EVOLUTIONARY ALGORITHMS FOR ACTIVE VIBRATION CONTROL OF FLEXIBLE MANIPULATOR

HANIM BINTI MOHD YATIM

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

MARCH 2016

In the name of Allah, The Most Gracious, The Most Merciful

A lot of thanks

To my lovely husband Norsawar bin Set Nazari, who always encourages me with support and help. To my son Aqil Ziqri and my daughter Auni Zahra who have brought great motivation and wonderful fun in my life.

To my beloved parents Mohd Yatim bin Abd Hamid and Rohani binti Yusoff, and my siblings who are always there and pray for me.

To my respectable supervisors Assoc. Prof. Dr. Intan Zaurah and Dr. Maziah Mohamad for their kindness and provided me with boundless of knowledge.

ACKNOWLEDGEMENT

Alhamdulillah, all praise to Allah, the Most Beneficient and the Most Merciful.

First and foremost, I would like to express my deepest gratitude to my thesis supervisor, Assoc. Prof. Dr. Intan Zaurah binti Mat Darus for all her kindness, support, continuous patience, generous amount of time and supervision given throughout the progress of this thesis. It has been an honor and a privilege to have the opportunity to work with her. Special thanks also to Dr Maziah Mohammad, my honorable co-supervisor, for her committed support and invaluable advice throughout my study.

Sincere appreciation to my beloved husband, Norsawar bin Set Nazari, my father, Mohd Yatim bin Abdul Hamid, my mother, Rohani binti Yusoff and all my family members who have been supporting and bear with me until the end.

I would like to further extend my gratitude to all my friends, suppliers and technicians who assisted me directly or indirectly throughout the progress of this thesis. A special expression of gratitude is extended to everyone for their tolerance and patience.

Thank You.

ABSTRACT

Flexible manipulator systems offer numerous advantages over their rigid counterparts including light weight, faster system response, among others. However, unwanted vibration will occur when flexible manipulator is subjected to disturbances. If the advantages of flexible manipulator are not to be sacrificed, an accurate model and efficient control system must be developed. This thesis presents the development of a Proportional-Integral-Derivative (PID) controller tuning method using evolutionary algorithms (EA) for a single-link flexible manipulator system. Initially, a single link flexible manipulator rig, constrained to move in horizontal direction, was designed and fabricated. The input and output experimental data of the hub angle and endpoint acceleration of the flexible manipulator were acquired. The dynamics of the system was later modeled using a system identification (SI) method utilizing EA with linear auto regressive with exogenous (ARX) model structure. Two novel EAs, Genetic Algorithm with Parameter Exchanger (GAPE) and Particle Swarm Optimization with Explorer (PSOE) have been developed in this study by modifying the original Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithms. These novel algorithms were introduced for the identification of the flexible manipulator system. Their effectiveness was then evaluated in comparison to the original GA and PSO. Results indicated that the identification of the flexible manipulator system using PSOE is better compared to other methods. Next, PID controllers were tuned using EA for the input tracking and the endpoint vibration suppression of the flexible manipulator structure. For rigid motion control of hub angle, an auto-tuned PID controller was implemented. While for vibration suppression of the endpoint, several PID controllers were tuned using GA, GAPE, PSO and PSOE. The results have shown that the conventional auto-tuned PID was effective enough for the input tracking of the rigid motion. However, for end-point vibration suppression, the result showed the superiority of PID-PSOE in comparison to PID-GA, PID-GAPE and PID-PSO. The performance of the best simulated controller was validated experimentally later. Through experimental validation, it was found that the PID-PSOE was capable to suppress the vibration of the single-link flexible manipulator with highest attenuation of 31.3 dB at the first mode of the vibration. The outcomes of this research revealed the effectiveness of the PID controller tuned using PSOE for the endpoint vibration suppression of the flexible manipulator amongst other evolutionary methods.

