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Quasistatic displacement self-sensing method for cantilevered piezoelectric actuators

Ioan Alexandru Ivan, Micky Rakotondrabe, Philippe Lutz, and Nicolas Chaillet

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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 the charge, can be compensated against 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 introductory 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 actuator 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 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).
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;</td>
<td>Quite expensive, large sizes, and limited range</td>
</tr>
<tr>
<td>Interferometers</td>
<td>Very high precision and range; increased band</td>
<td>Very expensive and large sizes</td>
</tr>
<tr>
<td>Diffraction grating target</td>
<td>and spot 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 sensibility, high precision, and fair price</td>
<td>Fragile, noisy output signal, and temperature</td>
</tr>
<tr>
<td>Magnetic Hall effect,</td>
<td>Good precision, band pass, and fair price</td>
<td>responsiveness</td>
</tr>
<tr>
<td>and magnetostrictive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Using image processing</td>
<td>Large measurement range and in-plane displacement</td>
<td></td>
</tr>
<tr>
<td>Piezoelectric self-sensing</td>
<td>Double functionality, high band pass, high</td>
<td>Require nonlinear compensation and long-term</td>
</tr>
<tr>
<td></td>
<td>resolution, and lowest price</td>
<td>charge leaking</td>
</tr>
</tbody>
</table>

The developed self-sensing systems can be divided into three main parts, as in Fig. 1: the piezoelectric actuator, the electronic circuit, and the data processing system. The latter is the proposed self-sensing estimator. The estimate displacement could be used for further feedback or closed-loop control systems.

Piezoelectric actuators are submitted to $V_{in}$ external voltages in a range of up to several hundred volts, depending on actuators. Resulted charge $Q$ (in fact integrated current) is converted by the electronic amplifier to a measurable voltage $V_{out}$. This signal will be converted for further numerical processing. Data is further processed on a computer or is deployed into a real-time processor or microcontroller. External signals can be provided to improve the self-sensing accuracy, for instance temperature variation may be compensated with a small thermistor. As the charge cannot be kept indefinitely, external resetting before each measurement prevents saturation and offsets large parts of the static error.

Among the contributions of this paper include: the introduction of an antiparallel reference capacitance, numerical compensations of amplifier bias currents and of piezoelectric leaking resistance, and dielectric absorption. A step by step approach of the identification of the self-sensing parameters is presented as well as experimental results.

The paper is organized as follows. First, we present the principle and related equations of the self-sensing estimator. 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 piezoeactuator 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:

$$
\delta = \frac{3d_{31}}{1 + \frac{d_{31}^2}{4S_{11}E_{33}}} \frac{L^2 h}{V_{in}},
$$

(1)

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

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

$$
Q = \frac{4W L E_{33}^2}{h} V_{in},
$$

(2)

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

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

![FIG. 2. A bimorph piezoelectric cantilever beam.](image2)
where \( Q \) 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 only for characterization 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) was 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.

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

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 \( V_{\text{in}} \) is inverted and applied to a “reference capacitor” \( C_R \) whose 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 higher \( V_{\text{in}} \) 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 \( V_{\text{out}} \) 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.

C. Integrator amplifier

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\[
V_{\text{out}} = -\frac{1}{C} \int_0^T i(t) dt = -\frac{1}{C} Q,
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where, for the free beam \((F_{\text{ext}}=0)\), charge is

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\[ Q = -C R \frac{V_{in}}{C} + \alpha \delta, \]

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-
193 fication:

\[ Q = -C R \frac{V_{in}}{C} + (\alpha \delta + Q DA), \]

where \( Q DA \) is an internal amount of charge depending on \( s \) 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 piezoeactuator, output voltage \( V_{out} \) of the free 200 cantilever beam is given by

\[ V_{out} = \frac{C R}{C} \frac{V_{in}}{\alpha} - \frac{1}{\alpha} \int \frac{V_{in}(t) - \alpha}{R_{FP}} dt \]

Extracting the displacement \( \delta \), we obtain the estimate as 203 follows:

\[ \delta_{est} = \frac{C R}{\alpha} \frac{V_{out} - Q DA(V_{in}(t))}{\alpha} + \frac{C R}{\alpha} \frac{V_{in}}{\alpha} - \frac{1}{R_{FP} \alpha} \int V_{in}(t) dt \]

We will consider a simple relaxation effect described by a 207 first-order transfer function for the dielectric absorption term

\[ Q'_{DA}(s) = \frac{Q DA(s)}{\alpha} = \frac{k_{i}}{s + 1}, \]

where static gain \( k_{i} = k_{o}/\alpha \). Based on the previous equations, 211 Fig. 7 presents the detailed estimation bloc-scheme. Some 212 parameters of the identification in Eq. (8) have to be identi-
213 fied. It will be presented in the next section.

