# Measurement of Pre-Travel Distance of a Touch Probe for Nano-CMM

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**Abstract**: In this paper, a measurement method of pre-travel distance of a touch probe, intended for a nano-coordinate measuring machine (CMM), was proposed. During the contact of the probe to the object, two key points are to be determined, namely the touched point and the triggered point, between which the pre-travel distance is defined. To calibrate this high-sensitive probe, the experimental system required three conditions: a nano-motion actuator, a high-resolution sensor and a multi-speed control method. An ultrasonic motor HR4 was used to generate both the long-stroke motion and the nano-positioning on the same stage that carried the object. A linear diffraction grating interferometer (LDGI) provided the displacement feedback to the resolution of 1 nm. The multi-speed control was carried out by generating a high speed motion of the object for approaching to the probe and then a low speed motion for triggering the probe. A double-trigger method was proposed to ensure the precision of the triggered point. The touched point was sensed by means of a switching circuit. The probe triggered signal and the stage displacement signal were sampled simultaneously through a DAQ card. Experiments show that with the proposed method the unidirectional repeatability of the pre-travel distance is within ±5 nm.

**Keywords**: nano-coordinate measuring machine (CMM); touch probe; unidirectional repeatability; pre-travel; double-trigger

# 纳米三坐标测量机接触式测头预行程测量

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**摘　要**：提出了一种用于纳米三坐标测量机接触式测头预行程测量的方法. 确定了预行程需侦测接触点和触发点两个关键点. 为了对该高灵敏度的测头进行标定，整个实验系统需要3个基本条件：纳米级驱动器，高分辨率传感器和多级速度控制算法. 本研究使用一种超声波马达HR4在同一平台上实现大行程粗略驱动以及微位移调整. 位移测量使用光栅传感器LDGI（linear diffraction grating interferometer），其分辨率可达1 nm. 在测试过程中采用高速逼近和低速触发，使用"双触发"方式获得触发点位置. 接触点位置的侦测使用开关电路. 触发信号和位移信号由同一块数据采集卡同步采集. 实验表明，使用该方法测量预行程，单方向重复性在±5 nm以内.

