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Quasistatic displacement self-sensing method for cantilevered piezoelectric actuators

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Piezoelectric meso- and microactuator systems required for manipulation or assembly of microscale objects demand reliable force and/or displacement information. Available sensors are prone to dimension restrictions or precision limitation. Self-sensing method, based on the electric charge measurement, may represent a solution in terms of cost-effectiveness and integration, the actuator performing simultaneously as its own sensor. This paper presents a self-sensing method dedicated to free uni- and bimorph piezocantilevers but can also be adapted to other piezoactuator types. The integrated electric current, used to convert a piezoelectric material nonlinearities to provide accurate displacement information. The advantages relative to existing self-sensing methods consist in the ability to keep this displacement information for long-term periods (more than a thousand seconds) and in the reduction in signal noise. After informative issues related to the method the base principle allowing the estimation of tip displacement is presented. Then, the identification procedure of the estimator parameters is depicted and representative experimental results are shown. Finally, a series of aspects related to electronic circuits are discussed, useful for successful system implementation.

I. INTRODUCTION

Piezoelectric cantilevered actuators usually made up of one or two piezoelectric layers (called uni- or bimorph) are present in many micromanipulation and microrobotic applications, thanks to their high displacement resolution and fast response time. The static and dynamic behaviors of piezoelectric actuators, their inherent nonlinearities (hysteresis and creep), and limits were studied and modeled especially during the past 2 decades in attempting to provide more efficient control solutions.

In order to perform very accurate and fast response time closed-loop micromanipulation tasks, various sensors have been used. Unfortunately, these sensors are not ideally adapted to the micro- and nanoworld because of their sizes, performances, and limited measurement of degrees of freedom. Table I summarizes mostly available sensors in the field. Hence, an alternative to the use of sensors is the self-sensing method. There are several advantages of the self-sensing method relative to the use of external sensors. Among them, it allows a consistent reduction in the costs by eliminating expensive sensors. As can be seen, resolution can also be submicrometric and comparable to that of external sensors. Self-sensing is based on charge conversion. In fact, charge is nearly proportional to the displacement, hence there is no need to further compensate the complex nonlinearities (hysteresis and creep) such as in (Ref. 8).

The idea of self-sensing in piezoelectric cantilever has been started by the work of Dosch et al. While it is not a new concept on vibration damping or control, more recently, it has shown its feasibility for piezoelectric tubes of atomic force microscopy. But to our knowledge, self-sensing methods have not yet been adapted for long-term (more than hundreds of seconds) displacement measurement of cantilevered actuators, as required by micromanipulation and microrobotic tasks. In this paper, we present a compensated self-sensing approach especially dedicated to long-term static measurement. We especially focus on the displacement measurement of a piezoelectric cantilever beam.

Drawbacks of displacement self-sensing method refer to inherent charge leaks and temperature influence. With proper actuators and electronic circuits, charge information may be preserved even for thousands of seconds. However, because of the temperature variations, extra care will be required for proper thermal isolation especially in the case of nonsymmetric cantilevers (example: unimorph) to limit temperature-related uncertainties.

There are several self-sensing schematics depending on application. Capacitive bridges are convenient for vibration control but are not easy to balance for long-term measurements. Structures with both electrodes for actuation and electrodes for sensing are a simple solution but their inconvenience is a partial reduction in the total actuating range. A current integrator was introduced in Ref. 17 for a piezostack. The disadvantage was a poor compensation of leaking resistance with a very high value potentiometer across the integrating capacitor. Another method quite related to self-sensing concept was linearization of the actuator displacement using voltage-to-charge amplifiers.