ABSTRAK

Sistem pengolah mudah lentur menawarkan banyak kelebihan berbanding sistem tegar termasuk ringan, tindak balas sistem yang lebih cepat, dan lain-lain. Walaubagaimanapun, getaran tidak diingini akan berlaku apabila sistem pengolah mudah lentur ini terdedah kepada gangguan. Sebuah model yang jitu dan sistem kawalan berkesan perlu dibangunkan untuk mengeksploitasi kelebihan sistem mudah lentur.Tesis ini membentangkan pembangunan kaedah talaan pengawal kadaran-kamiran-terbitan (PID) menggunakan algoritma evolusi (EA) untuk sistem pengolah mudah lentur satu lengan. Pada mulanya, rig sistem pengolah mudah lentur satu lengan, telah direka dan difabrikasi, dengan kekangan untuk bergerak pada arah mendatar. Data masukan dan keluaran yang untuk sudut pangkal dan getaran di hujung sistem pengolah mudah lentur diperolehi secara eksperimen. Model sistem dinamik kemudiannya diperolehi melalui kaedah sistem identifikasi (SI) menggunakan struktur model linear autoregresif dengan input eksogenus (ARX). Dua algoritma evolusi baru iaitu algoritma genetik dengan penukar parameter (GAPE) dan pengoptimuman kerumunan zarah dengan penjelajah (PSOE) telah dibangunkan di dalam kajian ini dengan memodifikasi algoritma genetik (GA) dan pengoptimuman kerumuhan zarah (PSO) yang asli. Algoritma-algoritma ini telah diperkenalkan untuk identifikasi sistem pengolah mudah lentur. Keberkesanannya kemudian dinilai dengan perbandingan kepada GA dan PSO yang asli. Keputusan menunjukkan identifikasi untuk sistem pengolah mudah lentur menggunakan PSOE lebih baik berbanding dengan kaedah lain. Seterusnya, pengawal PID telah ditala menggunakan algoritma-algoritma evolusi untuk menjejak masukan dan menghapus getaran hujung struktur pengolah mudah lentur. Untuk kawalan gerakan tegar sudut pangkal, talaan-automatik PID telah digunakan. Manakala untuk penghapusan getaran hujung, beberapa pengawal PID telah ditala menggunakan GA, GAPE, PSO dan PSOE. Keputusan telah menunjukkan bahawa pengawal konvensional menggunakan talaan-automatik PID adalah cukup berkesan untuk menjejak masukan gerakan tegar. Bagi penghapusan getaran pada hujung struktur, keputusan menunjukkan kelebihan pengawal PID-PSOE mengatasi pengawal PID-GA, PID-GAPE dan PID-PSO. Pengawal yang mempunyai prestasi terbaik secara simulasi telah dipilih untuk disahkan secara eksperimen. Melalui pengesahan secara eksperimen, didapati PID-PSOE telah mampu mengurangkan getaran sistem pengolah mudah lentur satu lengan sebanyak 31.3 dB pada mod pertama getaran. Hasil kajian menunjukkan keberkesanan pengawal PID yang ditala menggunakan algoritma PSOE untuk menghapuskan getaran hujung pengolah mudah lentur yang lebih baik berbanding kaedah evolusi yang lain.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABC	-	Artificial Bees Colony
ACO	-	Ant Colony Optimization
ANFIS	-	Adaptive neuro-fuzzy inference system
APSO_RW	-	Adaptive particle swarm optimization using random inertia weight
ARX	-	Auto regressive with exogenous input
AVC	-	Active vibration control
BFA	-	Bacterial foraging algorithm
CMPSO	-	cooperative multiple particle swarm optimization
DAQ	-	Data acquisition system
DC	-	Direct current
DE	-	Differential evolution
DFS	-	Delayed feedback signal
DOF	-	Degree of freedom
EA	-	Evolutionary algorithm
FLC	-	Fuzzy logic controller
FPPD	-	Fuzzy pre-compensated proportional-derivative
FSR-GA	-	Fitness sharing replacement-genetic algorithm
GA	-	Genetic algorithm
GAPE	-	Genetic algorithm with parameter exchanger
GBSO	-	Genetically bacterial swarm optimzation
HPSO-TVAC	-	Hierarchical particle swarm optimization with time varying acceleration coefficient
ICP	-	Integrated Circuit Piezoelectric

IEPSO	-	Immunity enhanced particle swarm optimization
ILA	-	Iterative learning algorithm
ILC	-	Iterative learning control
LQR	-	Linear quadratic regulator
LS	-	Least square
MGA	-	Modified genetic algorithm
MPSO	-	Modified particle swarm optimization
MSE	-	Mean squared error
MSEE	-	Mean squared error of training data
MSET	-	Mean squared error of testing data
NARX	-	Nonlinear auto regressive with exogenous input
NARMAX	-	Nonlinear auto regressive moving average with exogenous input
NI	-	National Instruments
NN	-	Neural network
ORSE	-	Observability range space extraction
OSA	-	One step-ahead prediction
PC	-	Personal computer
PD	-	Propotional-derivative
PI	-	Proportional-integral
PID	-	Proportional integral derivative
PSO	-	Particle swarm optimization
PSOE	-	Particle swarm optimization with explorer
PZT	-	Piezoelectric
QFT	-	Quantitative feedback theory
RCGA	-	Real-coded genetic algorithm
RLS	-	Recursive least square
RO	-	Reverse osmosis
SDRE	-	State-dependent riccati equation
SI	-	System identification
SISO	-	Single input single output
SIMO	-	Single input multiple outputs