**关键词**：纳米三坐标测量机；接触式测头；单方向重复性；预行程；二次触发

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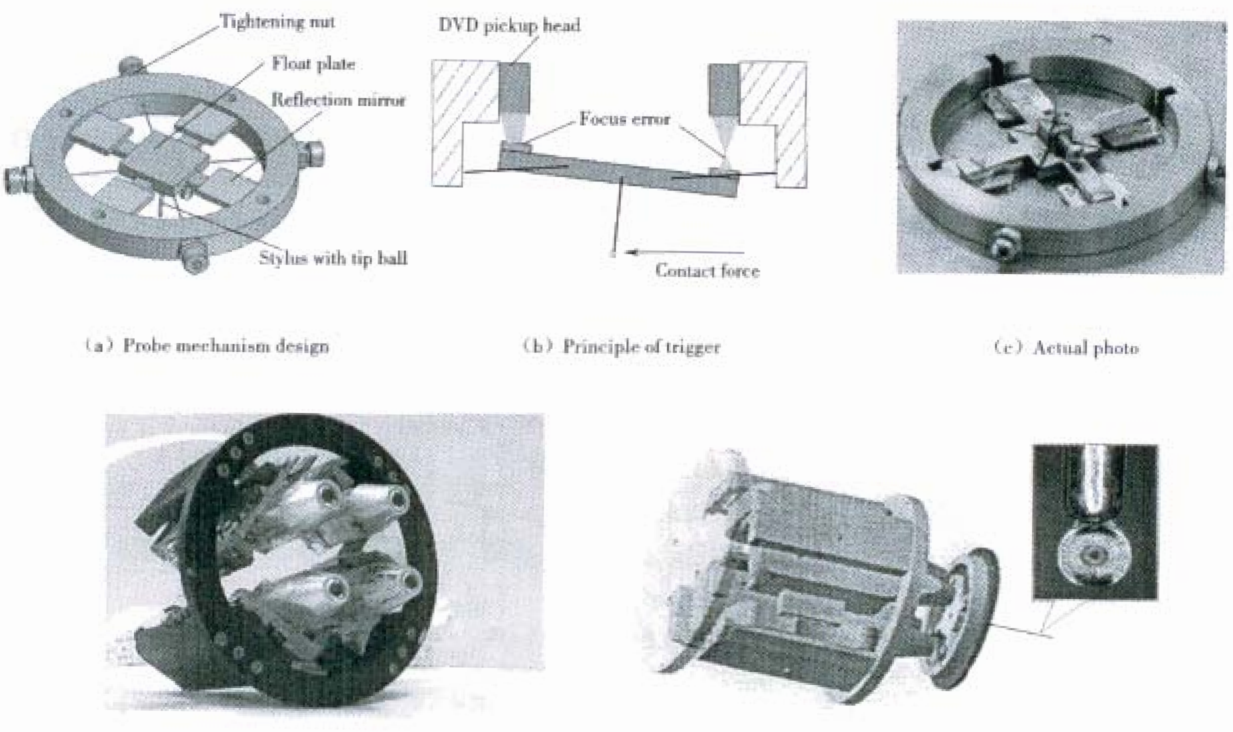
In recent years, several research groups have devoted to developing nano-coordinate measuring machine (CMM) that can measure three-dimensional meso- to micro-parts in nanometer resolution [1-2]. Some new probing systems are designed for various nano-CMMs[3-4]. The tiny deformation of the probe mechanism caused by weak contact force will generate an output signal [5-6]. Similar to the conventional CMM, probe characteristics include the touched point sensing when the probe is touched by the sample and the triggered point sensing when the output of the probe system is triggered. The pre-travel is the distance between the touched point and triggered point of the probe, which has to be compensated for in order to obtain the exact touched point[7]. Since the response range of the probing system is usually narrow, the detection of the touched point and triggered point is critical. Conventional servo motors are not appropriate because of their rough resolution and high speed, which will cause a permanent deformation on the probe mechanism. Piezoelectric transducer (PZT) actuators are often used to generate a high-resolution and low-speed motion but the travel length is limited[8]. An ultrasonic motor, HR4 made by Nanomotion Co[9], can generate different speeds with respective driving modes. This motor is used to actuate a long-stroke and nanopositioning stage in this work. For the probe calibration, the integration of high speed approaching and low speed touching is a necessary procedure for any CMM.

A nano-CMM has been developed by the authors' group [10]. Its sensing probe is of a non-contact type based on the astigmatic principle modified from a DVD pick-up head[11-12]. Although the non-contact probe is good for use in sensing the surface profile, it is not suitable for side wall measurement of the object. A scanning contact probe, therefore, has been developed by the authors' group in order to enhance the measurement capability of the nano-CMM[13]. This research further studies the repeatability and the pre-travel distance of this touch probe.

## 1 Design of the touch probe

The probe system includes three parts: a rigid stylus with tip ball, an elastically suspended mechanism and high-resolution sensors, as shown in Fig. 1(a). A four-armed floating plate is connected to the frame via four




(a) Probe mechanism design (b) Principle of trigger (c) Actual photo

(d) Four-focus sensors (e) Probe assembly

Fig. 1 Probe structure

thin wires. The stylus is fixed to the center of the floating plate and four reflection mirrors are mounted onto the four arms. Four thin wires serve as the elastic components, whose tension can be adjusted by corresponding nuts. Four reconfigured DVD pickup heads, playing the role of focus sensor, are fixed to the frame and adjusted to focus on the corresponding mirrors, respectively. As shown in Fig. 1(b), when the probe is touched by the workpiece, the tiny displacement of corresponding mirror will generate the focus error signal (FES) with the resolution of 1 nm[14]. Fig. 1(c) is the actual photo of the floating mechanism. Fig. 1(d) shows the installation of configured DVD pickup heads in the probe head and Fig. 1(e) is the schematic drawing of a complete probe.