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TABLE I. Displacement sensors for the microworld.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangulation lasers</td>
<td>High precision and resolution; fair band pass; and spot measurement</td>
<td>Quite expensive, large sizes, and limited range</td>
</tr>
<tr>
<td>Interferometers</td>
<td>Very high precision resolution and range; increased band pass; and spot(s)</td>
<td>Very expensive and large sizes</td>
</tr>
<tr>
<td>Diffraction grating target</td>
<td>High precision and multidimensional measurement</td>
<td>Large sizes, require attaching target, and</td>
</tr>
<tr>
<td>Strain gages</td>
<td>Less expensive and millimeter size</td>
<td>expensive</td>
</tr>
<tr>
<td>Capacitive or inductive</td>
<td>High sensitivity, high precision, and fair price</td>
<td>Require linearization, from fair to quite large</td>
</tr>
<tr>
<td>Magnetic Hall effect, magneto-</td>
<td>Good precision, band pass, and fair price</td>
<td>dimensions, and close vicinity requirements</td>
</tr>
<tr>
<td>resistive, and magnetostrictive</td>
<td></td>
<td>Expensive and limited resolution and</td>
</tr>
<tr>
<td>Using image processing</td>
<td>Large measurement range and in-plane displacement</td>
<td>response time</td>
</tr>
<tr>
<td>Piezoelectric self-sensing</td>
<td>Double functionality, high band pass, high resolution, and lowest price</td>
<td>Require nonlinear compensation and long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>charge leaking</td>
</tr>
</tbody>
</table>

Afterwards, we detail the parameter identification. Hence, we present the experimental results. Finally, we relate some issues to be taken into account when deploying self-sensing systems.

II. DISPLACEMENT DETECTION

A. Charge output of piezoelectric cantilever

Consider a bimorph cantilevered beam piezoactuator subjected to an electrical excitation $V_{in}$ (Fig. 2). The beam is characterized by its length $L$, its width $w$, and its half-thickness $h$.

In the absence of external force, we have a theoretically linear relation between displacement and applied voltage:

$$\delta = \frac{3d_{31}}{1 + \frac{d_{31}^2}{4\varepsilon_{33}^2}} \frac{L^2}{h^2} V_{in},$$

where $\varepsilon_{33}$ is the compliance coefficient along the beam (X direction), $\varepsilon_{33}$ and $d_{31}$ are dielectric and piezoelectric material coefficients.

Using the relation between the applied voltage and the capacitance for bimorph piezoelectric cantilever beam:

$$Q = \frac{4wL \varepsilon_{33}^2}{h} V_{in},$$

charge directly results and, as stated previously, is quasiproportional to free displacement $\delta$. 

![FIG. 1. (Color online) Displacement self-sensing system.](image1)

![FIG. 2. A bimorph piezoelectric cantilever beam.](image2)
\[ Q = \frac{4}{3} \text{d}_{31} \text{S} \left( 1 + \frac{d_{31}^2}{4\text{e}_{31}^2} \right) \delta = \alpha \delta, \]  

where \( \alpha \) is denoted as an actuator charge-displacement coefficient. In the sequel, this charge will be converted into a measurable voltage \( V_{\text{out}} \) from which the deflection \( \delta \) will be estimated, as described in Fig. 1.

### B. Experimental setup

A schematic overview of the setup is depicted in Fig. 3. Several uni- and bimorph rectangular actuators (PZT on Cu or Ni substrate) were tested, of length between 10–15 mm, width between 1–2 mm, and total thickness of 0.27–0.45 mm. A Keyence LC-2420 optical displacement reader was only used for intermediate tests on actuators displacement; for some measurements requiring better precision a SIOS SP-120 miniature plane-mirror interferometer was employed (Fig. 4). However displacement readings served only for referencing and evaluating purposes of the self-sensing method. The high voltage (HV) amplifier allowed applying a voltage up to \( \pm 150 \) V. A current integrator amplifier circuit (modified charge amplifier) to be discussed next chapter provided \( V_{\text{out}} \) output signal. The Matlab Simulink detection model was deployed on a high speed DSpace DS1103 real-time controller board. A PC-based CONTROLDESK interface served for model parameterization and data acquisition/presentation.

The static electrical equivalent schematic of piezoelectric bender is a charge generator in parallel with a capacitor and a leaking resistance, as seen in Fig. 5, and its electromechanical model is shown in Ref. 2. \( C_p \) capacitance is in the order of nanofarad depending on the shape and dimensions of the microactuator’s structure while \( R_{fp} \) is the insulating resistance, whose order of magnitude is between \( 10^9 \ldots 10^{12} \) \( \Omega \).