TRMS	-	Twin rotor multi inputs-multi outputs
TVAC	-	Time varying acceleration coefficients
UAV	-	Unmanned aerial vehicle
ZN	-	Ziegler Nichols

LIST OF SYMBOLS

$A(z^{-1})$	-	Polynomials parameters of autoregressive
A_c	-	Transfer function of motor
A_p	-	Transfer function of PZT actuator
a	-	Unknown system parameter to be identified
a_{max}	-	Upper bound of parameters to be optimize
a_{min}	-	Lower bound of parameters to be optimize
b	-	Unknown system parameter to be identified
$B(z^{-1})$	-	Polynomials parameters of autoregressive
binrep	-	Equivalent real number to the binary coded
C	-	Transfer function of auto-tuned controller
C_p	-	Transfer function of PID tuned by EA controller
C_1	-	Cognitive component
C_2	-	Social component
count	-	Count array
d	-	Dimensional search space
$e_v(t)$	-	Error of the flexible control system
$e(t)$	-	Error of the rigid control system
F_d	-	Disturbance force
G	-	Transfer function of encoder sensor
G_s	-	Transfer function of accelerometer sensor
P_{gd}	-	Overall best position of all particles
H_1	-	Transfer function of endpoint acceleration model
H_2	-	Transfer function of hub angle model

K_d	-	Derivative gain for rigid motion controller
K_{ds}	-	Derivative gain for flexible motion controller
K_i	-	Integral gain for rigid motion controller
K_{is}	-	Integral gain for flexible motion controller
K_p	-	Proportional gain for rigid motion controller
K_{ps}	-	Proportional gain for flexible motion controller
L	-	Length of manipulator
limit	-	Limit of iteration array
m	-	Momentum factor
n	-	Model order
n_j	-	Number of bits
P_{id}	-	Particles' best position
rand	-	Random number
S	-	Number of samples
s	-	Laplace domain
T_s	-	Settling time
U_m	-	Control signal for hub angle response
U_p	-	Control signal for endpoint acceleration response
$u(t)$	-	System input
t	-	Time
T_{max}	-	Maximum number of time step
$v(t)$	-	Velocity vector
w	-	Inertia weight
$x(t)$	-	Position vector
$y(t)$	-	Endpoint Acceleration
$y_d(t)$	-	Reference endpoint acceleration
$y_m(t)$	-	Measured output
$\hat{y}(t)$	-	Estimated output
$y_1(t)$	-	Input hub acceleration
z^{-1}	-	Backshift operator
$\tau(t)$	-	Input torque

$\theta(t)$	-	Hub angle
$\theta_d(t)$	-	Reference hub angle
$\xi(t)$	-	White noise
ξ	-	Precision constant
$\Delta Fitness$	-	Error function of particle fitness
Δt	-	Time step
Δx	-	Length of segment

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In the past, rigid structure has been chosen in many applications to avoid unwanted vibration. Unfortunately, this heavy and strong metal is not always acceptable because it limits the operation speed and consumes more energy during application (Mohamed *et al.*, 2003). In addition, many industries such as spacecraft and aircraft engineering require the weight of mechanical structures to be kept as low as possible. Therefore flexible manipulator systems have received substantial attention in recent years motivated by the requirements of industrial applications. Flexible manipulators offer several advantages over rigid manipulators including lighter weight, lower energy consumption, faster system response, safer operation due to reduced inertia, smaller actuator requirement, low-strength mounting and low-rigidity requirement, less bulky design and are more transportable and maneuverable (Mohamed *et al.,* 1996; Choi *et al.*1999; Tokhi *et al.,* 2001)

However, flexible manipulator systems are known to demonstrate an intrinsic property of vibration when subjected to disturbance forces due to low stiffness (Abdul Razak, 2007). Light weight manipulators will vibrate during and after a maneuver. This vibration will become more severe and deflection will increase when the maneuver becomes faster (Vakil, 2008). Vibration can result in noise, disturbances, and discomfort which are undesirable in any operation. Vibration can reduce system effectiveness, affect machine precision and lead to structural fatigue. Therefore, it is important to control the vibration of flexible structures.

