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A TDC-Based nano-scale displacement measure method inside Scanning Electron Microscopes*

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***Abstract*—The one of the most important foundations of micro-manipulation is the micro- and nano- displacement's accurate measurement. This paper focused on the end effectors measurement for a nano-manipulation robot, which is working in the scanning electron microscope's vacuum chamber. A standard capacitor are charged and discharged through the strain gauge, and the time are measured by time-digital convertor, which can be used to calculate the displacement. The power consumption are analyzed and compared with traditional Wheatstone bridge. The power consumption is greatly reduced while the error is optimized, so it takes advantages in the environment of vacuum, which is hard to dissipate heat. The drift, resolution and linearity are tested, and demos of closed-loop control and repeated micro unit probing are given to verify the validity of this method.**

I. Introduction

The manipulation inside a scanning electron microscope (SEM) with the piezoelectric nano-manipulators is developing fast these days and many prototypes are report by many commercial institutions[1-5]. And in the academic institution, Y. Sun from University of Toronto reported a system that can be exchanged via loadlock, and the system used to remove the nanowire from FFT device. S. Fatikow from Univeresity of Oldenburg developed several kinds of micro manipulation system driven by piezoelectric ceramics and utilizing the visual servo to manipulate micro object and move AFM into SEM chamber. The Nagoya University developed a system with four manipulator units, and had 16 degree of freedom in total. They used AFM cantilevers to position in multilevel and achieve the pickup, fixing, bending, twisting and so on[2] [6][7]. These systems have been demonstrated, including the handling of micro-nanomaterials [8], nanomaterial characterization [9], and nanoprobing [10].

The domestic research are focusing on the manipulation under the optical microscope, such as the MEMS assembling system developed by HIT and the macro/micro auto-assembling system developed by BUAA. The manipulation systems inside the SEM are not abundant now. The teleoperated manipulation systems driven by stick-slip strucuture. The MM3A manipulators from Kleindiek are used to develop micro/nano manipulation system by Peiking University [11][12] and Beijing University of Technology[13].

In the micro operating, the position method is one of the most important technologies. With the development of high precision processing, new measure methods were developed recently [14]. There is specific limitation in the SEM, including the narrow space, the difficulty of heat dissipation, and the electron beam radiation. The related research is still not enough. The main methods used inside SEM include the visual servo, optical encoder, capacitance/ inductive sensor and resistance strain gauge.

Utilizing SEM image feedback, the target of nano-scale can be position and manipulated, because e SEM is a understand realtime visual platform. However, the image quality is limited by the brightness fluctuation, drift, and noise, which means that this method is not good enough. Optical encoder introduces extra heating value and causes the temperature changing. Both the capacitance and inductive sensor are costly and intricate to integrate into nanomanipulation systems due to the demand for carefully routing sensing signals over long distances.

Strain gauge-based sensing is reliable method to measure deformation. However, the traditional sensing circuitry of Wheatstone bridge can generates significant heat and the drift is too severe inside the SEM. In this paper, a measure method based time-digital-covertor (TDC) is proposed to measure the nano-scale displacement of a nano-manipulator inside SEM. The basic idea is to charge and uncharge a standard capacitive and measure the time, which can be used to calculate the resistance value. The displacement is proportional to the increment value. This method has the advantages of high precision and very low power consumption.

In this paper, our nano manipulator system is briefly introduced in Section II. Section III presents the measure method based on time-digital-covertor. SectionIV characterize

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method's specification. Section V gives a demo on this system and finally, section VI concludes the paper.

II. THE NANO MANIPULATOR

In the form work, a nano-scale manipulator working inside SEM is developed, which is consisted by four units. Every unit is consisted by coarse and fine positioner. The coarse positioner is a Cartesian coordinate robot with three slip-skip linear positioner, which can expand the range of motion. The fine positioner is a combination of three flexure hinges driven by PZT stack actuators, which is also a Cartesian coordinate robot. Fig.1 is the system.