If we ignore nonlinear effects, charge is proportional to the applied voltage and the external force. To measure charge, we propose a precise integrator circuit scheme, as pictured in Fig. 6 and described below.

The input signal \( V_{in} \) is inverted and applied to a “reference capacitor” \( C_R \) whose the value is close to \( C_p \) value; it will “absorb” a significant part of the charge due to the applied voltage, according to the second Kirchoff law. Although \( C_R \) and HV inverter may miss from the circuit, their use is recommended. Indeed, the output will saturate at a \( 75 \) higher \( V_{in} \) input voltage value (up to several hundred volts) while preserving the same sensitivity. Feedback capacitor \( C \) will integrate the current due to external force variation and applied voltage (depending on \( C_R / C_p \) fraction). An electro-mechanical relay-switch \( k \) (in series with several kilo ohms resistor) allows resetting \( V_{out} \) voltage from DSpace environment in order to avoid the saturation. Electronic switches are not suitable because of their “off” source/drain leakage currents. Further details and propositions are discussed in Sec. V.

Output voltage is

\[ V_{\text{out}} = -\frac{1}{C} \int_0^T i(t) dt = -\frac{1}{C} Q, \]

where, for the free beam \( F_{\text{ext}} = 0 \), charge is...
\[ Q = -C_R V_{in} + \alpha \delta, \]  
(5)

where \( \alpha \) was introduced in Eq. (3).

If we consider a nonlinear dielectric absorption effect of 192 piezoelectric material, we propose the following slight modi-

\[ Q = -C_R V_{in} + (\alpha \delta + Q_{DA}), \]  
(6)

where \( Q_{DA} \) is an internal amount of charge depending on \( \varepsilon_{33} \) 195 variation.

D. Detected displacement formula

Adding the influence of the nonzero bias current \( i_{BIAS} \) of 199 the operational amplifier (op-amp) and finite leaking resis-

tance \( R_{FP} \) of the piezoactuator, output voltage \( V_{out} \) of the free 201 cantilever beam is given by

\[
V_{out} = \frac{C_R}{C_{in}} \frac{\alpha \delta + Q_{DA}}{C} - \frac{1}{C} \int V_{in}(t) R_{FP} dt \\
- \frac{1}{C} \int i_{BIAS}(t) dt.
\]

(7)

Extracting the displacement \( \delta \), we obtain the estimate as 205 follows:

\[
\delta_{est} = -\frac{C}{\alpha} V_{out} - \frac{Q_{DA}(V_{in}, t)}{\alpha} + C_R V_{in} - \frac{1}{R_{FP} \alpha} \int V_{in}(t) dt \\
- \frac{1}{\alpha} \int i_{BIAS}(t) dt.
\]

(8)

We will consider a simple relaxation effect described by a 208 first-order transfer function for the dielectric absorption term

\[ Q'(s) = \frac{Q_{DA}(s)}{s} = \frac{k_0}{s + 1}, \]  
(9)

where static gain \( k_0 = k_0 / \alpha \). Based on the previous equations, 211 Fig. 7 presents the detailed estimation block-scheme. Some 212 parameters of the identification in Eq. (8) have to be identi-

\[ \alpha = (CV_{out} + C_R V_{in}) / \delta. \]  
(10)

A step signal is applied on the free actuator. To avoid 242 dynamic oscillations of the actuator, the step signal is shaped 243 with ramp of around 20 V/s (Fig. 9). Measured values of \( \delta \) 244 and \( V_{out} \) immediately after \( V_{in} \) step signal will serve to com-
pute \( \alpha \).

\[ \alpha = (CV_{out} + C_R V_{in}) / \delta. \]  
(10)

An alternate method for deriving \( \alpha \) is to apply one or several 248 sinusoidal signals as in Fig. 10 and use amplitude values in 249 Eq. (10).
D. Identification of dielectric absorption transfer function

The last part to be identified in displacement in Eq. (2) is the dielectric absorption $Q_{DA}(s)$ of the piezoelectric material.

$$\Delta \delta_{tip}(s) = Q_{DA}(s)V_{in}(s),$$  

where $\Delta \delta_{tip} = \delta_{est} - \delta$ is the difference between estimated (using already identified parameters) and measured tip displacements (Fig. 11). Identification of $k_s$ and $\tau$ is performed on a step response, calculating the static gain and response time to reach 63.2% of final value.