Generally, the purpose of vibration control in flexible manipulator is to suppress unwanted vibration and to enable satisfactory endpoint tracking. A common approach is the use of passive control methods with the addition of passive material to increase the damping and stiffness properties. However, the performance of these conventional control strategies may not be satisfactory at low frequency problems. Moreover, mounting the passive material will add to the dynamic load of the system which is undesirable in many applications (Fan and Silva, 2007). Hence, particular emphasis has been placed on active vibration control (AVC).

AVC introduced anti-phase excitation to destructively interfere with the system disturbances, hence resulting in a vibration reduction (Mat Darus and Tokhi., 2003a). AVC has successfully been applied, offered cost effective solution and reliable at low frequency vibration control problems (Mat Darus and Tokhi, 2005). Thus, vibration reduction using AVC has received considerable attention from many researchers.

Furthermore, the exploitation of smart material in AVC area presents a more attractive solution in the studies. A smart material such as piezoelectric material is able to change its behavior in response to a signal. Piezoelectric material mounted along the link serves as an actuator and sensor adding sensing and control capabilities for vibration suppression. The unique ability of smart material to achieve transformation between mechanical deformation and electric field leads to the development of AVC using smart structure which is expected to obtain better control performance. Many papers have been reported on modeling of smart material in intelligent structure (Crawley and Anderson, 1990; Vincent, 2001) and on control schemes for smart flexible structure (Wei *et al.* 2010; Mohamad, 2011).

Challenging jobs for control design of flexible smart structure involve optimization. A large number of papers deal with optimization of size and sensor/actuator location on structures (Molter *et al*., 2010) and controller parameters (Choi *et al.*, 1999; Davighi *et al*., 2006). Optimization is a term of finding for the optimal solution with different objectives and subject to a variety of constraints. Further development of evolutionary algorithm (EA), aim for an efficient practical algorithm to find optimal solutions especially for nonlinear optimization problems.

EA method has attracted the attention of the wider control community due to their various advantageous features in relation to identification and control. Many EA have been develop, among them includes genetic algorithm (GA) and particle swarm optimization (PSO) are the two popular methods. GA mimics the biological evolution, while, PSO tries to imitate the intelligence emergence behavior of social insect (Mohamad, 2011). Both GA and PSO have been extensively used in many fields and various optimization areas. Consequently, the use of GA and PSO as optimizers in identification and control problem is a promising solution.

1.2 Problem Statement

At the present time, flexible manipulators are gaining considerable attention of researchers due to their suitability in many applications such as manufacturing, aerospace equipment, and the semiconductor industry, among others. Vibration of the structure is often a limiting factor in the performance of many industrial processes and can lead to structural damage, fatigue, instability and reduced performance (Tavakolpour, 2010). Many researches have been done for vibration suppression of this traditionally complex system. Conventional control methods have not been widely successful due to the complexity of flexible structures. Moreover, the frequency associated with these structures is commonly low and vibration control becomes an important issue. As a result, AVC has been devised to optimally reduce vibration suppression for flexible manipulator.

In an attempt to provide better control performance, smart material is included in the AVC studies to serve as an alternative approach to researchers and engineers. Smart material is more attractive because this material is usually small in size, light in weight, have faster response and can be embedded with flexible structures (Preumont, 2006). In the case of AVC of flexible manipulator, smart material is normally embedded along the structure and works as an actuator or sensor.

Thus, this thesis serves to present alternatives to cope with the vibration control problem of such complex systems. In this research, optimization procedure of PID control parameters is tackled using EA. Two novel EAs are developed, namely, Genetic Algorithm with Parameter Exchanger (GAPE) and Particle Swarm Optimization with Explorer (PSOE) in such a way that the optimization can be improved. The PID control tuning method using EA is implemented on the identified model using system identification (SI) technique with regards to the knowledge of the system acquired from the experimental test. The performance of these control schemes are then analyzed via experimental validation. An understanding of the principles involved in the analysis is crucial as this research aimed to investigate a new optimization methodology for intelligent AVC of a flexible manipulator system.

1.3 Objectives of the Research

This research focused on intelligent AVC schemes for flexible manipulator structure. Thus, four important objectives of this thesis are as follows:

1. To develop novel tuning methods using Particle Swarm Optimization with Explorer (PSOE) and Genetic Algorithm with Parameter Exchanger (GAPE) for PID controllers in comparison to Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) for suppression of the unwanted endpoint vibration of single-link flexible manipulator.

2. To model the dynamic of single-link flexible manipulator system via parametric system identification (SI) method using PSOE and GAPE in comparison with its original of PSO and GA.

