MODEL REFERENCE COMMAND SHAPING FOR CONTROL OF A MULTIMODE DOUBLE-PENDULUM OVERHEAD CRANE

HAZRIQ IZZUAN JAAFAR

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

To my dearest parents, Jaafar Che Lah and Jamaliah Sabar for their love, blessing and prayers.

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ABSTRACT

Cranes with double-pendulum dynamics are extensively used in industrial applications to transport massive or hazardous materials from one location to another. In such situations, the hook and payload generate significant oscillations during fast transportation with different modes of frequency. The crane control challenge increases under payload hoisting and payload mass variations as the system's natural frequency and damping ratio change during these conditions. Most existing feedforward approaches need measurements of system's parameters for controller design. This thesis proposes a new Model Reference Command Shaping (MRCS) based on a reference model for a multimode Double-Pendulum Overhead Crane (DPOC). This technique avoids the need for measurement or estimation of system's frequency and damping ratio in contrast to the existing input and command shaping approaches. Several formulations are used to find the shaper's numerator to ensure an exact cancellation of system poles that significantly contributes to the reduction of hook and payload oscillations. As the MRCS design involves complicated procedures and mathematical formulations, a simpler MRCS approach using the Particle Swarm Optimization (PSO) algorithm namely MRCS-PSO is subsequently designed. Furthermore, in an attempt to achieve the objectives of precise trolley positioning with minimal hook and payload oscillations of DPOC, a hybrid control structure of MRCS and Proportional-Integral-Derivative (PID) feedback control called MRCS+PID is proposed and implemented. The hybrid controller is designed such that all the control parameters can be tuned concurrently to ensure optimal responses of both objectives. Simulations using a nonlinear DPOC model and experiments on a laboratory DPOC are carried out to investigate the effectiveness and robustness of the proposed controllers. In all investigations, crane operating conditions under payload hoisting and payload mass variations which pose difficult crane control are considered. Performance assessments of the controllers are performed based on the maximum and overall oscillations of the hook and payload, together with the speed and final position of the trolley response. The simulation and experimental results demonstrate a higher robustness of MRCS as compared to the established multimode Zero Vibration and Zero Vibration Derivative input shapers designed with the average travel length technique. The MRCS achieved 21.1% and 1.2% reductions in the overall hook oscillations, as well as 27.1% and 9.2% in the overall payload oscillations respectively. The advantage of the MRCS-PSO approach is confirmed by achieving a near exact pole-zero cancellation that provides almost a similar performance in the oscillation reductions when compared to the MRCS approach. For the hybrid controller, experimental results show that the MRCS+PID control design enables the trolley to move with a smoother response and it is 15.9% faster than the PID+PID feedback control. Moreover, the MRCS+PID control is found to be superior with reductions of the maximum and overall payload oscillations by 36.6% and 83.8% respectively. It is envisaged that the MRCS and the hybrid MRCS with a feedback controller can be utilized for efficient oscillation and vibration control of various multimode systems.