Let the four FES values be $s_1$, $s_2$, $s_3$ and $s_4$, the triggered signal of the probe is defined as:

$$y = |s_1| + |s_2| + |s_3| + |s_4| \tag{1}$$

The touched and triggered processes can be illustrated by a simulated signal curve, as shown in Fig. 2. Before the tip ball touches the object the probe has no output signal. A signal cannot be generated immediately at the moment of touch due to the inertia of the floating mechanism. Only when the deformation of the floating mechanism is big enough, can the trigger signal be generated. Then, after this triggered point, a linear signal curve will arise corresponding to the movement of the tip ball. This over-travel range (the post-travel after the trigger point) is recorded in real time. The motion stops when the trigger signal reaches a threshold value of Eq. (1). In practice, the selected threshold should be high enough to identify the noises. Besides, the least-squares linear fitting of the over-travel range requires adequate sampled points. Experiments show that 20 mV of the threshold voltage is a moderate value.

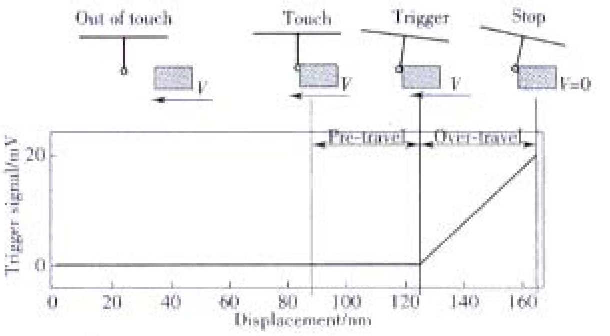



Fig. 2 Touched and triggered processes

## 2 Displacement sensor

In this study, a grating-based sensor linear diffraction grating interferometer (LDGI) is adopted for the displacement measurement of the linear stage that carries the object[10]. Similar to the traditional optical encoder, the outputs of LDGI have one sine and one cosine waveforms with 416 nm wavelength. Its optical system has been modified to a simpler configuration[15]. Using waveform correction and phase subdivision techniques, the resolution can reach 1 nm. Calibrated by an Agilent 5528 Laser Interferometer for different travel lengths up to 15 mm, results are listed in Tab. 1. The maximum standard deviation is less than 10 nm. The accumulated positioning error increases with the travel length. It is due to the alignment error of the grating direction with respect to the laser beam axis and this systematic error can be compensated for.

**Tab. 1 Experimental data of LDGI calibration**

| Position/mm | Error 1/nm | Error 2/nm | Error 3/nm | Error 4/nm | Error 5/nm | Average error/nm | Standard deviation/nm |
|---|---|---|---|---|---|---|---|
| 0.1 | 1 | 2 | -1 | 0 | 3 | 1 | 1.6 |
| 1 | 96 | 105 | 88 | 87 | 99 | 95 | 7.6 |
| 5 | 432 | 421 | 439 | 418 | 425 | 427 | 8.5 |
| 10 | 882 | 881 | 861 | 875 | 876 | 877 | 8.0 |
| 15 | 1 315 | 1 338 | 1 332 | 1 321 | 1 329 | 1 327 | 9.1 |

## 3 Double-trigger method

A large over-travel at high speed will cause permanent deformation of the probe mechanism due to large contact force. However, if the probe is far away from the touched point, low speed simply wastes the traveling time. A double-trigger method is thus developed.

### 3.1 Integration of three driving modes with ultrasonic motor

Conventional long-stroke and nanopositioning motion usually needs two stacked up stages, i. e., one long travel stage and one fine motion PZT stage. It requires complicated dual-loop motion control scheme. The authors' group has developed a single stage capable of long-stroke and nano-positioning motions[8]. Based on the same requirement, a co-planar stage for $X$ and $Y$ motions is also developed[16]. This co-planar stage is a module of the developed nano-CMM and is adopted for use in this work, only equipped with the new LDGI. An ultrasonic motor, HR4 made by Nanomotion Co, is employed to generate the 3-mode motions of a co-planar stage in different scales. In AC mode, HR4 generates a successive motion with 4 piezoelectric elements. With a neural network PID controller [17] the speed can be controlled to 1 mm/s. Then, in GATE mode, HR4 drives the stage in pulses with short steps of 20 nm—50 nm and the average speed is controlled to 25 μm/s. Finally, in DC mode, HR4 works like a conventional PZT actuator with low speed and nano steps [8-9].