3. To assess, analyze and compare the performance of the PID controller using the novel tuning method of PSOE and GAPE with their original counterparts.

4. To verify and validate the performance of the PID controller tuned using the best tuning method of PSOE via experimental test.

1.4 Scope of the Research

The scope of this research comprises the following aspects:

1. The development and fabrication of laboratory size single-link flexible manipulator test rig constrained to move in horizontal direction only and gravity effect is neglected.

2. Shear deformation, rotary inertia and effect of axial force are neglected. The elastic deformation of the link is assumed very small with respect to the hub motion.

3. Response of an aluminum alloy of flexible manipulator is limited to hub angle and endpoint acceleration only.

4. Parametric modeling of single-link flexible manipulator system using SI method limited to PSOE and GAPE in comparison to the original of PSO and GA algorithms only.

5. All developed models are validated using mean squared error (MSE) and correlation tests only.

6. Rigid and flexible motion controls of flexible manipulator are conducted using two different PID control feedback loops, respectively.

7. Rigid motion control scheme constrained to auto-tuned PID controller and evaluated in input tracking only.

8. Flexible motion control scheme using PID controller tuned by EA limited to PSOE, PSO, GAPE and GA only and the performance is assessed in vibration attenuation at the first mode of vibration.

9. Experimental validation based on the best performance of control schemes of PID-PSOE obtained from the simulation evaluations is performed on the developed flexible manipulator rig using piezoelectric (PZT) actuator.

10. The robustness test for the PID control schemes on experimental rig are limited to speed and angle variation and endpoint mass payload.

1.5 Research Contributions

The main contributions of this research are given as follows:

- This research proposed novel EAs of Genetic Algorithm with Parameter Exchanger (GAPE) and Particle Swarm Optimization with Explorer (PSOE). The effectiveness of this new approach is presented in parametric modeling of single-link flexible manipulator for hub angle and endpoint acceleration analysis in comparison to the original of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). A comparative study is provided between the tuning algorithm to highlight the ability of the algorithm in finding the global optimum with faster convergence and improved diversity.

- Detailed implementation of EAs for tuning the PID controller using PSOE, PSO, GAPE and GA. This allows PID parameter to be tuned on the dynamic model obtained from parametric modeling technique. The performance of the control schemes is observed in vibration suppression of single-link flexible manipulator at the first mode of vibration.

- The outcome from the experimental PID tuned by EA based AVC on flexible manipulator using piezoelectric (PZT) actuator is provided. Its offer a good platform for evaluation and validation of the proposed novel EA. The advantages of the algorithms are assessed in terms of vibration attenuation.

1.6 Research Methodology

The flowchart describing the research methodology used in this research is shown in Figure 1.1.

After a literature review has been carried out, a single-link flexible manipulator constrained to move in horizontal direction was chosen and presented in this research. Initially, test rig of flexible manipulator was designed and fabricated in order to acquire the input and output data. The instrumentation and data acquisition system were setup and integrated with the rig. Manipulator rig then underwent an impact test. Results from this test will identify the first three modes of vibration which are the modes of interest in vibration control. These results will eventually be compared with the experimental studies to show the validity of the developed model.

Movement of the flexible link is driven by the motor at hub which serves as a disturbance producing unwanted vibration at the endpoint of flexible link. Responses at the hub and endpoint of flexible manipulator were recorded including hub angle and endpoint acceleration. The input-output data acquired were then utilized to develop the model of the system through simulation environment. For this research, system identification (SI) modeling technique was employed in representing the dynamic response of flexible manipulator system. Relationship between input and output of the system was expressed using linear auto regressive with exogenous (ARX) model structure. In this study, two novel EAs were introduced included Genetic Algorithm with Parameter Exchanger (GAPE) and Particle Swarm Optimization with Explorer (PSOE). The effectiveness of novel EAs was evaluated using SI of single-link flexible manipulator in comparison to their standard counterparts of GA and PSO. A comparative study of the performance of the approaches in SI of flexible manipulator is provided. The best model that characterizes the dynamic system will be used in designing the PID controller in the simulation environment.

Next, PID control schemes were implemented on the best model achieved for hub angle and endpoint acceleration analysis. For flexible motion control of endpoint acceleration, PID parameter was optimized using GA, GAPE, PSO and PSOE for AVC of flexible manipulator to find the best agreement that can attenuate the vibration most. While for rigid motion control of hub angle, PID tuned by auto tuning function in MATLAB/Simulink environment was implemented for input tracking. Simulation study is provided and the performance of control system is investigated.

