Hybrid Digital Control of Piezoelectric Actuators

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Abstract

Nanopositioning, as a core aspect of nanotechnology, concerns the control of motion at nanometre scale and is a key tool that allows the manipulation of materials at the atomic and molecular scale. As such it underpins advances in diverse industries including biotechnology, semiconductors and communications.

The most commonly used nanopositioner is the piezoelectric actuator. Aside from being compact in size, piezoelectric actuators are capable of nanometre resolution in displacement, have high stiffness, provide excellent operating bandwidth and high force output. Consequently they have been widely used in many applications ranging from scanning tunnelling microscopes (STM) to vibration cancellation in disk drives. However, piezoelectric actuators are nonlinear in nature and suffer from hysteresis, creep and rate-dependencies that reduce the positioning accuracy.

A variety of approaches have been used to tackle the hysteresis of piezoelectric actuators including sensor-based feedback control, feedforward control using an inverse-model and charge drives. All have performance limitations arising from factors such as parameter uncertainty, bandwidth and sensor-induced noise.
This thesis investigates the effectiveness of a synergistic approach to the creation of hybrid digital algorithms that tackle challenges arising in the control of non-linear devices such as piezoelectric actuators. Firstly, a novel digital charge amplifier (DCA) is presented. The DCA overcomes inherent limitations found in analog charge amplifiers developed in previous research.

In order to extend the DCA operational bandwidth, a complementary filter was combined with the DCA along with a non-linear black-box model derived using system identification techniques. To maximize the model accuracy a novel method is utilized that reduces error accumulation in the model. This method is generally applicable to many dynamic models. A non-linear model is also used with a data fusion algorithm to ensure the DCA does not exhibit drift, an issue common to most of charge amplifiers.

The proposed hybrid digital system is evaluated and it is shown that hysteresis is significantly decreased, while operational bandwidth is extended with no displacement drift. Experimental results are presented throughout to fully validate the proposed system.
Declarations

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Mohsen Bazghaleh

Date
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## Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+x</td>
<td>Positive electrode in the x direction</td>
</tr>
<tr>
<td>-x</td>
<td>Negative electrode in the x direction</td>
</tr>
<tr>
<td>+y</td>
<td>Positive electrode in the y direction</td>
</tr>
<tr>
<td>-y</td>
<td>Negative electrode in the y direction</td>
</tr>
<tr>
<td>b</td>
<td>Bias in semi-linear ANN</td>
</tr>
<tr>
<td>b</td>
<td>Damping of a piezoelectric actuator</td>
</tr>
<tr>
<td>C</td>
<td>Centre of a cluster</td>
</tr>
<tr>
<td>C_L</td>
<td>Capacitance of a load capacitance</td>
</tr>
<tr>
<td>C_p</td>
<td>Capacitance of a piezoelectric actuator</td>
</tr>
<tr>
<td>C_s</td>
<td>Sensing capacitor</td>
</tr>
<tr>
<td>C_series</td>
<td>Capacitor in series with a piezoelectric actuator</td>
</tr>
<tr>
<td>D</td>
<td>Density function</td>
</tr>
<tr>
<td>D</td>
<td>Electrical displacement (charge per unit area)</td>
</tr>
<tr>
<td>d</td>
<td>Piezoelectric material constants (Chapter 2)</td>
</tr>
<tr>
<td>d</td>
<td>Displacement of a piezoelectric actuator (other chapters)</td>
</tr>
<tr>
<td>( \hat{d}_{\text{ANN}} )</td>
<td>Output displacement of the ANN model</td>
</tr>
<tr>
<td>d_a</td>
<td>Actual displacement</td>
</tr>
<tr>
<td>d_d</td>
<td>Desired displacement</td>
</tr>
<tr>
<td>( \hat{d}_{\text{GDCDE}} )</td>
<td>Output displacement of the GDCDE unit</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>( d_t )</td>
<td>Reference displacement</td>
</tr>
<tr>
<td>( E )</td>
<td>Electric field</td>
</tr>
<tr>
<td>( e )</td>
<td>Error</td>
</tr>
<tr>
<td>( e_{IS} )</td>
<td>Error of an electric current</td>
</tr>
<tr>
<td>( e_m )</td>
<td>Error at the output of the NARX model</td>
</tr>
<tr>
<td>( e_{q_{opt}} )</td>
<td>Error in the optimal output charge</td>
</tr>
<tr>
<td>( F )</td>
<td>Artificial neural network</td>
</tr>
<tr>
<td>( f )</td>
<td>Output of fuzzy rules and FISs</td>
</tr>
<tr>
<td>( f )</td>
<td>Function</td>
</tr>
<tr>
<td>( f_{\text{critical}} )</td>
<td>Break (critical) frequency of a system</td>
</tr>
<tr>
<td>( F_{\text{ext}} )</td>
<td>Force imposed from an external mechanical source</td>
</tr>
<tr>
<td>( F_t )</td>
<td>Transduced force from an electrical domain</td>
</tr>
<tr>
<td>( H(s) )</td>
<td>Continuous transfer function between ( V_o(t) ) and ( V_s(t) )</td>
</tr>
<tr>
<td>( H(z) )</td>
<td>Discrete transfer function between ( V_o(t) ) and ( V_s(t) )</td>
</tr>
<tr>
<td>( I_L )</td>
<td>Electric current of a load</td>
</tr>
<tr>
<td>( I_n )</td>
<td>Electric Current source</td>
</tr>
<tr>
<td>( I_p )</td>
<td>Electric current of a piezoelectric actuator</td>
</tr>
<tr>
<td>( I_s )</td>
<td>Electric current of a sensing resistor/capacitor</td>
</tr>
<tr>
<td>( k )</td>
<td>Proportional gain</td>
</tr>
<tr>
<td>( K )</td>
<td>Gain (Charge to displacement)</td>
</tr>
<tr>
<td>( K_c )</td>
<td>Closed loop gain</td>
</tr>
<tr>
<td>( k_p )</td>
<td>Stiffness of a piezoelectric actuator</td>
</tr>
<tr>
<td>( m )</td>
<td>Mass of a piezoelectric actuator (Chapter 2)</td>
</tr>
<tr>
<td>( m )</td>
<td>The number of rules of a FIS (Others)</td>
</tr>
<tr>
<td>( MSE_{e_{opt}} )</td>
<td>Mean square error (MSE) of ( e_{q_{opt}} )</td>
</tr>
</tbody>
</table>
\( N \)  
Number of previous displacements (Chapter 4)

