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

Ahmadreza Argha

A Dissertation Submitted for the Degree of Doctor of Philosophy

at the

School of Electrical, Mechanical and Mechatronic Systems
Faculty of Engineering and Information Technology
University of Technology, Sydney

October 2016

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 $\mathscr{H}_2$-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

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*

Acknowledgements

At the University of Technology, Sydney I have had the opportunity to meet some wonderful people. First of all, I would like to thank my principal supervisor Associate Professor Steven Su and my co-supervisor Dr. Li Li. I cannot put into words what I have learnt from them. Their attitude to research and intellect have been my source of inspiration. It was a great honor to work with them and learn from them.

I was also fortunate to have the chance to collaborate with an excellent Professor Hung Nguyen. I thank Professor Hung Nguyen for being incredibly supportive.

I am grateful to my external supervisor Professor Branko Celler for supporting me and helping me in the biomedical part of my research. Professor Branko Celler, thank you for being such a nice person.

I am thankful to the center for health technologies and school of Electrical, Mechanical and Mechatronic systems at UTS for contributing to such a pleasant atmosphere. The librarians at University of Technology Sydney deserve special thanks for their assistance in supplying the relevant literatures.

Finally, my deepest appreciation goes to my wife Naghmeh for her support, never-ending patience, and inspiration who endured this long process with me, always offering support and love. I am so lucky to have you in my world, and I hope I can be as supportive when you need it. I also owe a lot to my sister-in-law Ghazal for her supports and helps. I have also to greatly thank my family and my wife's family for their unfailing love and encouragement.

Ahmadreza Argha

University of Technology, Sydney

October 2016

Contents

List of Figures

List of Tables

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,
$\left[\Sigma_{ij}\right]_{r\times r}$	is a block matrix with block entries $\Sigma_{ij},\ i = 1,\cdots,r,\ j = 1,\cdots,r$,
$\|A\|$	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,
$\mathbf{col}(v_i(k))_{i=1}^r$	denotes a block-vector with block entries $v_i(k),\ i = 1,\cdots,r$,
$\mathbf{diag}\left[\Sigma_{ii}\right]_{i=1}^r$	is a block-diagonal matrix with block entries $\Sigma_{ii},\ i = 1,\cdots,r$,
$\{\circ\}$	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 $\Xi \circ W = [\xi_{ij} W_{ij}]_{h\times h}$,
1D	One-Dimensional,
2D	Two-Dimensional,
CSMC	Continuous-Time Sliding Mode Control,

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

SISO Single Input, Single Output,

SMC Sliding Mode Control,

UPS Un-interruptible Power System,

VSDCS Variable Structure Discontinuous Control Strategy,

WAM 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.
- A. Argha, L. Ye, S. W. Su, H. Nguyen, B. G. Celler, “Heart Rate Regulation During Cycle-Ergometer Exercise Using Damped 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.
- A. Argha, S. W. Su, A. Savkin, and B. G. Celler, “ H_2/H_{infty} Based Sliding Mode Control: A Partial Eigenstructure Assignment Method”, (Accepted) To be appeared in Proc. the 55th Conference on Decision and Control (CDC), Dec. 12-14, 2016, Las Vegas, USA.
- A. Argha, S. W. Su, A. Savkin, “Optimal Actuator/Sensor Selection Through Dynamic Output Feedback”, (Accepted) To be appeared in Proc. the 55th Conference on Decision and Control (CDC), Dec. 12-14, 2016, Las Vegas, USA.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "$\boldsymbol{H}_2$-Based Optimal Sparse Sliding Mode Control for Networked Control Systems", (Accepted) To be appeared in Proc. the 55th Conference on Decision and Control (CDC), Dec. 12-14, 2016, Las Vegas, USA.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "Robust Output-feedback Discrete-Time Sliding Mode Control Utilizing Disturbance Observer", in Proc. the 54th Conference on Decision and Control (CDC), Dec. 15-18, 2015, pp. 5671-5676, Osaka, Japan.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "Discrete-time sliding mode control for networked systems with random communication delays", in Proc. the 2015 American Control Conference, July 2015, pp. 6016-6021, Chicago, America.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "Controllability analysis of the first FM model of 2D systems: A row (column) process", in Proc. the 53th Conference on Decision and Control (CDC), Dec. 2014, pp. 2414-2419, LA, America.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "A new LMI-based robust Sliding Mode Control for the uncertain discrete-time systems", in Proc. the 53th Conference on Decision and Control (CDC), Dec. 2014, pp. 4747-4752, LA, America.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "Decentralized Sliding Mode Control for Uncertain Discrete-Time Large-Scale Systems: An LMI Approach", in Proc. 2013 Australian Control Conference (AUCC), pp. 251-256, Nov. 2014, Canberra, Australia.

