UNIVERSITY OF TECHNOLOGY SYDNEY
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On Data-driven Modelling and Terminal Sliding Mode Control of Dynamic Systems with Applications

by

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Certificate of Authorship/Originality

I hereby certify that the work produced in this thesis has neither been previously submitted for a degree nor has it been submitted as a part of the requirements for other degree except as fully acknowledged within this text.

I also certify that this thesis has been written by myself. Any help that I have received in my research and in the preparation of the thesis itself has been fully acknowledged.

In addition, I certify that all information sources and literature used are quoted in the thesis.

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ABSTRACT

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This thesis addresses critical issues in system modelling and control with some applications to robotics and automation. The main content is divided into three parts, namely data-driven identification, fast terminal sliding mode control alongside underactuated crane control, and robotic pointing system for thermoelastic stress analysis (TSA).

The first part is devoted to system modelling. A dynamic model can be identified from data collected (input and output data from the plant). However, the data obtained is often affected by noise. Hence, such algorithms for modelling the plant should be robust enough to accurately predict the dynamic behaviour of the system in the presence of noisy data. Taking this into account, this thesis focuses on subspace-based identification methods, and proposes an effective algorithm based on the Least-Square Support Vector Regression (LS-SVR). In the proposed algorithm, the system identification is formulated as a regression problem to be solved by applying multi-output LS-SVR.

The second part of the thesis deals with the control of underactuated systems which are subjected to uncertainties including nonlinearities, parameter variations, and external disturbances. Among many control methodologies, Sliding Mode Control (SMC) is known for its strong robustness. Conventional SMC usually consists of linear sliding surfaces, which can only guarantee the asymptotic stability of the system, and hence, takes infinite time to reach the equilibrium. Requirements of finite-time stability can be fulfilled by adding the sliding function with a fractional

nonlinear term to achieve the Terminal Sliding Mode, and using another attractor can lead to a faster response, called the Fast Terminal Sliding Mode (FTSM). FTSM is theoretically promising but it has limited application in real-time systems. This thesis is devoted to bridging this practical gap by developing a FTSM controller for underactuated mechanical systems.

The third part of this thesis presents the applications of the proposed LS-SVR based identification algorithm and FTSM control scheme. Here, theoretical developments are implemented on a laboratorial gantry crane and an optical pointing system, respectively. Performance of both LS-SVR identification and FTSM control is verified through extensive simulation and experimental results. Notably, the work for this thesis has been applied to the RobotEye, an industrial pointing system of Ocular Robotics Pty. Ltd., which consists of a mirror integrated with other sensors such as laser sensors and vision cameras for robotic navigation or structural health monitoring with TSA.

To my late grandfather
Hutendra Man Singh
&
my late grandmother
Ratna Kumari Singh

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List of Publications

Journal Papers

J-1. **A. M. Singh**, and Q. P. Ha "Fast Terminal Sliding Control Application for Second-Order Underactuated Systems," *International Journal of Control, Automations and Systems*, 2018. (Accepted for publication)

J-2. **A. M. Singh**, and Q. P. Ha "System Identification using Multiple Output Least-Square Support Vector Regression," *International Journal of Systems Science*, 2018. (Submitted)

Conference Papers

C-1. **A. M. Singh**, V. T. Hoang and Q. P. Ha, "Fast terminal sliding mode control for gantry cranes, *Proc. 33rd International Symposium on Automation and Robotics in Construction*, pp. 437-443, July 18-21, 2016.

C-2. **A. M. Singh**, Q. P. Ha, D. Wood, M. Bishop "Low-latency Vision-based Fiducial Detection and Localisation for Object Tracking, *Proc. 34th International Symposium on Automation and Robotics in Construction*, pp. 706-711, June 28- July 1, 2017.

C-3. **A. M. Singh**, Q. P. Ha, D. Wood, M. Bishop, Q. Nguyen, and A. Wong "RobotEye Technology for Ther- mal Target Tracking Using Predictive Control, *Proc. 35th International Symposium on Automation and Robotics in Construction*, pp. 1167-1173, July 20- 25, 2018.

C-4. **A. M. Singh**, M. D. Phung, and Q. P. Ha "Modelling and Fast Terminal Sliding Mode Control for Mirror-based Pointing Systems, *Proc. 15th International Conference on Control Automation Robotics and Vision*, pp. 1151-1157, Nov. 18-21, 2018.

Contents

List of Figures

List of Tables

List of Algorithms

List of Abbreviations

2-DOF - 2 Degree of Freedom

SMC - Sliding Mode Control

TSM - Terminal Sliding Mode

FTSM - Fast Terminal Sliding Mode

HSM - Hierarchical sliding mode

UMS - Underactuated Mechanical System

MPC - Model Predictive Control

SVR - Support Vector Regression

KKT - Karush Kuhn Tucker

LS-SVR - Least Square Support Vector Regression

MLS-SVR - Multi-output Least Square Support Vector Regression

SVD - Singular Value Decomposition

PCA - Principal Component Analysis

N4SID - Numerical Algorithm for Subspace State Space System Identification

MOESP - Multivariable Output-Error State Space Model Identification

CVA - Canonical Variable Analysis

SIMPCA - Subspace Identification Methods Principal Component Analysis

TSA - Thermoelastic Stress Analysis

RMSE - Root Mean Square Error

NRMSE - Normalised Root Mean Square Error

MRSE - Mean of Relative Square Error

MVAF - Mean Variance Accounted-for

ISE - Integral of Square Error

ITSE - Integral of Time Square Error

IoT - Internet of Things

AIC - Akaike Information Criterion

API - Application Programming Interface

GA - Genetic Algorithm

List of Notations

$\mathbb{R}$ - Field of real numbers

$\mathbb{R}^n$ - n-dimensional space

$\mathbb{R}^{n\times m}$ - Space of all matrices of $(n \times m)$-dimension

$A^\top$ - Transpose of matrix A

A^{-1} - Inverse of matrix A

I_n - Identity matrix of $(n \times n)$-dimension.

$A^\perp$ - Orthogonal complement of matrix A.

$\mathbf{0}_{(n\times m)}$ - Zero matrix of $n \times m$-dimension.

$\mathbf{1}_{(n\times m)}$ - One matrix of $n \times m$-dimension.

rank(A) - Rank of matrix A.

trace(A) - Trace of matrix A.

$A^\dagger$ - Moore-Penrose pseudo inverse of matrix A.

$\|.\|$ - Euclidean norm of a vector or spectral norm of a matrix.

$\forall$ - For all.