DESIGN, MODELING, AND MICROMANIPULATION EXPERIMENTS OF A NOVEL 2-D MICRO FORCE SENSOR

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Received 3 February 2010
Accepted 30 March 2010

Because of the micro/nano manipulation’s complexity, the accurate feedback information of the micro interactive force acting on micro devices is quite important and necessary for micro/nano manipulation, especially the 2-D micro interactive force feedback information. At present, there are no reliable and accurate 2-D micro force sensors applied in micro/nano manipulation. To solve the above problem, a novel 2-D micro force sensor that can reliably measure force in the range of submicro Newton (µN) is designed and developed in this paper. Based on the model of 1-D micro force sensor designed by us, the model of this 2-D sensor is set up. To verify the model of the 2-D sensor, micromanipulation experiments are designed and realized. Experiment results show the submicro Newton resolution, and verify the validity of the 2-D sensor’s model. The developed 2-D micro force sensor will contribute to promoting the complexity of micro/nano manipulation, and will facilitate to automate the micro/nano manipulation.

Keywords: Micromanipulation; 2-D; micro force; sensor.

1. Introduction

Micromanipulation, microassembly and related technology are quite important for MEMS. They also provide brand-new methods of manufacturing and experiments for physics, chemistry, and automation. However, at the micro scale, structures of micro devices are fragile and easily breakable, and they typically break at the micro Newton (µN) force range that cannot be felt by human beings, and cannot be reliably measured by the existing force sensors during assembly [Fatikow et al., 2000]. At present, the measurement and feedback control of micro interactive force (e.g., adhesion, surface tension, friction, and assembly force) cannot be realized directly [Bhringer et al., 1999]. Therefore, it is extremely difficult to manipulate components for assembly at micro Newton scale. Moreover, this situation decreases the efficiency and drives up the cost of micro/nano manipulation [Reid et al., 1997]. It has been estimated that the assembly cost of micro devices can run as high as 80% [Chollet et al., 1999]. For instance, a micro-reflecting mirror needs to be
rotated from its plane of fabrication through a fragile micro-hinge. This kind of micro mirrors will be broken by micro force in the range of \( \mu \)N. Therefore, an operator hoping to lift the micro mirrors will often break them unconsciously due to excessive force through the micromanipulator probe.

For the above reasons, various force sensing mechanisms have already been investigated in sensing contact force during micromanipulation and microassembly [Carrozza et al., 2000; Thompson & Fearing, 2001; Zesch & Fearing, 1998; Peters, 1993; Sun et al., 2003; Boukallel et al., 2003; Nelson et al., 1998]. In summary, the resolution of piezoresistive sensors, capacitive sensors and sensors with strained layers is in the range of sub-\( \mu \)N or \( \mu \)N. Theoretically speaking, although some magnetic effect-based sensors have high resolution in the range of nano Newton (nN) [Boukallel et al., 2003; Nelson et al., 1998], this kind of sensing techniques is quite sensitive to electric magnetic environment. This feature makes the resolution of this kind of sensors decrease to the range of mN. Generally, optical techniques-based sensors have low depth of focus, small dynamics range, and bad flexibility. Furthermore, the optical techniques-based sensors are more expensive than other micro force sensing technique.

Compared with the above micro-force sensing technologies, the micro-force sensors based on the piezoelectric effect is able to reliably and accurately measure the micro-force in the range of \( \mu \)N. Yiyang et al. designed a novel micro force sensor with PVDF. This kind of sensor is able to reliably measure the micro contact force in the range of sub-\( \mu \)N [Liu et al., 2008]. However, the sensor designed in this paper is just a 1-D sensor that is not able to satisfy the need in complex micromanipulation and microassembly.

Therefore, this paper aims at designing a 2-D micro force sensor that is able to sense the force in two directions. In this paper, a novel 2-D PVDF micro force sensor is designed and realized, the model of the 2-D sensor is built up, and experiments in micromanipulation is designed to verify the performance of the 2-D micro force sensor.

2. Design and Modeling of the 2-D Micro Force Sensor

To model the 2-D micro force sensor, the model of the 1-D micro force sensor designed by us before is briefly introduced as below [Liu et al., 2008].

Based on piezoelectric effect, the charge \( Q \) across the PVDF surfaces:

\[
Q = \int d_{31} \sigma dA, \tag{1}
\]

where

\[
\sigma = \frac{2}{Wh} \int_0^b \sigma_1 da, \tag{2}
\]

where \( W \): width of PVDF film; \( h \): thickness of PVDF film; \( A \): surface area of PVDF film (\( L \times W \)); \( L \): length of PVDF film; \( d_{31} \): piezoelectric constant of PVDF film; \( \sigma_1 = (M/I_e)y \) (stress of one point in the cross sectional area of PVDF film), \( I_e = Wh^3/12 \) (inertia moment of PVDF film’s cross sectional area), \( M = F(L - x + L_0) \) (flexural moment of PVDF film’s cross sectional area), where \( L_0 \): length of probe tip. Therefore Eq. (1) can be rewritten as:

\[
Q = \frac{3d_{31}}{Wh^2} \int_0^L F(L - x + L_0)W dx
=\frac{3d_{31}L(L + 2L_0)}{2h^2} F. \tag{3}
\]

Equation (3) shows the relationship between the micro interactive force and the charge \( Q \) generated across the PVDF surfaces.