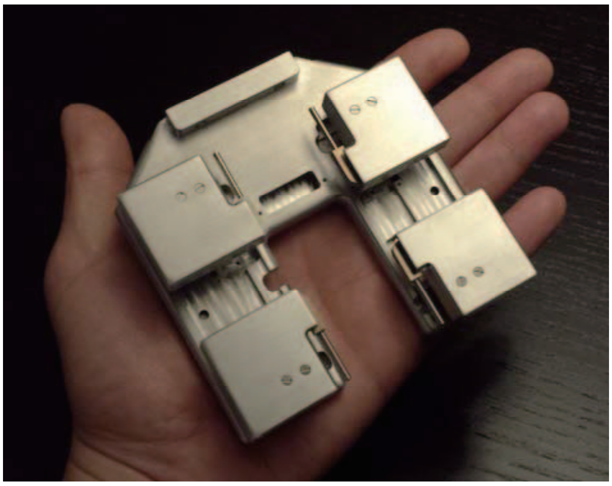

Figure 1. Nanomanipulation system with coarse and fine positioners

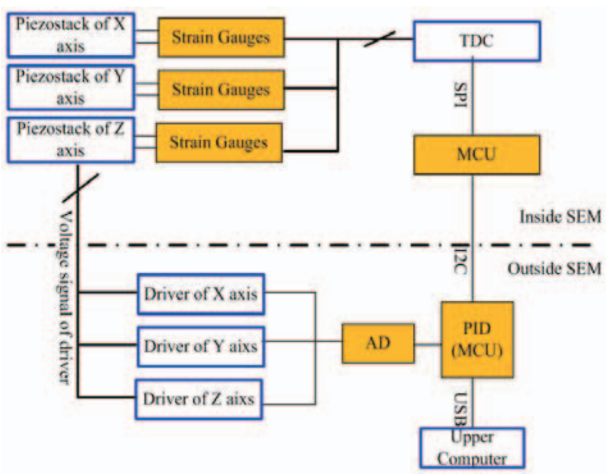

Figure 2. The circuit system of the manipulator

The system's circuit system is divided into two parts: the sensor and controller. Since the manipulator is installed inside the vacuum chamber, all the part which may emit heat was installed outside the chamber, such as high voltage operational amplifier. All the sensor system was installed inside the chamber, collecting the data, simply filtering and sending out via I2C bus, as shown in Fig. 2.

I. THE MEASURE METHOD

The resistance strain gauge can be used to measure the deformation when it is attached to the changing parts. In our system, we glued the strain gauge to the surface of PZT stack directly. When the strain gauge is extended by the stack, the change of the resistance value is proportional to the displacement. The classical method to measure the resistance change is the Wheatstone bridge, which is widely used in common cases. However, this method is not suitable for vacuum condition because the resistance is energizing all the time, and the subsequent operational amplifiers are also of high power consumption. The heat dissipation condition will be terrible in minutes. The method used in this paper based on TDC is to charge and uncharging a standard capacitance to measure the time, which can calculate the resistance value. The extremely low power consumption can guarantee the low drift.

A. The TDC method

As described above, the time of charging and uncharging need be measured, and time to digital convertor is a proven technique, and can get a 15ps precision. The detailed measurement is given below.

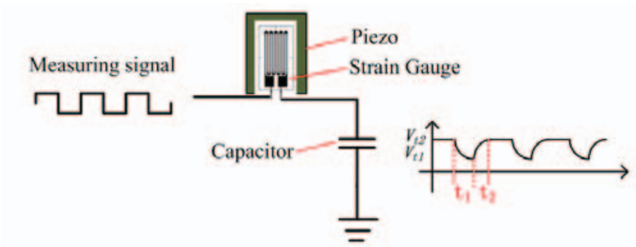

Figure 3. The charging and uncharging process

The signals of specific time series are used to control the charging and uncharging. As shown in Fig. 3, when square wave is used, we have:

$$t_1 = R \cdot C \cdot \ln(\frac{v_2}{v_1})$$
$$t_2 = R \cdot C \cdot \ln(\frac{v_s - v_1}{v_s - v_2}) \quad (1)$$

where the v_s is the charging voltage, v_1 and v_2 are the thresholdof charging and uncharging, respectively. t_1 and t_2 are the time of them, respectively.

The resistance value can be calculated by t_1 or t_2 . Because the deformation / displacement is needed, so we can compare the time with this of un-deformated strain gauge. Taking the uncharging time as example, we have:

$$\varepsilon = \frac{\Delta R}{R} = \frac{t_1 - t_{s1}}{t_{s1}} \quad (2)$$

where t_{s1} is the uncharging time of un-deformated resistance. ΔR is the variation of resistance value. The deformation ε is representation of the displacement, and it can be calibrated by the SEM's image or laser ranging method.

