



**Advances in Discrete-Time Sliding Mode Control:  
Theory and Applications**

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*To my wife ...*









# Abstract

While a large number of investigations in the control systems literature focus on the analysis of continuous-time systems, more and more practising control engineers implement the control laws using micro-processors. The controllers can either be carried out from continuous-time representations using fast sampling ideas, or the continuous-time controllers can be converted to their discrete-time representations. However, the choice of the high sampling rate, which nearly approximates continuous-time, may not always be possible. Alternatively, discrete-time controllers can be designed directly from a discrete-time representation of the plant. One thread of the literature develops discrete-time controllers to stabilize discrete-time uncertain linear systems with bounded uncertainties. A great deal of the work in this field considered state-feedback control laws based on Lyapunov ideas. In this dissertation, our main focus is on the design of a specific control strategy using the digital computers. This control strategy referred to as Sliding Mode Control (SMC) has its roots in (continuous-time) relay control. This dissertation aims to explain our recent investigations' output in the field of discrete-time sliding mode control (DSMC). Firstly, this dissertation explains a new robust LMI-based (state-feedback and observer-based output-feedback) DSMC. Furthermore, it is stated in the current related literature that a fully decentralized control strategy may lead to unacceptable control performance, especially if the subsystems interact strongly, and further, a centralized control strategy for large, networked systems is found to be impractical and unrealistic by practitioners. In this dissertation, then, a new scheme for sparsely distributed DSMC is presented. Moreover, this dissertation includes a novel framework for the design of optimal  $\mathcal{H}_2$ -based structured distributed SMC, and presents a procedure to sparsify the control network structure while taking into account the available control actions to avoid high level of control efforts that each

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subsystem's controller requires to apply, and ensuring the stability of the composite reduced-order closed-loop dynamics. In addition, this dissertation will present our work to apply DSMC to two-dimensional (2D) systems using 1D approaches. Additionally, a specific chapter will also discuss the controllability of the 2D systems through 1D approaches. This dissertation also presents a novel event-driven control mechanism, called actuator-based event-driven scheme, using a synchronized-rate biofeedback system for heart rate regulation during cycle-ergometer. Indeed, this event-driven control mechanism has been designed by exploiting an adaptive integral SMC scheme along with several embedded practical technologies to construct an automated exercise testing system for different applications such as sports training, medical diagnosis, rehabilitation and analysis of cardiorespiratory kinetics.

## CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student: *Ahmadreza Argha*

Date: *... Oct. 2016*



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# Glossary

$A^T$	Transpose of the matrix $A$ ,
$I_m$	Identity matrix of size $m \times m$ ,
$\dot{x}(t)$	Time derivative of the vector $x(t)$ , i.e. $\dot{x}(t) = \frac{dx(t)}{dt}$ ,
$\lambda(A)$	Eigenvalues of the matrix $A$ ,
$\lambda_{\max}(A)$	Maximum eigenvalue of the matrix $A$ ,
$\lambda_{\min}(A)$	Minimum eigenvalue of the matrix $A$ ,
$[\Sigma_{ij}]_{r \times r}$	is a block matrix with block entries $\Sigma_{ij}$ , $i = 1, \dots, r$ , $j = 1, \dots, r$ ,
$\ A\ $	2-Norm of the matrix $A$ defined as $\max \frac{\ Ax\ ^2}{\ x\ ^2}$ ,
$\ x(t)\ $	2-norm of the vector $x$ at time $t$ ,
$\ x\ $	2-Norm of the vector $x$ defined as $\sqrt{x^T x}$ ,
$\mathbb{R}$	Collection of real numbers,
$\otimes$	Kronecker product,
$\text{col}(v_i(k))_{i=1}^r$	denotes a block-vector with block entries $v_i(k)$ , $i = 1, \dots, r$ ,
$\text{diag} [\Sigma_{ii}]_{i=1}^r$	is a block-diagonal matrix with block entries $\Sigma_{ii}$ , $i = 1, \dots, r$ ,
$\{\circ\}$	denotes an operator for $\Xi = [\xi_{ij}]_{h \times h}$ in which $\xi_{ij} \in \mathbb{R}$ and $W = [W_{ij}]_{h \times h}$ in which $W_{ij} \in \mathbb{R}^{r_i \times s_j}$ such that $\Xi \circ W = [\xi_{ij} W_{ij}]_{h \times h}$ ,
<b>1D</b>	One-Dimensional,
<b>2D</b>	Two-Dimensional,
<b>CSMC</b>	Continuous-Time Sliding Mode Control,

<b>DSMC</b>	Discrete-Time Sliding Mode Control,
<b>FM</b>	Fornasini and Marchesini,
<b>HR</b>	Heart Rate,
<b>ISMC</b>	Integral Sliding Mode Control,
<b>KVA</b>	Kilo-Volt-Ampere,
<b>LMI</b>	Linear Matrix Inequality,
<b>MIMO</b>	Multiple Input, Multiple Output,
<b>NCS</b>	Networked Control System,
<b>OCSMC</b>	Output Based Continuous-Time Sliding Mode Control,
<b>ODSMC</b>	Output Based Discrete-Time Sliding Mode Control,
<b>OSMC</b>	Output Based Sliding Mode Control,
<b>PID</b>	Proportional, Integral and Derivative,
<b>PIO</b>	Proportional Integral Observer,
<b>PWM</b>	Pulse Width Modulation,
<b>QSM</b>	Quasi Sliding Mode,
<b>RLS</b>	Recursive Least Squares,
<b>RM</b>	Roesser Model,
<b>RMS</b>	Root Mean Squares,

<b>SISO</b>	Single Input, Single Output,
<b>SMC</b>	Sliding Mode Control,
<b>UPS</b>	Un-interruptible Power System,
<b>VSDCS</b>	Variable Structure Discontinuous Control Strategy,
<b>WAM</b>	Wave Advanced Model,



# Publications

**Full Length Refereed Conference Papers (published in full in proceedings):**

- A. Argha, L. Ye, S. W. Su, H. Nguyen, B. G. Celler, “Real-time Modelling of Heart Rate Response During Exercise Using A Novel Constrained Parameter Estimation Method”, in Proc. the 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC’16), Aug. 17-20, 2016, Orlando, America.
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