Based on the 1-D micro force sensor, the 2-D micro force sensor is designed in Fig. 1. To conveniently introduce the structure of 2-D sensor, the schematic diagram of 2-D sensor is shown in Fig. 2.

According to piezoelectric effect, the charge \( Q(t) \) on the surface of PVDF film generated by contact force \( F(t) \) can be written as

\[
\frac{V(t)}{R_P} + \frac{V(t)}{C_P} = \frac{dQ}{dt}, \tag{4}
\]

where \( V(t) \) delegates the output voltage of the PVDF sensor; \( C_P \) is the equivalent capacitance
of the PVDF film; \( R_P \) is the equivalent resistance of the PVDF film. The relation between \( V(t) \) and \( F(t) \) can be described as

\[
V(t) + \lambda \dot{V}(t) = B \dot{F}(t),
\]

where \( \lambda = R_P C_P \); \( B = R_P A d_{31} H (L_0 + L/2)/2I \); \( A \) is the area of PVDF film \((L \times W)\); \( L, W, H \) are, respectively, the length, width, and thickness of the PVDF film; \( d_{31} \) is the piezoelectric constant of PVDF; \( I \) is inertia moment of PVDF film’s cross sectional area.

Based on Eq. (5), the relation between output voltage \( V_x(t) \); \( V_z(t) \) along \( X, Z \) axes of the 2-D sensor and the contact force \( F_x(t) \); \( F_z(t) \) along \( X, Z \) axes is shown as

\[
\begin{align*}
V_x(t) + \lambda_x \dot{V}_x(t) &= B_x \dot{F}_x(t), \\
V_z(t) + \lambda_z \dot{V}_z(t) &= B_z \dot{F}_z(t),
\end{align*}
\]

where \( B_x = [R_P A d_{31} H (L_0 + 3L/2)]/I_d \); \( B_z = [R_P A d_{31} H (L_0 + L/2)]/I_d \); \( I_d = 2I + aH^2/2 \) is the inertia moment of the beam; \( a \) is the cross sectional area of beam; \( L, L_0 \) are, respectively, the length of PVDF film and probe; \( \lambda_z = \lambda_x = R_P C_P \).

The signal processing circuit designed for the 2-D sensor is shown in Fig. 3. In this circuit, a differential charge amplifier with high input impedance \( 10^{12} \Omega \) and low bias current 1.5 pA was designed for the PVDF force sensor. High input impedance can avoid the leakage of the charge on the feedback capacitor, and low bias current prevents the feedback capacitor from charging and discharging at excessive rates. To reject the high frequency noises, an active low pass filter was used before the voltage output.

Furthermore, to obtain the steady state force information, an integrator unit was added to process the output voltage information before the information went into the feedback loop.

According to the signal processing circuit, the output voltage of PVDF film along the \( X \) and \( Z \) axes can be written as (take output voltage of PVDF film along \( X \) axis as an example):

\[
V_c(s) = \frac{2sR_f \beta_x 1 + \tau_s}{1 + \tau_1 s} F_x(s).
\]

According to the circuit, the relation between output voltage of sensor \( V_{out}(s) \) and output voltage of PVDF film \( V_c(s) \) is shown as below

\[
\frac{V_{out}(s)}{V_c(s)} = \frac{K}{1 + \tau_1 s},
\]

where \( K \) is the voltage amplification coefficient; \( \tau_1 \) is the time constant of lowpass filter. From Eqs. (7) and (8), the transfer function of each dimension of the 2-D sensor is

\[
\begin{align*}
\frac{V_{out}(s)}{F_x(s)} &= \frac{2K \beta_x}{C_f} \cdot \frac{s}{(1 + \tau s)(1 + \tau_1 s)},
\end{align*}
\]
In the circuit, the time constant $\tau_1$ is quite small, so Eq. (9) can be rewritten as

$$\frac{V_{\text{out}}(s)}{F_x(s)} = \frac{2K\beta_x}{C_f} \cdot \frac{\tau s}{1 + \tau s}. \quad (10)$$

According to the inverse Laplace transformation of Eq. (10), we can conclude

$$F_x(t) - F_x(t_0) = \frac{1}{2K\beta_x R_f} \left[ \tau (V_{\text{out}}(t) - V_{\text{out}}(t_0)) + \int_{t_0}^{t} V_{\text{out}}(t) \, dt \right]. \quad (11)$$

Similarly, the contact force along $Z$ axis can be written as

$$F_z(t) - F_z(t_0) = \frac{1}{2K\beta_z R_f} \left[ \tau (V_{\text{out}}(t) - V_{\text{out}}(t_0)) + \int_{t_0}^{t} V_{\text{out}}(t) \, dt \right]. \quad (12)$$

With Eqs. (11) and (12), by measuring the output voltage $V_{\text{out}}(t)$ of each dimension of the 2-D sensor, the micro contact force of each dimension can be obtained.

