TOWARDS ROBUST SLIDING MODE CONTROL OF ELECTROSTATIC MICROACTUATORS

by

Argyrios Christou Zolotas

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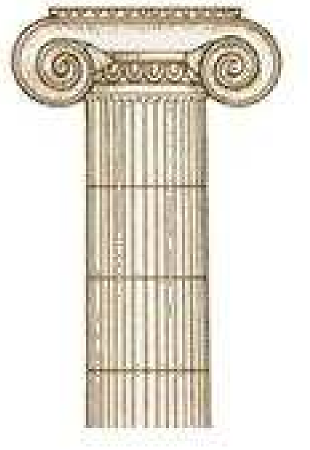
Αφιερωμένο στην πολυαγαπημένη μου γιαγιά, και στις αγάπες της ζωής μου Ματούλα και Άννα-Λυδία.



Dedicated to my beloved (late) grandmother, and the loves of my life Matoula and Anna-Lydia.

This Thesis was typeset in 12pt Roman *fonts using* LaTeX2ε, LaTeX-CAD,
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Synopsis (Abstract)

Micro Electro Mechanical Systems refer to formation of electro-mechanical systems in the scales of micrometers. In terms of popularity of the technology and interest toward this, Borovic et al have mentioned in their recent paper[28]:

> "*MEMS are the next step in the silicon revolution that began 40 years ago. Currently, MEMS are in an exponential growth stage such as that enjoyed by the semiconductor industry.*".

While MEMS technology enables significant reduction in physical size of various types of sensors, actuators and systems by several orders of magnitude, does not necessarily imply less system complexity. In fact, modelling or identifying characteristics of such devices can be difficult as a combination of advanced modelling techniques and Finite Element analysis would be necessary to obtain an appropriate mathematical model approximation.

In the context of MEMS actuator technology, the electrostatic microactuators have received much attention for real applications such as DLP technology and research work on more advanced control algorithms. Traditionally, such devices have been controlled in an open loop fashion but problems with the so-called pull-in phenomenon (a form of instability in the system due to the electrostatic forces that arise between the plate of the microactuator) limits performance. Feedback control has enabled improved performance, although still most works exist in research labs rather than already implemented and in mass production.

The work presented in this dissertation relates to voltage control of parallel-plate electrostatic microactuator devices, with the particular aim of extending the travelling range of the microactuator plates beyond the "pull-in" condition thus taking advantage of increase range of operation (which is useful when finer motion resolution is required in applications such as DLP etc.). The particular aim is studying the capabilities of state feedback related Sliding Mode Control to improving system performance and robustness to uncertainty compared to the linear control equivalents. Simulation studies are performed with the help of Matlab and Simulink.

Acknowledgements

I would like to express my gratitude to my advisor, Professor Christopher Edwards for introducing me to advanced nonlinear control and the concept of sliding mode control and giving me the opportunity to work on such an interesting problem. Chris' support, guidance and continuous encouragement during the period of my studies were invaluable.

The reason of being interested in the area for control for MEMS devices is thanks to Professor Anthony Tzes who did first introduce me to the research problem of micro-actuator control design during one of my visit's to Patras University of Greece few years ago.

A very big *thank you* to my wife Matoula for her love, patience, support and encouragement during the period of my M.Sc. studies; and an even bigger *thank you* for giving me the greatest "present" of all... our lovely "little princess", Anna-Lydia.

Loughborough, Leics, England
Argyrios Zolotas
Sep. 2010

Λάφμπροου, Λέστερσαϊρ, Αγγλία
Αργύριος Ζολώτας
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Glossary and Acronyms

$\eta, \dot{\eta}, \ddot{\eta}$	microactuator's gap, gap rate, gap acceleration
η_{max},η_{pi}	gap at rest (or maximum gap), gap at pull-in
A, B, C, D	State space realisation of a system
$Q, \dot{Q}$	capacitor's charge, rate of charge
AFM	Atomic Force Microscope
DLP	Digital Light Processing
DMD	Digital Micro-Mirror Device
SLM	Sliding Mode
SLMC	Sliding Mode Control
TF	Transfer Function

Other symbols and acronyms are defined as they appear

Chapter 1

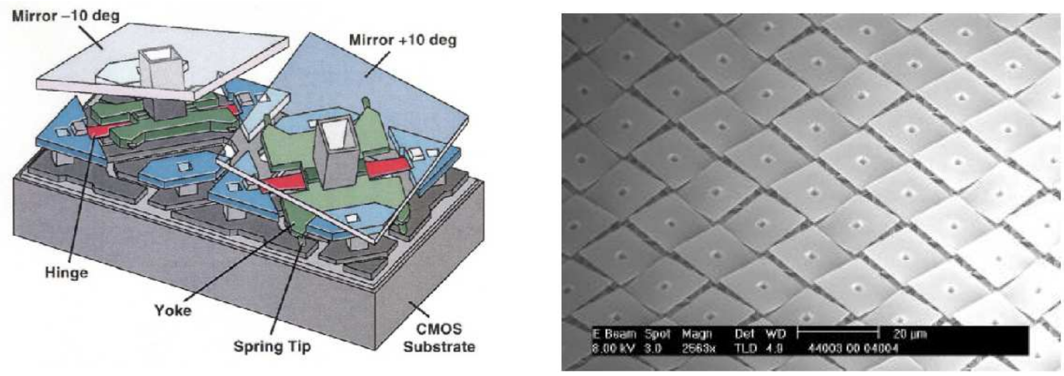
Introduction

Micro Electro Mechanical Systems or so-called MEMS sounds like a word of "tiny" dimension but miraculous nevertheless, referring to formation of electro-mechanical systems in the scales of micrometers[1, 2]. In terms of popularity of the technology and interest toward this, Borovic et al have mentioned in their recent paper [28]:

