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MODELLING AND CONTROL OF OFFSHORE CRANE SYSTEMS

by

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Certificate of Authorship/Originality

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

I also certify that this thesis has been written by me. Any help that I have received in my research work 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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Cranes are widely used in transportation, construction and manufacturing. Suspended payloads in crane system are caused to swing due to actuator movement, external disturbance such as wind flows, and motion of the crane base in the case of portable cranes. Recently, offshore cranes have become a new trend in stevedoring and in offshore construction as they can help to avoid port congestion and also to exploit ocean engineering applications. For crane operations, it is important to satisfy rigorous requirements in terms of safety, accuracy and efficiency. One of the main challenges in crane operations has been identified as the sway motion control, which is subject to underactuation of crane drive systems and external disturbances. Particularly in offshore cranes, the harsh conditions can produce exogenous disturbances during the load transfer at various scenarios of offshore crane operations in practice. Therefore, it is interesting as to how to design robust controllers to guarantee high performance in the face of disturbances and parameter variations in offshore cranes.

The motivation for this thesis is based on recent growing research interest in the derivation of dynamic models and development of control techniques for offshore cranes in the presence of, for example, the rope length variation, sway, ocean waves and strong winds in offshore crane systems. Accordingly, the work for this thesis has been conducted in the two main themes, namely analytical modelling and control design, for which new results represent its contributions.

Dynamic models of two types of offshore crane systems, namely the offshore gantry crane and offshore boom crane, are derived in the presence of vessel's ocean wave-induced motion. The effect of wind disturbances on the payload sway is also considered in the modelling. In the control context, sliding mode control techniques for a generic form of underactuated mechanical Lagrangian systems are presented, including the conventional first-order, second-order and adaptive fuzzy sliding mode controllers. The major component in this part of the thesis is the design of sliding mode control laws based on the developed offshore crane models for trajectory tracking problems, in the presence of persistent disturbances in severe open-sea conditions. Extensive simulation results are presented to demonstrate the efficacy of the models and robustness of the designed controllers.

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List of Publications

1. **R.M.T. Raja Ismail**, Nguyen D. That, Q.P. Ha (2015), *Modelling and robust trajectory following for offshore container crane systems*, "Automation in Construction" – accepted on 13 May 2015.

2. **R.M.T. Raja Ismail**, Nguyen D. That, and Q.P. Ha (2014), *Offshore container crane systems with robust optimal sliding mode control*, The 31st International Symposium on Automation and Robotics in Construction and Mining, Sydney, Australia, pp. 149-156.

3. **R.M.T. Raja Ismail**, Nguyen D. That, and Q.P. Ha (2013), *Adaptive fuzzy sliding mode control for uncertain nonlinear underactuated mechanical systems*, The 2nd International Conference on Control, Automation and Information Sciences, Nha Trang, Vietnam, pp. 212-217.

4. **R.M.T. Raja Ismail** and Q.P. Ha (2013), *Trajectory tracking and anti-sway control of three-dimensional offshore boom cranes using second-order sliding modes*, The 9th IEEE International Conference on Automation Science and Engineering, Wisconsin, Madison, USA, pp. 996-1001.

5. **R.M.T. Raja Ismail** and Q.P. Ha (2013), *Trajectory tracking control for offshore boom cranes using higherorder sliding modes*, The 30st International Symposium on Automation and Robotics in Construction and Mining, Montreal, Canada, pp. 894-904.

6. **R.M.T. Raja Ismail** and Q.P. Ha (2012), *Second-order sliding mode control for offshore container cranes*, The 22nd Australasian Conference on Robotics and Automation, Wellington, New Zealand, 7p.

7. **R.M.T. Raja Ismail**, Nguyen D. That, and Q.P. Ha (2012), *Observer-based trajectory tracking for a class of underactuated Lagrangian systems using higher-order sliding modes*, The 8th IEEE International Conference on Automation Science and Engineering, Seoul, Korea, pp. 1200-1205.

8. Nguyen D. That, Nguyen K. Quang, **R.M.T. Raja Ismail**, P.T. Nam and Q.P. Ha (2012), *Improved reachable set bounding for linear systems with discrete and distributed delays*, The 1st International Conference on Control, Automation and Information Sciences, Ho Chi Minh, Vietnam, pp. 137-141.

Contents

List of Figures

List of Tables

Nomenclature and Notation

Throughout the thesis, the following nomenclatures and notations are used:

- 1-SMC: First-order sliding mode control
- 2-SMC: Second-order sliding mode control
- 2-D: Two-dimensional
- 3-D: Three-dimensional
- AFSMC: Adaptive fuzzy sliding mode control
- DOF: Degree of freedom
- HOSM: Higher-order sliding modes
- LQR: Linear quadratic regulator
- LMI: Linear matrix inequality
- LTI: Linear time-invariant
- MIMO: Multi input multi output
- SISO Single input single output
- SMC: Sliding mode control
- SVD: Singular value decomposition
- UMS: Underactuated mechanical system
- VSC: Variable structure control
- $\mathbb{R}$: 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^T: Transpose of matrix A
- A^{-1}: Inverse of matrix A
- I_n: Identity matrix of $(n \times n)$-dimension
- $0_{n\times m}$: Zero matrix of $(n \times m)$-dimension
- C_θ: $\cos\theta$

- S_θ: $\sin\theta$
- $\lambda(A)$: Set of all eigenvalues of matrix A
- $\lambda_{\min}(A)$: Smallest eigenvalue of matrix A
- $\lambda_{\max}(A)$: Largest eigenvalue of matrix A
- $\mathrm{diag}(\lambda_1, \cdots, \lambda_i, \cdots, \lambda_n)$: Diagonal matrix with diagonal entries λ_i, $i = 1, \cdots, n$
- $\mathrm{rank}(A)$: Rank of matrix A
- $\mathrm{sign}(\cdot)$: Signum function
- $||\cdot||$: Euclidean norm of a vector or spectral norm of a matrix
- $\forall$: For all