ABSTRAK

Kren dengan dinamik bandul berkembar digunakan secara meluas dalam aplikasi industri untuk mengangkut bahan besar atau berbahaya daripada satu lokasi ke lokasi yang lain. Dalam keadaan sedemikian, cangkuk dan beban menghasilkan ayunan ketara semasa pengangkutan pantas bersama frekuensi mod yang berbeza. Cabaran kawalan kren meningkat di bawah variasi angkutan beban dan berat beban di mana frekuensi tabii dan nisbah redaman sistem berubah semasa keadaan ini berlaku. Kebanyakan pendekatan pengawal suap depan sedia ada memerlukan pengukuran parameter sistem untuk rekabentuk pengawal. Tesis ini mencadangkan sebuah Arahan Pembentuk Model Rujukan (MRCS) baru berasaskan model rujukan untuk Kren Gantung Bandul Berkembar (DPOC) pelbagai ragam. Teknik ini mengelak dari memerlukan pengukuran atau anggaran frekuensi dan nisbah redaman sistem, ia berbeza daripada kaedah pembentuk masukan dan arahan yang sedia ada. Beberapa formulasi digunakan untuk mencari pengatas pembentuk bagi memastikan pembatalan tepat kutub sistem yang menyumbang dengan ketara kepada pengurangan ayunan cangkuk dan beban. Oleh kerana rekabentuk MRCS melibatkan tatacara dan perumusan matematik yang rumit, pendekatan MRCS mudah menggunakan algorithma Pengoptimuman Kerumunan Zarah (PSO) iaitu MRCS-PSO kemudiannya direkabentuk. Selain itu, dalam usaha untuk mencapai objektif kedudukan troli yang tepat bersama ayunan cangkuk dan beban DPOC yang minimum, struktur kawalan hibrid MRCS dan kawalan suap balik Kamiran Terbitan Berkadaran (PID) yang digelar sebagai MRCS+PID dicadangkan dan dilaksanakan. Pengawal hibrid direka supaya semua parameter kawalan boleh ditala secara serentak untuk memastikan sambutan yang optimal bagi kedua-dua objektif. Simulasi menggunakan model DPOC tidak lelurus dan eksperimen terhadap DPOC bersaiz makmal dijalankan untuk menyiasat keberkesanan dan keteguhan pengawal yang dicadangkan. Dalam semua penyiasatan, keadaan operasi kren di bawah angkutan beban dan variasi berat beban yang menimbulkan kesukaran kawalan kren dipertimbangkan. Penilaian prestasi pengawal dilakukan berdasarkan ayunan maksimum dan keseluruhan cangkuk dan beban, bersama-sama dengan kelajuan dan kedudukan akhir sambutan troli. Keputusan simulasi dan eksperimen menunjukkan keteguhan MRCS lebih tinggi terhadap perubahan panjang kabel semasa angkutan beban dan variasi berat beban berbanding rekabentuk pembentuk masukan Getaran Sifar dan Pembezaan Getaran Sifar pelbagai ragam direka dengan teknik purata panjang gerakan. MRCS masing-masing mencapai 21.1% dan 1.2% dalam pengurangan ayunan keseluruhan cangkuk, dan 27.1% dan 9.2% dalam ayunan keseluruhan beban. Kelebihan pendekatan MRCS-PSO disahkan dengan mencapai pembatalan kutub sifar hampir tepat yang memberikan prestasi pengurangan ayunan hampir sama berbanding kaedah MRCS di bawah keadaan variasi operasi kren. Untuk pengawal hibrid, keputusan eksperimen menunjukkan bahawa rekabentuk kawalan MRCS+PID membolehkan troli bergerak dengan sambutan yang lebih lancar dan dengan 15.9% lebih pantas daripada kawalan suap balik PID+PID. Tambahan pula, kawalan MRCS+PID didapati lebih baik di dalam pengurangan maksimum dan keseluruhan ayunan beban masing-masing dengan 36.6% dan 83.8%. MRCS dan hibrid MRCS bersama kawalan suap balik dijangkakan boleh digunakan untuk kawalan ayunan dan getaran yang cekap bagi pelbagai sistem pelbagai ragam.

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LIST OF ABBREVIATIONS

ATL	-	Average Travel Length
DPOC	-	Double-Pendulum Overhead Crane
EC	-	Extension Control
FLC	-	Fuzzy Logic Controller
GA	-	Genetic Algorithm
IS	-	Input Shaping
LQR	-	Linear Quadratic Regulator
MRC	-	Model Reference Control
MRCS	-	Model Reference Command Shaping
MSE	-	Mean Squared Error
NCTF	-	Nominal Characteristic Trajectory Following
P	-	Proportional
PD	-	Proportional-Derivative
PID	-	Proportional-Integral-Derivative
PSO	-	Particle Swarm Optimization
SI	-	Specified Insensitivity
SIRMs	-	Single-Input-Rule-Modules’
SMC	-	Sliding Mode Control
ZV	-	Zero Vibration
ZVD	-	Zero Vibration Derivative
2D	-	Two-Dimensional
3D	-	Three-Dimensional

LIST OF SYMBOLS

A_{λ}	-	Positive amplitude of impulse λ
A_{ZV}	-	Amplitude of ZV shaper
A_{ZVD}	-	Amplitude of ZVD shaper
a_6, a_4, a_2	-	MRCS control parameters
c_1	-	Cognitive acceleration coefficients
c_2	-	Social acceleration coefficients
D	-	High dimensional
e	-	Position error
F_l	-	External force signal for payload hoisting
F_x	-	External force signal for trolley
f_l	-	Viscous damping coefficients of hoisting
f_x	-	Viscous damping coefficients of trolley
$G_c(s)$	-	Transfer function of linear system model
$G_r(s)$	-	Transfer function of reference model
$G_s(s)$	-	Transfer function of MRCS
g	-	Gravitational acceleration constant
$gbest_j$	-	Global best position
H	-	Constant parameter of input shaping
h_1	-	High of hook
h_2	-	High of payload
i	-	Swarm of individuals
J	-	Cost function/fitness value
J_{new}	-	New fitness function
j	-	Dimensional
K	-	Total kinetic energy
K_D, K_I, K_P	-	Derivative, Integral, Proportional parameters of PID controller
K_l	-	Kinetic energy of hoisting

