \mu N$ when the tip ball is displaced 20 $\mu m$. It is consistent with the analytical results.

7 Experiments

7.1 Experiment Setup

Figure 13 shows the schematic of the experimental setup. The scanning contact probe is assembled in a granite frame. The tip ball is displaced by a calibration gauge block which is fixed on the moving stage. The 3-D CMM stages are driven by three piezoelectric motors (PI Co.) in three axes. The displacements of the CMM stage are measured by three laser interferometers. The voltage signals from the two sensors are processed by their processing circuits and then transformed and recorded by data acquisition (DAQ) card (PCI-6251, National Instruments). An industrial computer is used to calculate and display. A photo of the experiment setup is shown in Fig. 14.

7.2 Measurement Range

The angle sensor is responsible for measurement in the horizontal plane. Figure 15 shows the measurement ranges in X direction. The measurement range in Y direction is similar because of the symmetrical design of the angle sensor and the probe. The displacement of the tip ball in Z direction is sensed by the miniature Michelson interferometer; Fig. 16 shows the measurement range in Z direction. From Figs. 15 and 16, we can see that the measurement range of the probe can achieve $\pm 20 \mu m$.

![Fig. 16 Measurement range in Z direction.](image1)

![Fig. 18 Signal processed by hardware filter only.](image2)

![Fig. 17 Output signal of the Michelson interferometer.](image3)

![Fig. 19 Signal further processed by software filter.](image4)
7.3 Resolution

The noise of the sensors’ output signals determines the probe’s resolution. The peak value of the Michelson interferometer’s output signal is 6.3 V (from Fig. 5), and the noise of the Michelson interferometer’s output signal is <70 mV, as shown in Fig. 17. Hence, the signal-to-noise ratio (SNR) of the Michelson interferometer’s output signal is about 90. The wavelength of the adopted laser diode is 632.8 nm. Based on the principle of interferometer, one signal period corresponds to half wavelength. In other words, 1/4 signal period (the voltage value is 6.3 V) corresponds to 1/8 wavelength (the displacement is 79.1 nm). Thus, the resolution of the Michelson interferometer can reach 0.9 nm.

Regarding the angle sensor, the voltage peak value corresponding to 20-μm measurement range is about 5 V (as shown in Fig. 15). In proportion, the required voltage resolution of 1 nm is 0.25 mV. Figure 18 shows one of the sensor’s output signals only processed by a hardware filter, whose noise level is about 40 mV. Figure 19 is the result of the signal being further processed by the sliding average filter whose sliding window size is 50 points. The noise level in Fig. 19 is only 0.2 mV. Therefore, the probe can accomplish 1-nm resolution in the horizontal plane.

7.4 Stability

Experimental results indicate that the fluctuation of the environmental temperature is the dominating factor affecting the stability of the probe. Further experiments reveal that the mechanical mechanisms in the probe are much more sensitive to temperature than the optical and electronic components of the probe. Therefore, we have to put the probe in a constant temperature chamber specially developed for this study. The measurement takes place until the temperature in the chamber is controlled to 20°C ± 0.025°C. Figure 20 shows the stability of the angle sensor. The signal drifts about 23 mV in nearly 2 h, or 0.2 mV (0.8 nm) per minute.

Figure 21 shows the stability of the Michelson interferometer. The two signals have almost no fluctuation after 4 h when the temperature is controlled to 20°C ± 0.025°C. It indicates that the measurement process has to wait for at least 4 h after the temperature in the chamber becomes stable.

8 Conclusions

This paper presents a large-scanning-range contact probe for nano-CMM based on a floating mechanism and two high-precision sensors. A special feature of this probe over other developed systems is that its detecting range can be up to ±20 μm in all directions. Two types of miniature sensors, namely the linear Michelson interferometer and the dual-axis angle sensor, were developed to fit into the probe head. Based on the design requirements and stiffness analysis for the probe, five constrained conditions are set and optimal structure parameters of the probe are obtained. Simulation and experimental results show that the probe can achieve equal stiffness, ±20-μm measurement range, and 1-nm resolution in three dimensions; the contact force is about 40 μN when the ball tip is displaced to ±20 μm. The average stability error is 0.8 nm/ min when the environment temperature is controlled to 20°C ± 0.025°C. It can be used as a contact scanning probe for a micro/nano-CMM.
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References


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