The optimized PID parameter for rigid and flexible motion control was also validated using experimental procedure to demonstrate the practicality of the control schemes. The validity, efficiency and the performance characteristic of the algorithms in attenuating the unwanted vibration of flexible manipulator in response to the input command were taken into account. Finally, discussion and recommendations to improve the results obtained for further studies is included.

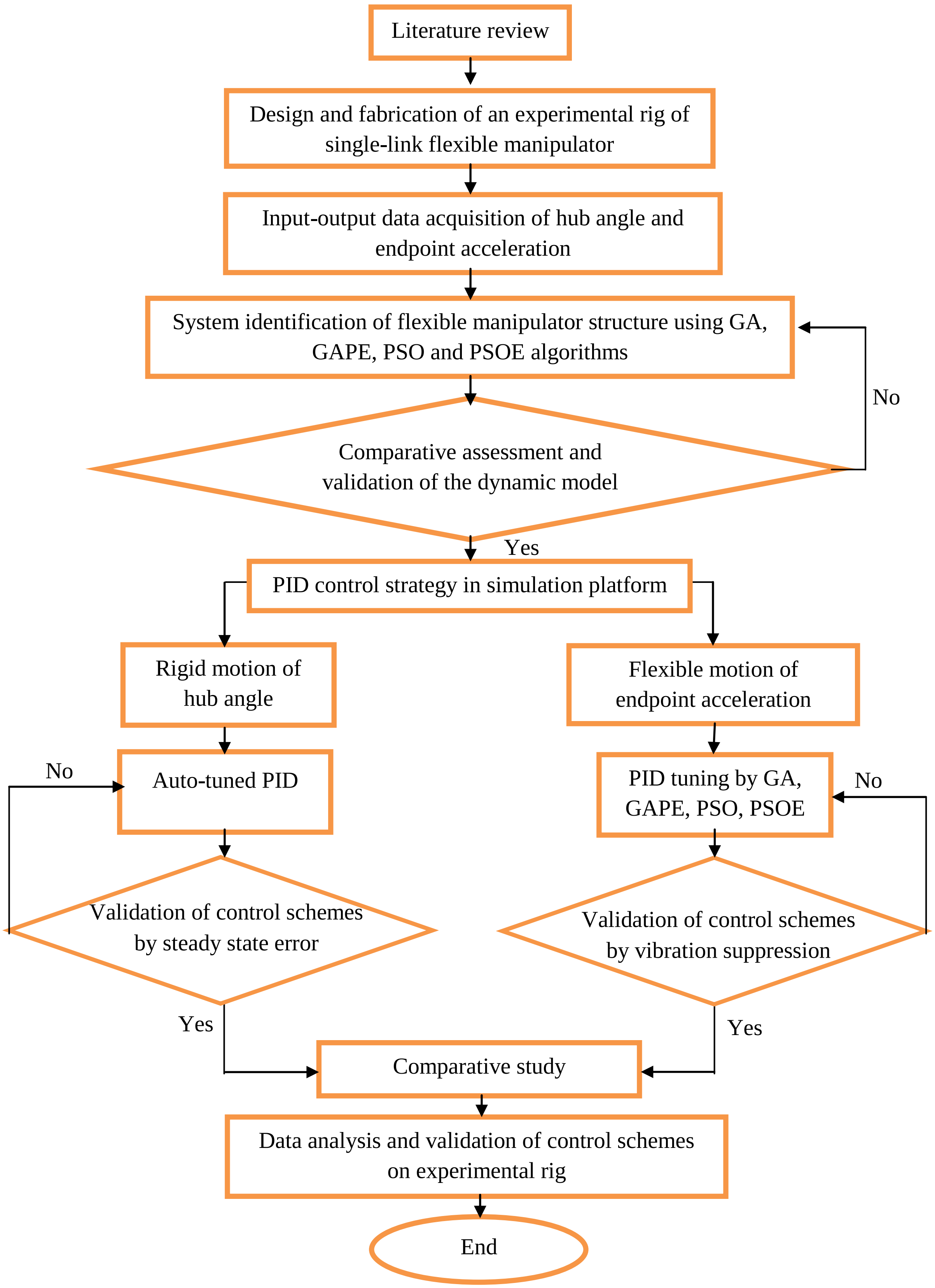

Figure 1.1: Research Methodology

1.7 Organization of thesis

This thesis is organized into eight chapters. A brief outline of the content of each chapter of the thesis is as follows:

Chapter 1 presents the introduction of the research problem. Background and problem statement as well as objective and scope of the research are included. The flowchart of research methodology and research contribution is also outlined in this chapter.