### 3.2 Double-trigger method

The initial distance of the object to the probe before touch can be roughly estimated. At first, the AC mode is used to drive the linear stage that carries the workpiece toward the probe at high speed. When the distance is shorter than 0.5 mm the motion control is switched to the GATE mode for stepping motion. When the workpiece touches the probe the sensing system will be triggered for the first time. It will cause an over-travel less than 50 nm when the given threshold value of Eq. (1) is reached, then the motion stops. The stage is then driven backward by around 200 nm with GATE mode and the trigger signal resumes to the original level. In the last step, the DC mode generates 200 nm forward motion again with very low speed of about 10 nm/s, during which the sensing system is triggered again and the triggered position is recorded. This double-trigger process is described by the flow chart in Fig. 3.

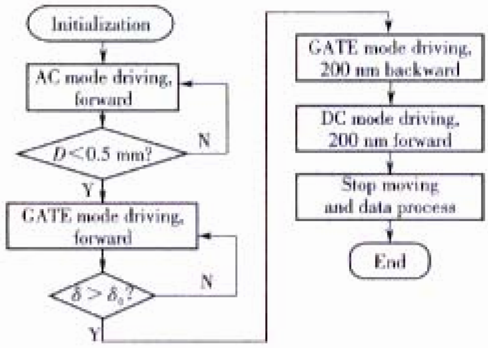



**Fig. 3 Double-trigger process** ($D$ stands for the distance between the probe and the touched point; $\delta$ stands for the signal voltage change; $\delta_0$ stands for threshold voltage)

### 3.3 Touched point detection

To detect the touched point, a switch circuit is designed as shown in Fig. 4. A copper block is used as the conducting material. When the copper block touches the stylus the circuit loop is immediately short, which will generate a step change of the output voltage. The copper block and the stylus are well polished to avoid unreliable contact, which will cause signal vibration at the step edge.

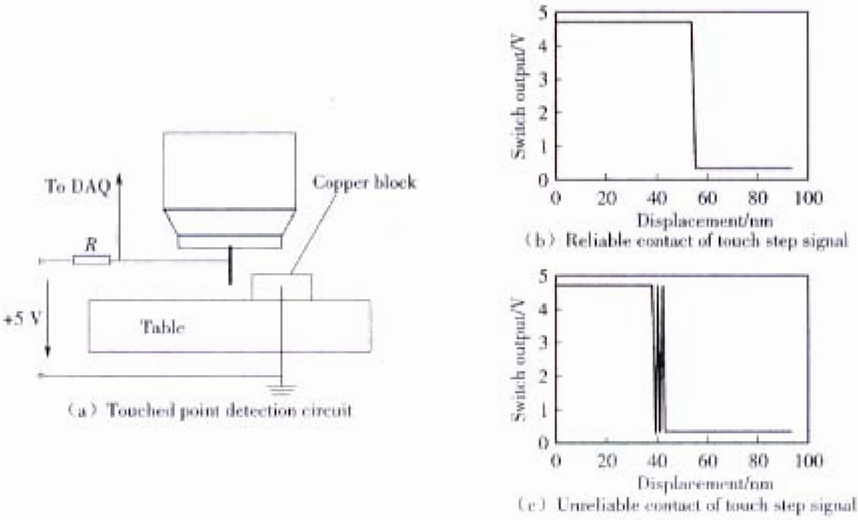



**Fig. 4 Touched point detection circuit and touch step signal**

## 4 Experiments

The schematic diagram of calibration system is shown in Fig. 5. Two position-based curves are shown in Fig. 6. The signals of trigger sensing are detected by focus probes, the signal of touch sensing is detected by the on/off switch circuit, and the signal of displacement sensing of the moving table is deteced by LDGI. All signals are sampled simultaneously by one DAQ card NI-PCI6259.