Actually, to improving the precision, a standard resistance can be measured under the same condition as the standard uncharging time. The standard resistance can choice the strain gauge without deformation and fixed on a place with same temperature. This will reduce the effect of temperature changing.

B. The dissipated power of this method

The whole sensor system works inside the vacuum chamber of SEM, in which the vacuum level is high to 10^{-3}~10^{-4} Pa, and the system can conduct the heat by a very small foundation. The dissipated power of this method is important. Low dissipated power is very helpful to reduce the drift when the system is long time working. As to the TDC method, the power on the resistance strain gauge is calculated and compared to Wheatstone bridge.

The power on strain gauge can be dived into two parts: charging and discharging:

$$W_1 = \int_{t_1} v_R \cdot i_R dt = \int_{RC\cdot\ln(\frac{v_s}{v_s - v_1})}^{RC\cdot\ln(\frac{v_s}{v_s - v_2})} v_s (1 - e^{-\frac{t}{RC}}) \frac{v_s}{R} e^{-\frac{t}{RC}} dt \quad (3)$$

$$W_2 = \int_{t_2} v_R \cdot i_R dt = \int_{RC\cdot\ln\frac{v_s}{v_1}}^{RC\cdot\ln\frac{v_s}{v_2}} v_s e^{-\frac{t}{RC}} \frac{v_s}{R} e^{-\frac{t}{RC}} dt \quad (4)$$

where W_1 and W_2 are the power of charging and discharging. v_c and i_c is the voltage and current of capacitance. Then, the dissipated power can be calculated as:

$$P_{TDC} = \frac{W_1 + W_2}{t_1 + t_2} = \frac{v_2^2 - v_1^2}{R * \ln \frac{v_2(v_s - v_1)}{v_1(v_s - v_2)}} \quad (5)$$

Take v_1=1.5V, v_2=3V and v_s=3.3Vas example, we can get $P_{TDC} \approx 0.0036W$. As to the Wheatstone bridge, take the same parameters, we can get the dissipated power $P_{bridge} = v_s^2 / R$, so $P_{dridge} \approx 0.031W$. Considering the subsequent operational amplifiers are also of high power consumption, the advantage of TDC method is more remarkable.

C. Other discussion

As to the TDC method, there are also errors, including the power source error, the quantization error, and so on. The quantization error of this method is low due to the high precision of TDC, which is as high as 15ps. So the quantization error is 15ps/100us=1.5*10^{-3} %. In the Wheatstone bridge, the quantization error is half of the resolution. When 12bi~14bit AD is used, the error is 0.5/2^{12}~2^{14}=0.012~3.1*10^{-3} %. This TDC method basic equal to a 15bit AD.

The measure frequency of the Wheatstone bridge can be very high, because it is limited by the bandwidth of the AD chip. However, The TDC method's frequency is limited by the charging and uncharging time, so we get $f < 1/(\mathrm{t}_1 + \mathrm{t}_2) \approx 2.9kHz$, which is far lower than the normal AD chip's frequency, but it is enough for the manipulator for nano scale.

II. CHARACTERIZATION OF SENSOR

We test our sensor system with the manipulator inside SEM vacuum chamber. The SEM is working under the magnification times of 800,000. Denoising and image stabilization method [36] are employed to compensate the image noise and drift at high SEM magnifications. Characterization of the position sensor was measured using sub-pixel visual tracking [20]. Table I summarizes the overall system performance. The characterization includes the sensor's drift, linearity, resolution, and accuracy.