3. Micromanipulation Experiments of 2-D Sensor

Based on the above design and model of the 2-D micro force sensor, micromanipulation experiments of 2-D micro force sensor are designed and realized as below. To carry out the micromanipulation experiments, an experiment platform shown in Fig. 4 is built up.

The experiment platform consists of 2-D micro force sensor, 3-D intelligent motor platform of New Focus Corporation in America (precision is 20 nm), microscope, sample platform and a computer. In the platform, the 2-D micro force sensor is fixed to the 3-D intelligent motor platform. The sensor and the probe moves together with the 3-D intelligent motor platform to manipulate the sample. The 3-D intelligent motor platform is shown in Fig. 5.

### 3.1. Micromanipulation experiment of single dimension

This experiment is designed to test the sensitivity of the 2-D sensor in one dimension and the performance of force controller designed for this sensor based on the model of the sensor. The program is shown as below. Firstly, make a micro flake (PVDF film) whose size is $800 \, \mu m \times 600 \, \mu m \times 200 \, \mu m$, and make the flake lie on the horizontal base (the base is made from steel); secondly, make the sensor probe horizontally approach one side of the flake and keep the probe and the side of the flake parallel until the probe touches the side of the flake; thirdly, increase the contact force until the flake begins to move, then decrease the contact force until the flake moves at a constant speed.

The process of experiment is shown in Fig. 6, and the experiment results are shown in Figs. 7 and 8.
As Fig. 7 showed, the contact force finally converged at approximately 0.44 \( \mu \)N.

According to the size of the flake, the volume of the flake is approximately 0.8 mm \( \times \) 0.6 mm \( \times \) 0.2 mm = 9.6 \( \times \) 10\(^{-5} \) cm\(^3\). Because the density is 1.78 g/cm\(^3\), the mass and gravity are \( m_{PVDF} = \rho V = 1.709 \times 10^{-4} \) g, \( G_{PVDF} = m_{PVDF} \cdot g = 1.745 \times 10^{-6} \) N. Since the coefficient of sliding friction of steel and PVDF is \( \mu = 0.25 \), the sliding friction force is \( f = \mu G_{PVDF} = 0.436 \mu \)N.

According to the above calculation, the actual sliding friction force, 0.44 \( \mu \)N, is close to the calculated friction force, 0.436 \( \mu \)N. Therefore, the sensitivity of sensor in one dimension is good, its resolution is in the range of sub-\( \mu \)N, the model of the sensor is accurate, and the controller designed according to the model is efficient.

### 3.2. Performance test of 2-D sensor

This experiment is designed to synchronously test the sensitivity and resolution of the 2-D sensor in two dimensions. The program is shown as below. Firstly, fix a slice of glass on a horizontal base, and make the glass 75 degrees relative to horizon; secondly, horizontally move the sensor to approach the glass, watch the human machine interface to monitor the contact force; thirdly, when the micro contact force reaches 1.2 \( \mu \)N, stop the sensor manually. The experiment results are shown in Fig. 9.
According to Fig. 9, the resolution of the 2-D sensor in two dimensions is in the range of sub-\(\mu\)N, and contact force along \(X\) and \(Z\) axes are decoupling. This 2-D sensor is able to synchronously measure micro contact force along two axes, and the measurement in either dimension will not disturb the measurement in the other dimension.

4. Conclusions

Because of the micro/nano manipulation’s complexity, accurate measurement information of the micro contact force acting on micro devices is quite important and necessary for micro/nano manipulation, especially the 2-D micro interactive force feedback information. In this paper, a novel 2-D micro force sensor is designed, the model of the sensor is built up, and micromanipulation experiments are designed to verify the sensitivity, resolution, and validity of the 2-D micro contact force sensor. According to the results of experiments, it can be concluded that the sensor’s resolution is in the range of sub-\(\mu\)N, the model built up in this paper is accurate.

With the 2-D micro contact force sensor designed in this paper, 2-D micro contact force in the range of sub-\(\mu\)N in complex micromanipulation and micro assembly can be reliably measured and controlled. This micro force sensing device will provide a feasible solution of 2-D micro-force feedback control during micro/nano manipulation, and promote the efficiency of the micro devices’ manufacture.

Acknowledgments

This research work is supported by the National Natural Science Foundation of China (No. 60575050) and National High Technology Research and Development Program of China (No. 2009AA03Z316).

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Biography

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