IV. SELF-SENSING RESULTS

Several tests have been performed to evaluate the accuracy of the proposed self-sensing technique. Known and identified parameters are entered into the real-time processor, we have

$$\alpha = -10.05 \times 10^{-9} \text{ C/m},$$

$$C = 47 \times 10^{-9} \text{ F},$$

$$C_p = 1.74 \times 10^{-9} \text{ F},$$

$$C_R = 8.2 \times 10^{-9} \text{ F},$$

$$R_{FP} = 0.435 \times 10^{12} \Omega,$$

$$j_{BIAS} = -1.7 \times 10^{-12} \text{ A},$$

$$\tau = 57 \text{ s},$$

$$k_s = 3.02 \times 10^8 \text{ m/V}.$$

A. Displacement self-sensing results

In Fig. 12, an input signal $V_{in}$ was applied in several steps between +20 and −25 V, under null external force. Data was recorded for 1020 s—largely sufficient for most applications involving piezoelectric actuators. A very good agreement is found; measured and detected displacement curves almost superpose.

A comparative representation of displacement errors is made as follows. Three graphs are traced (Figs. 13–15) from uncompensated to fully compensated with respect to leaking resistance and dielectric absorption. Measurement with Keyence optical displacement reader provided a poorer linearity than self-sensing signal, making it impossible for accurate error evaluation; SIOS interferometer was eventually em-
ployed. Our constraint on the utilized interferometer is that data is only available offline. Vertical error lines in the figures can be neglected and are due to the linear interpolation and sampling period mismatch between the two data sets acquired at sampling rates of 10 and 16.11 Hz.

As seen in the Fig. 13, peak-to-peak error of uncompensated signal is 2.75 μm. Compensation of $R_{FP}$ leaking resistance allowed a reduction in maximum error to 1.05 μm (Fig. 14). Adding the compensation of dielectric absorption provided a 0.38 μm peak-to-peak error.

Unaveraged measured self-sensing signal noise in displacement is of only 1.6 nm rms, being 10 times less noisy than that of filtered Keyence LC-2420 sensor 16.7 nm rms noise on 4096 averaged samples. However, as expected, SIOS SP 120 interferometer showed best results: 0.5 nm rms noise (Fig. 16).

B. Temperature influence on displacement self-sensing accuracy

Temperature exhibits changes in dielectric and piezoelectric constants. Also, differences in thermal expansion of piezoelectric and passive material tend to bend the structure like a thermal bimetallic, conducting to parasitic displacement (and charges). In this case Eq. (2) between charge and displacement no longer applies ($Q \neq a\delta$), leading to displacement errors. To analyze the thermal influence, we compared its effects on two types of piezoelectric beams: unimorph and bimorph cantilevers. As seen in figures and as expected, unimorphs (Fig. 17) are more affected by ambient temperature than bimorphs (Fig. 18). As bimorph cantilevers are intrinsically symmetric, charges from both sides sum up and self-compensate.

If we compare the above results, we see that unimorph cantilevers are five times more sensitive to temperature than bimorphs. Errors can be limited by a proper thermal isolation or compensated with a sensitive temperature sensor like a miniature thermistor. However, temperature sensor should be in contact with the actuator for more correlate readings.

V. CURRENT INTEGRATION RELATED ISSUES

An improper choice of charge amplifier will significantly reduce sensing accuracy. The circuit should be protected against temperature changes, with a special care to PCB design (guard rings, sufficient space between routes, vias, and pads) otherwise unwanted leakage will easily exceed op-amp bias current.

Integrating capacitor must have primarily an extremely high insulation resistance, low dissipation factor, and good temperature stability. Polypropylene plastic film capacitors were employed in our case, with a measured leaking resistance of 24 TΩ for $C=10$ nF, high enough to ignore its...
leaking influence in the circuit. Polystyrene or Teflon capacitors also showed better performance than ceramic or polyester film capacitors.