FIG. 7. Displacement detection model (Simulink).

III. SELF-SENSING PARAMETER IDENTIFICATION

Parameters identification of Eq. (8) can be performed under a manual or semiautomatic procedure. Capacitances are given (\( C = 47 \, \text{nF} \) and \( C_R = 8.2 \, \text{nF} \) in our case). The identification procedure for the rest of parameters (\( \alpha, \, i_{BIAS}, \, R_{FP}, \) and \( Q DA \)) is based on Eq. (7), where the displacement \( \delta \) is provided by the displacement sensor (optical or interferometer). The following steps describe the identification procedure.

A. Bias current \( i_{BIAS} \) identification

Under \( F_{ext} = 0, \, V_{in} = 0, \) and zero temperature change, there is no electric current through the piezoelectric material; the \( V_{out} \) rate of change is measured for several dozens of seconds, deriving \( i_{BIAS} \).

B. Leaking resistance \( R_{FP} \) identification

Under \( F_{ext} = 0, \) a constant voltage \( V_{in} \neq 0 \) is applied to the actuator. After several hundred seconds the creep influence becomes negligible, and the output voltage \( V_{out} \) shifts with a constant slope, depending on \( i_{BIAS} \) (identified before) and \( R_{FP} \) (to be identified).

The identification can be repeated for different \( V_{in} \) values and averaged. Each point in Fig. 8 was recorded after a 1000–2000 s delay, to eliminate residual creep influence. Linear regression was applied.

Quality piezocantilevers will exhibit \( R_{FP} \) values superior to 1010 \, \Omega. For our actuator we identified \( R_{FP} = 0.435 \, \text{T} \, \Omega \).

C. Displacement coefficient \( \alpha \) identification

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

\[ \alpha = \frac{-CV_{out} + C R V_{in}}{\delta}. \]

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

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

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

where $\Delta \delta_{eq} = \delta_{eq} - \delta$ 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

$\alpha = 10.05 e^{-9}$ C/m,

$C = 47 e^{-9}$ F,

$C_P = 1.74 e^{-9}$ F,

$C_R = 8.2 e^{-9}$ F,

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

$I_{BIAS} = 1.7 e^{-12}$ A,

$\tau = 57$ s,

$k_s = 3.02 e^8$ 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 \(\mu m\). Compensation of \(R_{FP}\) leaking resistance allowed a reduction in maximum error to 1.05 \(\mu m\) (Fig. 14). Adding the compensation of dielectric absorption provided a 0.38 \(\mu m\) (0.55%) 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\(^{21}\) 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 leakage resistance of 24 T\(\Omega\) for \(C=10\) nF, high enough to ignore its...

![FIG. 13. Error curve of detected displacement with no leaking resistance \(R_{FP}\) compensation.](image)

![FIG. 14. Error curve of detected displacement with only leaking resistance \(R_{FP}\) compensation.](image)

![FIG. 15. Error curve of detected displacement with compensation of leaking resistance \(R_{FP}\) and dielectric absorption \(Q_{DA}\).](image)
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 Fig. 18.

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

For our actuator the best compromise between response time, sensitivity, and noise was a series resistance of 82 k\(\Omega\) \((R_{Z1} + R_{Z2}) = 82 \text{ k}\Omega\). 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 \(V_t\) voltage is in the \(\mu\text{V}\) range or lower, op-amp offset voltage temperature drift \((\pm 0.5 \text{ \mu V/\degree C})\) 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.

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

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Zero-drift chopper op-amps (typically $\pm 0.03 \, \mu V/\degree C$) 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 resume, charge integration is prone to non-ideal effects, finite actuator leakage 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.

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 leakage 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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