Chapter 2 is devoted to the literature review of the related topics. It includes the AVC of flexible manipulator system and previous work of dynamic modeling based on SI of the system. A brief overview of GA and PSO is reviewed. The recent application of AVC system and PID tuning by EA control technique previously applied was highlighted. Finally, the research gap found is identified in this chapter.

Chapter 3 focuses on the mechatronic design and experimental development of single-link flexible manipulator structure. A rectangular aluminum beam attached to the motor at the hub is developed. The experimental hardware, instrumentation, data acquisition system and software used for experimental setup are elaborated. Then, the experimental devices are integrated with the test rig and method of capturing the data is explained. Impact test is carried out to identify the dominant mode of vibration of the flexible link. A result from the test was compared with the experimental data recorded for model validation.

Chapter 4 presents the development of novel EAs of PSOE and GAPE. A brief introduction to EA optimization of PSO and GA are provided. Details methodologies of the proposed novel EAs are highlighted in this chapter.

Chapter 5 presents the system identification technique employed for modeling of single-link flexible manipulator system. The ARX model is used to represent the system. The developed PSOE and GAPE are used as the optimization tools in obtaining the parameters of the ARX model. The effectiveness of these algorithms is tested in comparison to their original of GA and PSO. A comparative study among the optimization tools to identify the best model is presented. The transfer function that best represents the system is used as the system plant to be controlled in the simulation part.

Chapter 6 focuses on the approach for PID control tuning method on the identified model of flexible manipulator system in simulation environment. For hub angle control scheme, an auto-tuned PID within MATLAB/Simulink platform is investigated for input tracking. Meanwhile, for endpoint acceleration, PID controller tuning strategies using GA, GAPE, PSO and PSOE is applied to optimally attenuate the unwanted vibration of flexible manipulator. The performances of the control schemes are discussed.

Chapter 7 devoted the optimized PID control schemes of a flexible manipulator implemented on the experimental rig. In rigid motion control of hub angle, the performance of the controller is investigated by analyzing the angle positioning of the link to meet the input commands. For flexible motion control of endpoint acceleration, the proposed control scheme is evaluated in terms of suppressing unwanted vibration. The position of piezoelectric (PZT) actuator placement at the flexible link is also considered to find the best position that can attenuate the vibration most. Then, the robustness of the control schemes is tested subjected to speed and angle variation and addition of endpoint mass payload.

Chapter 8 sums up the work presented and relevant conclusions are drawn. The direction for future works and recommendations are also outlined.

- Additionally, other control techniques such as self-tuning controller and adaptive control can be applied to observe the performance in vibration attenuation of a flexible manipulator for future works.

- A well-known problem for motors that use gears is the backlash. This will create an effect of compliance resulting in a certain delay being introduced to the plant. This delay may have such big impact that one may be forced to reduce the dynamic behavior or the precision of the drive. Thus, dual loop or two individual encoders can be considered for improvement of this problem with one directly mounted to the motor and another mounted at the gear or directly on or near to the load. With this arrangement, motor movement as well as load movement can be controlled resulting in a precise and high dynamic regulation of motor.

- To test other higher blocking force of piezoelectric actuator patch to cope with higher disturbance and enhance the performance of control system.

- Aligned with the advance of microprocessor, embedded system could be considered in the control system. Several advantages of embedded system include light weight, compact size, cheap, low energy consumption, and satisfactory computational power to perform vibration control in real-time applications.

- In many industries, multiple link and ability to move in multi degree of freedom (DOF) is much preferred. The used of this arrangement may cause complexity to the control problem due to multipart dynamics of the structure. Hence, multi-link and multi DOF is one of the major challenges in vibration control which needs to be studied in the future.

- Extensive study on multi input multi output (MIMO) control structure is recommended prior to the multi-link and/or multi DOF arrangement.

REFERENCES

Abdul Razak, N. (2007). *Modeling of Single-link Flexible Manipulator with Flexible Joint*. Master, Universiti Teknologi Malaysia, Skudai.

Ahmad, M. A. (2008). Vibration and Input Tracking Control of Flexible Manipulator using LQR with Non-collocated PID controller. *Second UKSIM European Symposium on Computer Modeling and Simulation*. 40-45

Ahmad, M.A. and Mohamed, Z. (2008). Vibration Suppression Techniques in Feedback Control Loop of a Flexible Robot Manipulator. *Modern Applied Science*. 2(2), 59.