Precise operational amplifiers used in charge amplifiers must be unity-gain stable; otherwise they will tend to oscillate. Noise and bias currents have to be as small as possible. Several op-amp types were tested, OPA111BM Difet model was chosen for its very small bias current $1.7 \text{ pA}$, small offset voltage, small temperature drift, fair supply voltage, and on-chip guarding ring. OPA627 model is also suitable.

Attention has must be paid to supply and input voltages. The circuit is damaged if high input voltage is applied in the absence of supply voltage. Also, to prevent the output saturation, the $k$ switch allows resetting when necessary. Further increase in voltage over an already saturated op-amp will cause damage. Cables should be shielded properly to avoid the electromagnetic interference. Further noise rejection can be achieved by modifying the electronic schematic presented in

\[ V_{\text{out}} = - \frac{R_{Z2}}{RC(R_{Z1} + R_{Z2})} \int_0^T i(t) dt. \]

For our actuator the best compromise between response time, sensitivity, and noise was a series resistance of 82 kΩ ($R_{Z1} + R_{Z2} = 82 \text{ kΩ}$).

Noise was reduced by a factor of five but on the other hand this schematic was much more sensitive to temperature offset drifts than that of Fig. 6. As $V_c$ voltage is in the $\mu$V range or lower, op-amp offset voltage temperature drift ($\pm 0.5 \text{ \mu V/°C}$) and supply rejection ($\pm 3 \text{ \mu V/V}$) limited system accuracy. Usually op-amp offset is trimmed manually (with potentiometers); in our case this measure was not sufficient to compensate thermal drifts. We made an automatic compensation of the offset voltage with random temperature changes. This was performed by connecting DSpace DAC outputs (Fig. 20) to op-amp “trim” pins and by measuring and referencing the temperature to a miniature thermistor in close contact with op-amp chip. This way, we preserved a signal up to 100 s similar in accuracy with that of Figs. 12–15, however rms noise was reduced from 1.6 nm to only 0.4 nm, inferior to even that of SIOS SP120 interferometer.

FIG. 16. Zoomed in measure (Keyence LC2420) and detected displacement for noise evaluation.

FIG. 17. Typical self-sensing displacement error due to ambient temperature change in a unimorph actuator. Error is $\sim 0.2 \text{ \mu m/°C}$.

FIG. 18. Alternative schematic with voltage divider and integrator allowed noise reduction.

FIG. 19. Alternative schematic with voltage divider and integrator allowed noise reduction.
Zero-drift chopper op-amps (typically ±0.03 $\mu$V/°C) will probably ameliorate temperature drifts but other effects such as thermal electro motive force (EMF) (Seebeck effect) in cable junctions will still perturbate the circuit.

To generally reduce, charge integration is prone to nonzero bias currents offset voltages, temperature drifts, leaking resistance or currents, thermal EMF and electro magnetic interference influence. However, with proper measures, their influence can be eliminated or at least partially quantified and compensated.

**VI. CONCLUSION**

Displacement self-sensing of uni- and bimorph cantilevered actuators used for meso- and microscale gripping and manipulation is cost-effective and relatively simple to implement or upgrade to existing systems. To our knowledge it is a first paper focusing on displacement self-sensing of these devices. We referred to a current integration method self-compensated against some actuator nonlinearities (hysteresis and creep) and externally compensated to others (leaking resistivity and dielectric absorption).

In the case of detected or a priori—supposed absence of external forces, displacement is almost directly proportional to the charge. Further compensation of nonzero amplifier bias current, finite actuator leaking resistance, and dielectric absorption lead to a significant reduction in errors, up to 0.55% and an increase in measurement period to more than 1000 s, sufficient enough for most tasks. Signal noise was lower than that measured with expensive laser triangulation sensor. Two schematics were presented, the first one based on direct current integration showed its feasibility for long integration periods while the second integrating shunt voltage drop allowed a further reduction in signal noise with a cost of a more unstable long-term signal. Practical issues related to long-term charge preservation were presented, and temperature influence discussed.

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