K_x	-	Kinetic energy of trolley
K_{θ_1}	-	Kinetic energy of hook
K_{θ_2}	-	Kinetic energy of payload
k	-	Number of iteration
L	-	Lagrangian function
L_{fixed}	-	Lagrangian function with fixed cable lengths
L_{hoist}	-	Lagrangian function with payload hoisting
l_1	-	Massless cable length between trolley and hook
l_2	-	Massless cable length between hook and payload
M	-	Maximum number of impulses
m	-	Trolley mass
m_1	-	Hook mass
m_2	-	Payload mass
m_3	-	Cable mass
N	-	Maximum number of iterations
n	-	System order
P	-	Total potential energy
P_l	-	Potential energy of hoisting
P_x	-	Potential energy of trolley
P_{θ_1}	-	Potential energy of hook
P_{θ_2}	-	Potential energy of payload
p	-	Pole
$pbest_{ij}$	-	Personal best position
q_i	-	Generalized coordinate
r_1, r_2	-	Random function values
s	-	Linear matrix variable
T	-	Simulation time
$T_1(s)$	-	Overall transfer function of a MRCS+PID control stability
$T_2(s)$	-	Overall transfer function of a PID+PID control stability
t	-	Time
t_λ	-	Time location of impulse λ
t_{ZV}	-	Time location of ZV shaper

t_{ZVD}	-	Time location of ZVD shaper
u	-	Control input
V_{ij}^{k}	-	Velocity of k^{th} particle
V_{ij}^{k+1}	-	New velocity of k^{th} particle
v	-	Trolley velocity
v_1	-	Hook velocity
v_2	-	Payload velocity
v_3	-	Hoisting velocity
w	-	Inertia weight
X_{ij}^{k}	-	Position of the k^{th} particle
X_{ij}^{k+1}	-	New position of the k^{th} particle
x	-	Trolley position
x_d	-	Step input signal
x_r	-	Unit step responses of $G_s(s)G_c(s)$
$\hat{x}_r$	-	Unit step responses of $G_r(s)$
y	-	System output
z	-	Zero
α	-	Numerator coefficients for overall transfer function of a MRCS+PID control stability
β	-	Denominator coefficients for overall transfer function of a MRCS+PID control stability
γ	-	Numerator coefficients for overall transfer function of a PID+PID control stability
φ	-	Denominator coefficients for overall transfer function of a PID+PID control stability
ρ	-	Population size of particle
λ	-	Impulse series
ζ_c	-	Damping ratio of linear crane system
ζ_r	-	Damping ratio of reference model
θ_1	-	Hook angle
θ_2	-	Payload angle
θ_{1m}	-	Maximum oscillation of hook

θ_{2m}	-	Maximum oscillation of payload
θ_{1r}	-	Reference zero angle of hook
θ_{2r}	-	Reference zero angle of payload
ω_c	-	Natural frequency of second order linear model
ω_d	-	Damped frequency
ω_n	-	Natural frequency of oscillatory system
ω_r	-	Natural frequency of reference model
Δh	-	Vertical distance
Δt	-	Sampling time

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CHAPTER 1

INTRODUCTION

1.1 Research Background

As worldwide industrial applications, cranes have been tremendously utilized to transport massive payloads or hazardous materials from one location to another position. The cranes can be roughly classified into three categories (Abdel-Rahman *et al.*, 2003; Hong and Shah, 2019): (i) An overhead/gantry crane, (ii) A tower/rotary crane, and (iii) A boom crane as depicted in Figure 1.1. Generally, the cranes consist of three main components that represent a trolley to move along a rail in x- or y-direction, cable (including hoisting components) that is used to carry a payload, and payload with various types and sizes. In addition, most of industrial cranes are considered as being underactuated mechanical systems, which indicate lower number of control inputs than the number of system degrees of freedom (Dian-Tong *et al.*, 2006; Boscariol and Richiedei, 2018; Zhang *et al.*, 2019). Despite that those cranes system have different physical mechanical structures, safety, cost and productivity improvements are the similar major factors often emphasized.

