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.

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Mohsen Bazghaleh　　　　Date

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Contents

Notation

$+x$	Positive electrode in the x direction
$-x$	Negative electrode in the x direction
$+y$	Positive electrode in the y direction
$-y$	Negative electrode in the y direction
$\mathbf{b}$	Bias in semi-linear ANN
b	Damping of a piezoelectric actuator
C	Centre of a cluster
C_L	Capacitance of a load capacitance
C_p	Capacitance of a piezoelectric actuator
C_s	Sensing capacitor
C_series	Capacitor in series with a piezoelectric actuator
D	Density function
D	Electrical displacement (charge per unit area)
d	Piezoelectric material constants (Chapter 2)
	Displacement of a piezoelectric actuator (other chapters)
$\hat{d}_\mathrm{ANN}$	Output displacement of the ANN model
d_a	Actual displacement
d_d	Desired displacement
$\hat{d}_\mathrm{GDCDE}$	Output displacement of the GDCDE unit

d_{r}	Reference displacement
E	Electric field
e	Error
e_{Is}	Error of an electric current
e_{m}	Error at the output of the NARX model
$e_{\mathrm{q\_opt}}$	Error in the optimal output charge
F	Artificial neural network
f	Output of fuzzy rules and FISs
f	Function
f_{critical}	Break (critical) frequency of a system
F_{ext}	Force imposed from an external mechanical source
F_{t}	Transduced force from an electrical domain
$H(s)$	Continuous transfer function between $V_{\mathrm{o}}(t)$ *and* $V_{\mathrm{s}}(t)$
$H(z)$	Discrete transfer function between $V_{\mathrm{o}}(t)$ and $V_{\mathrm{s}}(t)$
I_{L}	Electric current of a load
I_n	Electric Current source
I_{p}	Electric current of a piezoelectric actuator
I_{s}	Electric current of a sensing resistor/capacitor
k	Proportional gain
K	Gain (Charge to displacement)
K_{c}	Closed loop gain
k_{p}	Stiffness of a piezoelectric actuator
m	Mass of a piezoelectric actuator (Chapter 2) The number of rules of a FIS (Others)
$MSE_{\mathrm{e\_opt}}$	Mean square error (MSE) of $e_{\mathrm{q\_opt}}$

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_f	Number of terms of discrete sum function
p	Consequent parameter of fuzzy inference system
q	Consequent parameter of fuzzy inference system
q_actual	Actual charge across piezoelectric actuator
q_DCA	Charge calculated by DCA unit
q_desired	Desired charge
q_in	Input charge
q_L	Charge across a load
q_measured	Measured charge across a piezoelectric actuator
q_model	Charge calculated by the NARX model
q_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_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
$\mathbf{T}$	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_{i} / V_{in}/ v_{in}	Input voltage
v_{mrc}	Voltage across the Maxwell elasto-slip element
V_{o}	Output of the voltage amplifier
V_{p}	Voltage across a piezoelectric actuator
V_{Pext}	Last extremum value of applied voltage
$\mathbf{V}_{\mathbf{ps}}$	Vector of the present and a number of previous piezoelectric-

	voltage values
V_{ref}	Reference voltage
V_{s}	Sensing voltage across the sensing resistor/Capacitor
V_{si}	Strain-induced voltage
v_{t}	Back-emf from the mechanical side of a piezoelectric actuator
$\mathbf{W}$	Weight of connections of the ANN
w	Weight of a rule in a FIS
w_{a}	DCA weighting coefficients
W_{ANN}	ANN weighting coefficients
w_{b}	NARX model weighting coefficients
W_{GDCDE}	GDCDE weighting coefficients
x	A datum in clustering
x	Input to the activation function N
y	Output of the model

Symbols

α	Switching value of Preisach model
β	Switching value of Preisach model
$\gamma_{\alpha\beta}$	Elementary hysteresis operator
Δ	Nonlinear impedance
ϵ	Permittivity
μ (.)	Membership grade in FISs
μ (.,.)	Weighting function of the Preisach model
μ_{n}	Mean
σ_{n}	Standard deviation
ω_{c}	Cut-off frequency