Activation function (Chapter 6)

\( n \)  
Number of inputs to a FIS (Chapter 4)

Number of data elements in each column of raw data (Chapter 6)

\( n_t \)  
Number of terms of discrete sum function

\( p \)  
Consequent parameter of fuzzy inference system

\( q \)  
Consequent parameter of fuzzy inference system

\( q_{\text{actual}} \)  
Actual charge across piezoelectric actuator

\( q_{\text{DCA}} \)  
Charge calculated by DCA unit

\( q_{\text{desired}} \)  
Desired charge

\( q_{\text{in}} \)  
Input charge

\( q_L \)  
Charge across a load

\( q_{\text{measured}} \)  
Measured charge across a piezoelectric actuator

\( q_{\text{model}} \)  
Charge calculated by the NARX model

\( q_{\text{optimal}} \)  
Optimal output charge

\( q_p \)  
Charge across a piezoelectric actuator

\( r \)  
Consequent parameter of fuzzy inference system

\( r_a \)  
Range of influence

\( r_b \)  
Squash factor

\( r_d \)  
Displacement (Output) order

\( r_{de} \)  
Discrete delay time

\( R_{\text{inputADC}} \)  
ADC input resistance

\( R_L \)  
DC impedance of a load

\( R_p \)  
Protection circuit resistor

\( R_s \)  
Sensing resistor
$R_t$  Total resistance

$r_u$  Input order

$r_v$  Piezoelectric voltage (input) order

$r_y$  Output order

$S$  Integration area

$S$  Strain of a piezoelectric actuator

$s$  Sampling (index)

$s$  Compliance matrix

$T$  weight of connections of the ANN

$T$  Stress

$t$  Time

$t_d$  Delay time (Dead time)

$t_f$  Final time of operation

$T_p$  Electromechanical transformer ratio

$T_s$  Sampling time

$u$  Input to the model

$V$  Applied voltage

$v$  piezoelectric actuator velocity

$V_{bias}$  Bias voltage at the input of an ADC

$V_{1/ V_{in}}, V_{in}$  Input voltage

$v_{mec}$  Voltage across the Maxwell elasto-slip element

$V_o$  Output of the voltage amplifier

$V_p$  Voltage across a piezoelectric actuator

$V_{p_{ext}}$  Last extremum value of applied voltage

$V_{ps}$  Vector of the present and a number of previous piezoelectric-
voltage values

\( V_{\text{ref}} \)  Reference voltage

\( V_s \)  Sensing voltage across the sensing resistor/Capacitor

\( V_{\text{si}} \)  Strain-induced voltage

\( v_t \)  Back-emf from the mechanical side of a piezoelectric actuator

\( W \)  Weight of connections of the ANN

\( w \)  Weight of a rule in a FIS

\( w_{\text{s}} \)  DCA weighting coefficients

\( W_{\text{ANN}} \)  ANN weighting coefficients

\( w_{\text{b}} \)  NARX model weighting coefficients

\( W_{\text{GDCDE}} \)  GDCDE weighting coefficients

\( x \)  A datum in clustering

\( x \)  Input to the activation function \( N \)

\( y \)  Output of the model

**Symbols**

\( \alpha \)  Switching value of Preisach model

\( \beta \)  Switching value of Preisach model

\( \gamma_{\alpha\beta} \)  Elementary hysteresis operator

\( \Delta \)  Nonlinear impedance

\( \epsilon \)  Permittivity

\( \mu (.) \)  Membership grade in FISs

\( \mu (...) \)  Weighting function of the Preisach model

\( \mu_n \)  Mean

\( \sigma_n \)  Standard deviation

\( \omega_c \)  Cut-off frequency