(a)

(b)

(c)

Figure 1.1 Types of cranes: (a) An overhead/gantry crane (b) A tower/rotary crane (c) A boom crane

In industrial cranes environment, accurate positioning with minimum payload oscillation is desirable for an efficient and safe operation of the crane systems, which can directly increase the industrial productivity. However, the fast crane's motion is prone to an excessive payload oscillation that could affect the positioning accuracy, the effectiveness, the quality and the safety. Therefore, high proficiency levels of crane operators are required to operate the crane and to compensate for the payload oscillation motions, as the payload behaves similar to a pendulum motion behaviour and likely to swing freely. In that case, the crane operator might need to slow down and properly compensate for the crane's manoeuvres, in order to dampen out the payload oscillation that may interrupt the crane's performance. If a severe oscillation occurs, the operation needs to be paused until it stops from swinging.

In addition, changes in the cable length during payload transportation (known as a payload hoisting) that are essential in crane operations and using different payload masses might also generate unexpected payload motions such as swinging, twisting and bouncing (Yoon *et al.*, 2014; Maghsoudi *et al*., 2019). In fact, the dynamic behaviour of crane system is sensitive to various operating conditions such as different trolley positions that affect to the crane performances (Jaafar *et al.*, 2013; Mar *et al*., 2017; Sun et al., 2019). Consequently, a failure to control the payload oscillation would lead to a difficulty in the automation of the system by the crane operator, together with a possible damage to the quality of the payload and the operating environment around the construction work. Moreover, it would take a longer time being required for the task's completion and this may reduce the production volume. Statistics have shown that traditional docking equipment wastes more than 30% for fixing the load per the loading time (Liu *et al.*, 2014). Hence, all these issues have attracted many researchers to explore more on the crane control.

1.2 Motivation

In many cases, most of researchers normally treat the crane systems as a single-pendulum motion. The model of the crane system is greatly simplified with some assumptions, which hides the presence of a second oscillatory mode of the crane system during payload transportation (Giacomelli *et al.*, 2018). Unfortunately, the simplified model are no longer sufficient in practical applications and has attracted few researchers to further investigate on the existence of multimode oscillations phenomenon that is more closer to the real practical crane, called a multimode double-pendulum overhead crane (DPOC) system. Due to the less reported works and still at a relatively primary stage (Lu *et al.*, 2019; Ouyang *et al*., 2019a; Zhang *et al.*, 2019), it becomes a motivation to continue exploring on the impact of multimode oscillations for the DPOC systems.

Safety issue is another reason of motivation to ensure a safe crane operation among crane operators, surrounding workers and environment. This is because several crane accidents have occurred regardless of time and places across the world. As reported in Neitzel *et al.* (2001), the cranes contribute to one-third of all construction fatalities and injuries resulting in permanent disability. In fact, a study by Rishmawi (2016) on the crane accidents between January 2011 to October 2015 showed that the main reason for the accident was due to the case of the crane overturning or tipping over. One of the major accidents was happened in Mecca, Saudi Arabia on 11th September 2015 which 107 people died and more than 230 people were injured (Essaid *et al.*, 2015). The latest crane accidents happened in Malaysia were on 10th February 2017 (Sidek, 2017), 11th July 2017 (Md Sani, 2017) and 2nd January 2018 (Kumar, 2018) which caused death and injuries. More surprising where another four people were killed and three others were injured recently when a crane collapsed in the Northwestern United State City of Seattle on 29th April, 2019 (Baumann and Geranios, 2019). All the accidents can be related to payload oscillation, where the payload with higher oscillation became a cause of broken cable, crane hook fell and tip-over.

A lot of effort have been made to minimize the higher payload oscillation of the crane systems. Implementations of feedforward control have received much attention as a preferable solution for the vast majority of cranes (Singhose, 2009; Vaughan *et al.*, 2010). This solution is the most appreciated in the crane industrial because it avoids the use of feedback sensors (cost saving) to measure the angle of payload oscillation (Giacomelli *et al.*, 2018). Without the feedback information signals, prior knowledge of the system uncertainties are significantly required, thus increases the difficulties in designing the feedforward control. In order to avoid the tedious controller design for the crane system, development of an alternative feedforward control without prior knowledge of the system uncertainties and simpler process design is essential as another motivation for this study.