TABLE I:
SYSTEM SPECIFICATION AND PERFORMANCE

dimension	complete system	100 ×100 × 20 mm^3
	one manipulator	30 × 30 × 17 mm^3
position sensor	resolution	<1 nm
	drift	<1 nm/minute
coarse positioner (open loop)	range	10 mm in XY, 5 mm in Z
	minimum step size	112.5 nm
fine positioner (open loop)	range	~22 µm
	minimum step size	0.12 nm
fine positioner (closed loop)	range	20 µm
	accuracy	5 nm
	maximum speed	45 µm/s

A. *Drift characteristics of the sensor*

Drift of sensor's readout is mainly caused by temperature changing of strain gauges. After the whole system was installed inside the SEM, the chamber of SEM is vacuumed and waiting for hours, so that the system and environment is in thermal balance. The long time waiting can exclude the effect of the initial thermal deformation of the system to the measure result. Then, the system was powered on, and the PZT is still un-driven. We recorded about 10000 seconds readout as shown in Fig. 5. The sensor drifts quickly at the first 60 seconds, as shown in Fig. 5(b). The drift was reduce to 3 nm/minute after 1min, and to 0.83 nm/minute at last 60 second as shown in Fig. 5(c).

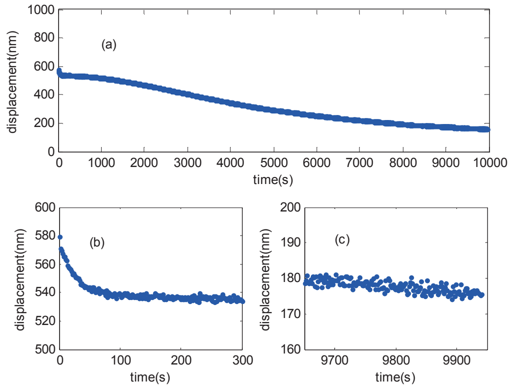

Figure 4. The drift of the sensor in 10000second.

B. *Linearity of the sensor*

Sensor linearity is the relationship between the system's measured output and the real results. The image recognition of the SEM can be taken as the real results. In this testing, 80,000 magnification is used, and the system taked a 2 μm motion step every 10 seconds over the entire travel range of a axis. The actual positioning was visually tracked using SEM images,as shown in Fig. 5. The r2 value of 0.9998 confirms excellent linearity of the position sensors.

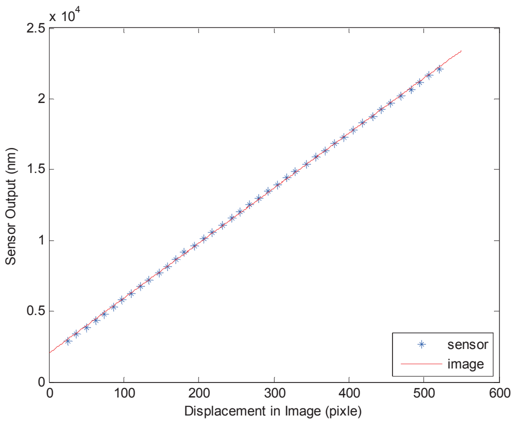

Figure 5. Linearity of the sensor

III. The Demo of Sensor's Application

The most important application of sensor is to feedback position information to the controller to calculate the control value. We design a simple PID controller by reading the output of TDC to calculate a control voltage to drive the PZT stack to demonstrating to sensor's application. As shown in Fig. 6, we used a input signal of 10 nm steps, can compared the output of sensor, image recognition and set value.

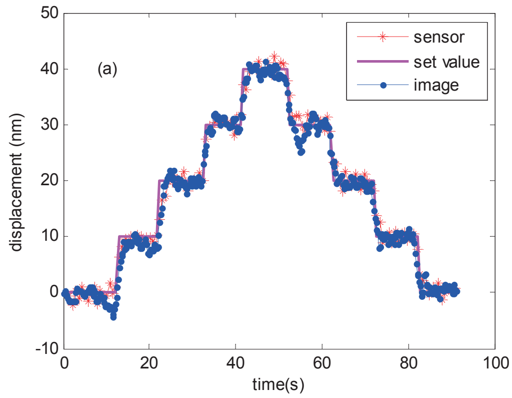

Figure 6. The step control result with the readout of TDC method.

A simple PID method can control the position very well with a position precision of 5nm, so the method in this paper is suitable to be applied in nano-scale manipulator.

IV. Conclusion

The paper proposed an end effectors measurement method based on TDC for a nano-manipulation robot, which is working in the scanning electron microscope's vacuum chamber. The standard capacitor are charged and discharged through the strain gauge, and the time is measured by time-digital convertor, which can be used to calculate the displacement. This method takes advantages in the environment of vacuum because it has very low dissipated power.

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