> "*MEMS are the next step in the silicon revolution that began 40 years ago. Currently, MEMS are in an exponential growth stage such as that enjoyed by the semiconductor industry.*".

In particular, MEMS technology has enabled the significant reduction in physical size of various types of sensors, actuators and systems by several orders of magnitude, still maintaining (and in many cases improving) their performance. Smaller size does not necessarily imply less system complexity, with a plethora of MEMS devices being no less complex compared to other macro-world electro-mechanical systems [28]. In fact, modelling or identifying characteristics of such devices can be difficult as a combination of advanced modelling techniques and Finite Element analysis would be necessary to obtain an appropriate mathematical model approximation.

MEMS technology comprises a number of applications in the area of sensors and actuators, mainly due to the successful integration of MEMS technology and integrated circuits (IC) since the 1980s [28] with a growing research interest point of view that continues to date. In particular, in the area of microactuators the so-called parallel plate electrostatic microactuator devices are rather popular and employed in a number of MEMS applications as in Texas Instrument's Digital Light Processing (DLP) (digital projectors using DMDs with an example seen in Figure 1.1), Atomic force microscopes, optical grating, variable capacitors, interferometers, [3, 4, 5, 6], and there has been an increasing research interest on the aforementioned components during the last 10 years or so [7, 8, 9].



(a) A schematic example of a Digital Micro-mirror Device (DMD) Texas Intrum.

(b) Micro-mirror array

Figure 1.1: Digital Micro-mirror Devices [18]

The advantage in employing electrostatic microactuators is low cost and reduced power consumption. However, operating the device effectively has drawbacks as in its uncompensated open loop operation (referring to the so-called parallel-plate electrostatic micro-actuators as mentioned previously) the device is subject to a phenomenon referred to as “pull-in” effectively being a breaking point towards system instability. In particular, these devices were traditionally controlled in an open-loop fashion due to the controller simplicity in implementation (note that simplicity in implementing controllers for microsystems is an important issue due to scaling) [14]. Problems of limited performance due to “pull-in” and sensitivity to uncertainty of the system affect open loop controllers, with closed-loop control a necessity [28]. In this context, as the sophistication level of MEMS devices progressed further, there is also a desire for more sophisticated control algorithms thus improving performance [14].

As mentioned previously, traditionally the microactuator devices were controlled in an open-loop fashion, the solution usually being the design of sufficiently large gap between the plates of the microcapacitor to allow for movement avoiding pull-in conditions. However, the gap distance in a microactuator adheres to the technology used and is not easily changed by the designer. From a closed-loop control point of view a number of approaches have been proposed both from a linear controller design and nonlinear control design point of view. A good survey on control techniques in this area appears in [14],[28]. Two main approaches are employed: (i) charge control and (ii) voltage control with the latter being more favourable due to the presence of parasitic capacitances in the former schemes.

Recently more nonlinear feedback control strategies have arisen in this area, with a well presented treatment in [29] on i/o linearisation, passivity in the context of static and dynamic feedback. In this same paper the author positively comments on the potential of using Sliding Mode Control for such devices. In fact, a sliding mode controller for a simplified optical switch system has been proposed in [16], while a couple of other strategies are explained in [17].

The work presented in this dissertation relates to voltage control of parallel-plate electrostatic microactuator devices, with the particular aim of extending the travelling range of the microactuator plates beyond the "pull-in" condition thus taking advantage of increase range of operation (which is useful when finer motion resolution is required in applications such as DLP etc.). The particular aim is studying the capabilities of state feedback related Sliding Mode Control to improving system performance and robustness to uncertainty compared to the linear control equivalents.

The report is organized as follows. Chapter 2 the mathematical modelling of a 1-DOF parallel-plate electrostatic microactuator, discussion on its nonlinear model nature and equilibrium points as well as the "pull-in" phenomenon and linearisation of the nonlinear equations. Chapter 3 presents simulation results on the uncompensated open loop system (comparing the linearised model to the original nonlinear equivalent) and lists a set of control specifications to attempt in feedback control design. Chapter 4 discusses on linear control design, in particular on a simple SISO classical PD controller and use of state feedback control designs as well as a note on stability when dealing with the implementation on the nonlinear system. Chapter 5 presents state feedback related Sliding Mode Control approach and compares its performance to the linear control equivalents. Conclusions are drawn in Chapter 6. For completeness, a number of Appendices is included, i.e. normalization of the modelling equations dealing with realistic parameter values, enhanced simulink model with pull-in point indication, the interim msc project proposal and a set of matlab files.