1.3 Problem Statement

A payload oscillation can be minimized by knowing the natural frequency and damping ratio values as practiced in the feedforward control designs. However, the changes in crane's natural frequency and damping ratio yield unwanted oscillation that caused difficulties to place the payload accurately and increases task of completion time. Moreover, it is noted that obtaining accurate oscillation frequency and damping ratio of the crane systems are challenging. Small measurement or estimation errors could lead to an inefficient controller and may also result in a higher system oscillation (Giacomelli *et al.*, 2018). In solving this issue, a successful design of an alternative feedforward control without the need for the multimode frequencies and damping ratios will be an advantage and desirable for a DPOC system.

In addition, strong dependence on the analytical approaches make the feedforward control designs involved with complicated procedure and mathematical formulations. As a results, the analytical feedforward controllers are quite challenging to be implemented by many researchers, especially with respect to the changes of payload mass variations (Qian *et al.*, 2016a) and cable length during payload hoisting (Lu *et al.*, 2019). In such situations, the analytical feedforward controllers need to be redesigned for every changes, which is not effective in practical applications. Therefore, an effective and robust feedforward control is crucial to be designed using an established metaheuristic approach with less massive mathematical formulations.

Despite that the feedforward control is a superior strategy in minimizing the payload oscillations, unfortunately, the control technique does not have the ability to control the crane movement for various positions tracking (Mar *et al.*, 2017). It is extremely challenging in the situation where the crane moves to different locations while ensuring minimal oscillations during payload hoisting and different payload mass (Hong and Shah, 2019). In order to overcome this problem, a hybrid feedforward control with a feedback control that provides an efficient position tracking with minimal oscillations of the DPOC system under payload hoisting and different payload mass has to be developed.

1.4 Research Objectives

The work focuses on designing an effective feedforward control for a multimode DPOC through extensive simulation and experimental exercises. The objectives of this research are listed as follows:

i. To design a new model reference command shaping (MRCS) based on a reference model without a prior knowledge of the multimode system's frequency and damping ratio for effective oscillation control.

ii. To improve the proposed MRCS by simplifying a process of control design using particle swarm optimization algorithm (MRCS-PSO) for optimal oscillation control.

iii. To design and implement a hybrid MRCS with proportional-integral-derivative (MRCS+PID) using an improved PSO algorithm for an efficient position tracking with minimal oscillations.

iv. To test and validate the proposed methods in real-time implementation using a laboratory overhead crane system under the effects of fixed cable lengths, payload hoisting and payload mass variations.

1.5 Research Scopes

The scopes of the overall research are listed as follows:

i. A two-dimensional (2D) nonlinear DPOC model is formulated using the Lagrange equation for the evaluation of proposed controller performances by using MATLAB/Simulink software.

ii. A 2D INTECO laboratory overhead crane is used to validate the nonlinear DPOC model, and to verify the robustness and effectiveness of proposed controller.

iii. The proposed controller is developed based on a feedforward control and augmented with a practical PID feedback control for position tracking and oscillation control.

iv. Varying cable length (payload hoisting) is restricted from 0.20 m to 0.40 m due to height limitations of the laboratory overhead crane.

v. Inextensible cables are used for simulation and experimental tests.

vi. Two cylindrical loads that represent a hook and a payload are considered where the payload mass does not exceed the hook mass throughout the simulation and experimental executions.

vii. The hook and the payload are modelled as a point mass.

viii. RT-DAC/PCI Programmable I/O by INTECO (2007) is used for real-time data acquisition and the sampling time used is 5 ms.

ix. The feedforward control is not designed to handle the influence of external disturbances such as wind.

1.6 Research Contributions

This thesis provides several contributions in the field of feedforward control for the multimode DPOC system. In addition, several articles have been published in journals, book chapters and conference proceeding resulting from these contributions as shown in the list of publications. The contributions of the research work are listed as follows:

i. The main contribution of this thesis lies on a new feedforward control design called MRCS, which is based on a reference model and does not require system's natural frequency and damping ratio for oscillation control of a DPOC. This is in contrast to the existing feedforward approaches that highly dependent on natural frequency and damping ratio parameters for control designs. The performance of existing feedforward control becomes weak and ineffective especially at the presence of varying cable length during payload hoisting and payload mass variations. Simulation and experimental results show that the proposed MRCS is effective in oscillations suppression as compared to the other established feedforward control approaches.

ii. The establishment of the PSO algorithm in engineering applications has been used for controller tuning parameters, especially for single-pendulum crane systems with significant results. However, the PSO has never been reported for DPOC systems, which seems limit the practical applicability. In this thesis, the ability of the PSO is fully utilized in simplifying a process of the MRCS design (MRCS-PSO) with less mathematical formulations that contribute to the oscillation reductions of the DPOC. The advantage of the designed MRCS-PSO approach has achieving almost a similar performance in the oscillations reduction under payload hoisting and payload mass variations when compared to the analytical MRCS approach.