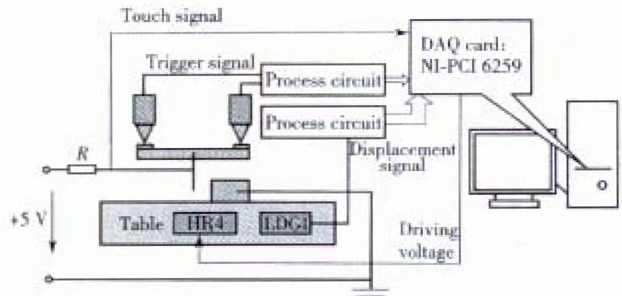
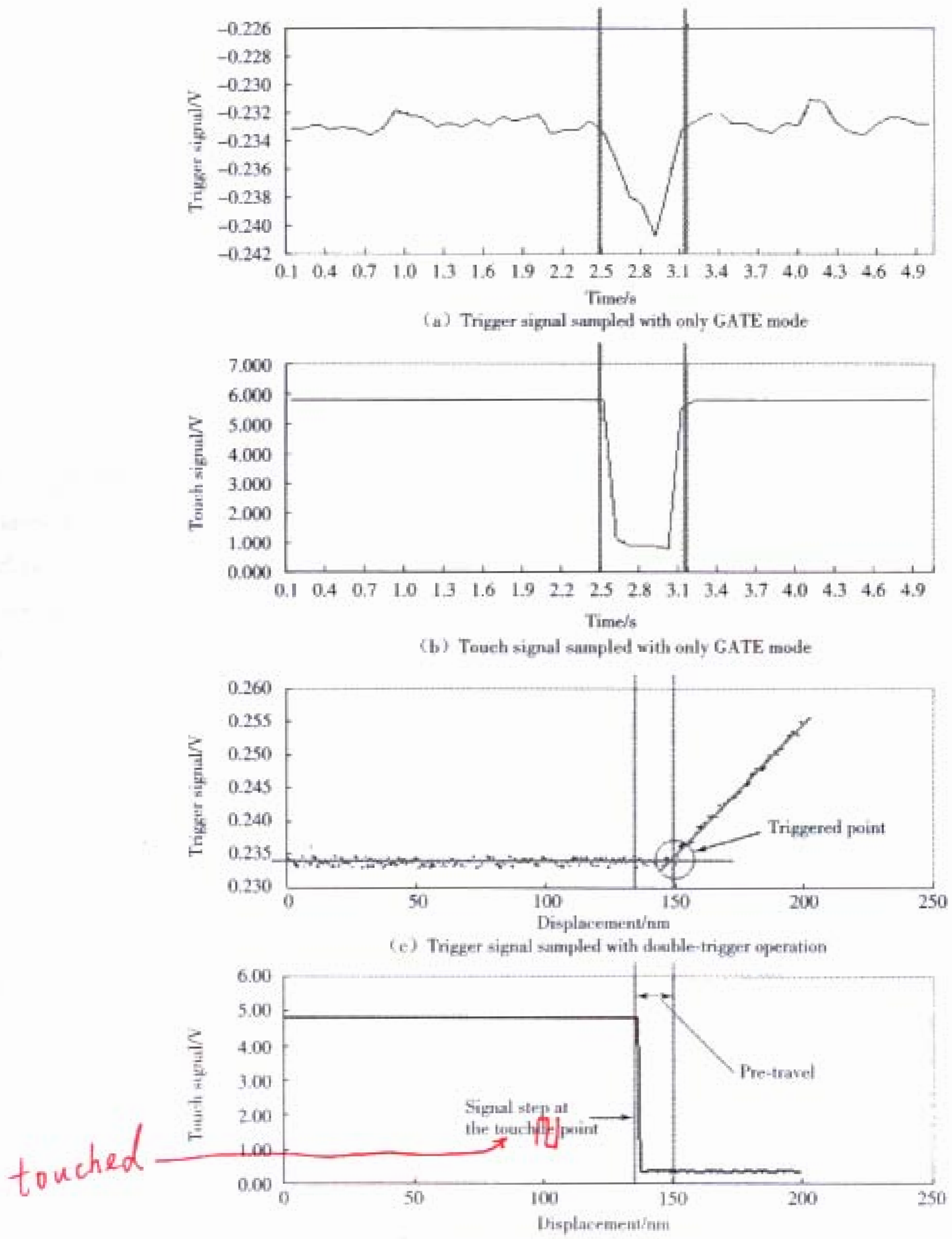