- A. Argha, L. Li, S. W. Su, "A New Approach to Apply Discrete Sliding Mode Control to 2D Systems", in Proc. the 52th Conference on Decision and Control (CDC), Dec. 2013, Italy.

- A. Argha, L. Li, S. W. Su, H, Nguyen, "The Application of Discrete Sliding Mode Control in Parabolic PDE Dynamics," in Proc. 2013 Australian Control Conference (AUCC), Nov. 2013, Perth, Australia.

- A. Argha, S. W. Su, H. Nguyen, B. G. Celler, “Designing Adaptive Integral Sliding Mode Control for Heart Rate Regulation During Cycle-Ergometer Exercise Using Biofeedback”, in Proc. the 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC’15), Aug. 25-29, 2015.

- A. Argha, S. W. Su, H. Nguyen, B. G. Celler, “Heart Rate Regulation During Cycle-Ergometer Exercise via Biofeedback”, in Proc. the 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC’15), Aug. 25-29, 2015.

- A. Argha, S. W. Su, S. Lee, H. Nguyen, B. G. Celler, “On Heart Rate Regulation in Cycle-Ergometer Exercise”, in Proc. the 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC’14), Aug. 26-30, 2014.

- J. Zhang, D.G. Dorrell, L. Li, A. Argha, “A novel sliding mode controller for DC-DC boost converters under input/load variations”, in Proc. Industrial Electronics Society, IECON 2015-41st Annual Conference of the IEEE (pp. 001698-001703), Nov. 2015.

Refereed Journal Articles:

- A. Argha, L. Li, S. W. Su, H. Nguyen, "Controllability Analysis of Two-dimensional Systems Using 1D Approaches", IEEE Transactions on Automatic Control, 60(11): 2977-2282, Nov. 2015.
- A. Argha, L. Li, S. W. Su, H. Nguyen, "Stabilising the networked control systems involving actuation and measurement consecutive packet losses", IET Control Theory & Applications, 10(11):1269-1280, July 2016.
- A. Argha, S. W. Su, B. Celler, "Heart Rate Regulation During Cycle-Ergometer Exercise via Event-Driven Biofeedback", Medical & Biological Engineering & Computing, Accepted on 18/05/2016, DOI 10.1007/s11517-016-1530-9.
- A. Argha, L. Li, S. W. Su, H. Nguyen, "On LMI-based sliding mode control for the uncertain discrete-time systems", Journal of the Franklin Institute, 353(15): 3857-3875, Oct. 2016.
- A. Argha, S. W. Su, B. Celler, "Real-Time Identification of Heart Rate Response Dynamics During Treadmill Exercise", Medical & Biological Engineering & Computing, Submitted, under review.
- A. Argha, S. W. Su, A. Savkin, B. G. Celler, "Mixed $\boldsymbol{H}_2/\boldsymbol{H}_\infty$-based actuator selection for uncertain Polytopic systems with regional pole placement", International Journal of Control, Submitted, under review.
- A. Argha, L. Li, S. W. Su, H. Nguyen, "Sparse Observer-based Sliding Mode Control for Networked Control Systems", Automatica, Submitted, Under review, Revision 2.
- A. Argha, L. Li, S. W. Su, "Design of $\boldsymbol{H}_2$ ($\boldsymbol{H}_\infty$)-based optimal structured and sparse static output feedback gains", Journal of the Franklin Institute, Submitted, under review.
- A. Argha, L. Li, S. W. Su, "$\boldsymbol{H}_2$-based optimal sparse sliding mode control for networked control systems", International Journal of Robust and Nonlinear Control, Submitted, under review.