iii. This thesis also contributes in the design of an efficient control approach that involves a hybrid MRCS with a PID feedback control (MRCS+PID) to achieve various desired positions with minimal oscillations under payload hoisting and payload mass variations. Interestingly, the hybrid control parameters are tuned concurrently using an improved PSO algorithm as most existing hybrid control approaches have been designed independently for DPOC with massive mathematical formulations. Within the simulation and experimental executions, the proposed MRCS+PID approach is capable to achieve various trolley positions precisely with superior control performance of oscillation suppressions over a PID+PID feedback control.

1.7 Thesis Organization

This thesis is organized in seven chapters that reflects the sequence of steps involved in the development of control schemes for a multimode DPOC system. A brief outline of the thesis contents is as follows:

Chapter 1 presents research background of the crane systems, motivation, problem statement, research objectives, research scopes and contribution of research works.

Chapter 2 describes the dynamic of the double-pendulum behaviour in practical operations. Then, the literature review on the existing control approaches for the DPOC is also discussed. From the conducted literature review, research gaps of the study have been identified.

Chapter 3 explains the methodology of the overall research in achieving all the research objectives. The details modelling derivations of a nonlinear DPOC model with fixed cable lengths and payload hoisting are formulated. The experimental laboratory setup is also presented. Then, a control algorithm including the proposed and benchmarking control approaches for real-time implementation are briefly explained.

Chapters 4, 5 and 6 present various simulation and experimental results of the proposed and benchmarking control approaches. Several tests including fixed cable length, payload hoisting and payload hoisting with different payload masses are carefully conducted.

Finally, Chapter 7 provides a concluding remark on the overall research work. Recommendations of possible future research direction for this work are also outlined in this chapter.

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LIST OF PUBLICATIONS

Journals

1. **Jaafar**, **H**. **I**., Mohamed, Z., Shamsudin, M. A., Mohd Subha, Ramli, L. and Abdullahi, A. M. (2019) 'Model reference command shaping for vibration control of multimode flexible systems with application to a double-pendulum overhead crane', *Mechanical Systems and Signal Processing*, 115, 677–695 (ISI Indexed, Q1, IF: 5.005)

2. **Jaafar**, **H**. **I**., Mohamed, Z., Mohd Subha, N. A., Husain, A. R., Ismail, F. S., Ramli, L., Tokhi, M. O. and Shamsudin, M. A. (2019) 'Efficient control of a nonlinear double-pendulum overhead crane with sensorless payload motion using an improved PSO-tuned PID controller', *Journal of Vibration and Control*, 25(4), 907–921 (ISI Indexed, Q1, IF: 2.865)

Book Chapters

1. **Jaafar**, **H**. **I**., Mohamed, Z. and Ramli, L. (2019) 'Optimal PSO-tuned PID for a double-pendulum overhead crane', in Ismail, F. S., Siong, L. S. (Eds) *Studies in Control and System Automation*. Malaysia: Penerbit UTM Press, 47–64.

2. **Jaafar**, **H**. **I**. and Mohamed, Z. (2017) 'PSO-tuned PID controller for a nonlinear double-pendulum crane system', in Mohamed Ali, M. S., Wahid, H., Mohd Subha, N. A., Sahlan, S., Md Yunos, M. A., Wahap A. R. (Eds) *Modeling, Design and Simulation of Systems, Communications in Computer and Information Science*. Singapore: Springer, 203–215.

Conference Proceeding

1. **Jaafar**, **H**. **I**., Mohamed, Z., Ramli, L. and Abdullahi, A. M. (2018) 'Vibration control of a nonlinear double-pendulum overhead crane using feedforward command shaping', in *2018 IEEE Conference on Systems, Process & Control*. Melaka, Malaysia, 118–122.

LIST OF AWARDS

1. **Silver Award** (Top 5 in Engineering Category), 2nd Graduate Research Exhibition Competition, Universiti Teknologi Malaysia, 2019.
2. **Best Presenter Award**, IEEE Conference on Systems, Process and Control (ICSPC), 2018.
3. **First Place Winner**, Three Minute Thesis (3MT) Competition, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 2018.
4. **Bronze Award** (Top 10 in Engineering Category), 1st Graduate Research Exhibition Competition, Universiti Teknologi Malaysia, 2017.