**Fig. 5 System configuration**




(a) Trigger signal sampled with only GATE mode

(b) Touch signal sampled with only GATE mode

(c) Trigger signal sampled with double-trigger operation

(d) Touch signal sampled with double-trigger operation

**Fig. 6 Signal curves for triggered point and touched point detection**

The error caused by the time delay can be neglected. With a software-based signal correction and subdivision technique [8, 15, 18], the LDGI outputs accurate and stable positions even at room temperature.

Fig. 6(a) and (b) show the bidirectional touch signal and the trigger signal sampled after the first trigger with only GATE mode, where the pre-travel distance cannot be distinguished because the GATE mode steps are not fine enough. Fig. 6(c) and (d) show the curves after the double-trigger operation, where the pre-travel can be clearly identified. The over-travel range is ignored since only the touched point and triggered point are of interest in this work. During the triggered process the optimized driving voltage is worked out by the motion control software.

The whole system is placed on an air-suspension table, where the surrounding vibration is well isolated. In the calibration system, the touch trigger probe, the LDGI and the motor HR4 are fixed on different base mounts to make sure the vibration caused by HR4 will not influence the probe and the sensor.

The triggered point cannot be determined directly when noises are considered. To solve this problem, the lines before and after triggering are best fitted by least-squares method and the intersection point defines the triggered position. These two lines can be expressed by a piecewise linear function

$$y = \begin{cases} a & x \leqslant x_0 \\ kx + b & x > x_0 \end{cases} \tag{2}$$

where, $y$ is the probe output signal; $x$ is the displacement recorded by the LDGI; $x_0$ is the triggered point; $a$, $b$ and $k$ are constants.

Meanwhile, the step edge of the touch signal is more easily determined. The pre-travel distance can thus be found.

To test the proposed method, the touched point and triggered point are measured five times. The averaged pre-travel distance of this probe is found to be 10 nm. The repeatability of the experimental data listed in Tab. 2 shows the reliability of this double-trigger method.

**Tab. 2 Position of touched point and triggered point**

| Touched point/mm | Triggered point/mm | Pre-travel/nm |
|---|---|---|
| 1. 102 387 | 1. 102 397 | 10 |
| 1. 102 399 | 1. 102 405 | 6 |
| 1. 102 376 | 1. 102 389 | 13 |
| 1. 102 380 | 1. 102 390 | 10 |
| 1. 102 395 | 1. 102 406 | 11 |
| $\sigma$ = 10 nm | $\sigma$ = 8 nm | $\sigma$ = 2. 5 nm |

Note: $\sigma$ stands for standard deviation

## 5 Conclusions

In this paper, a measuring equipment to determine the touched point and the triggered point of a nano-CMM probe is proposed in order to realize the pre-travel distance of the developed touch probe. This pre-travel distance is an inherent constant to each probe and has to be compensated for from the triggered position to ensure the accuracy of contact measurement. A double-trigger method is developed through the integration of three driving modes of a commercial ultrasonic motor. A precision switch circuit is designed for the touched point detection. The triggered point is obtained from the deflection point of the trigger signal curve. Unidirectional tests show the repeatability is within 10 nm and the average pre-travel of tested probe is about 10 nm with repeatability around ±5 nm (2$\sigma$).

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