Ahmed, E. S. M. and Mohamed M. A. E. (2009). PID controller tuning scheme for Twin Rotor Multi-input Multi-Output system based Particle Swarm Optimization Approach. *Journal of Engineering Sciences*. 37(4), 955 – 967.

Alam, M. S. and Tokhi, M. O. (2008). Designing feedforward command shapers with Multi-objective Genetic Optimisation for vibration control of a Single-link Flexible Manipulator. *Engineering Applications of Artificial Intelligence*. 21(2), 229-246.

Alam, M. S. (2012). Dynamic Modeling of Flexible Manipulator System using Genetic Algorithm. *Dhaka University Journal of Science*. 60(2), 239 – 245.

Ali, M. O., Koh, S. P., Chong, K. H., Tiong, S. K. and Obaid, Z. A. (2009). Genetic Algorithm tuning based PID Controller for Liquid-level Tank System. *Proceedings of the International Conference on Man-Machine System (ICoMMS)*. 11 – 13 October. Batu Ferringhi, Penang. 2009.

Angelova, M. and Pencheva, T. (2011). Tuning Genetic Algorithm Parameters to Improve Convergence time. *International Journal of Chemical Engineering*. 2011.

Astrom, K. J. and Hagglund, T. (1988). *Automatic Tuning of PID Controllers*. Instrument Society of America.

Blevins, R. D. (1979). *Formulas for Natural Frequency & Mode Shape*. New York: Van Nostrand Reinhold.

Boucette, R, Ali, S. B. H. and Abdelkarim M. N. (2011). Global hybrid Fuzzy Controller for a Flexible Single-link Manipulator. *Journal of Engineering and Applied Sciences*. 6(1), 1-5.

Chan, F. T., Mishra, N. and Kumar, V. (2007). *A CMPSO algorithm based approach to solve the Multi-plant Supply Chain Problem.* INTECH Open Access Publisher.

Chatterjee, A., Chatterjee, R., Matsuno, F. and Endo, T. (2007). Neuro-Fuzzy state Modeling of Flexible Robotic Arm employing Dynamically Varying Cognitive and Social Component based PSO. *Measurement*. 40(6), 628 – 643.

Cheng, J., Chen, W., Chen, L. and Ma, Y. (2002). The Improvement of Genetic Algorithm searching Performance. *Proceedings of the First International Conference on Machine Learning and Cybernetics*, 4-5 November. Beijing. 2, 947 – 951.

Choi, S. B., Cho, S. S., Shin, H. C., and Kim, H. K. (1999). Quantitative feedback theory control of a single-link flexible manipulator featuring piezoelectric actuator and sensor. *Smart Material and Structure*. 8(1999), 338 - 349.

Clerc, M., (1999). The Swarm and the Queen: Towards a Deterministic and Adaptive Particle Swarm Optimization. *Proceedings of the 1999 Congress on Evolutionary Computation, CEC 99*. Washington, DC. 1951 – 1957.

Cui, L. L. and Xiao, Z. Q. (2003). Optimum Structure Design of a flexible manipulators based on GA. *IEEE Intelligent Transportation System 2003*. 12 - 15 October. 2, 1622 – 1626.

Crawley, E. F. and Anderson, E. H. (1990). Detailed Models of Piezoceramic actuation of beams. *Journal of Intelligent Material Systems and Structures*. 1(1), 4 - 25.

Davighi, A., Romano, M. and Bernelli-Zazzera, F. (2006). Vibration suppression of Flexible-link Manipulator by PZT actuators and sensors. *Earth & Space 2006 @ sEngineering, Construction, and Operations in Challenging Environment*. 1-8.

Deif, S., Tawfik, M., and Kamal, H. A. (2011). Vibration and Position control of a Flexible Manipulator using a PD-tuned Controller with Modified Genetic Algorithm. *ICCTA 2011*., 15-17 October. Alexandria, Egypt. 15 – 17.

Dutta, R., Ganguli, R. and Mani, V. (2011). Swarm Intelligence algorithms for Integrated Optimization of Piezoelectric Actuator and Sensor Placement and Feedback Gains. *Smart Materials and Structures*. 20(10), 105018 – 105032.

Eiben, A. E. and Smith, J. E. (2003). *Introduction to Evolutionary Computing*. Springer Science & Business Media.

Elanayar, S. V. T., and Yung, C. S., (1994). Radial basis function neural network for approximation and estimation of non-linear stochastic dynamic systems, *IEEE Transaction on Neural Networks*. 5(4), 594 – 603.

Fan, T. and Silva, C. W. D. (2007). Model Predictive Control of a Flexible Robot. In Silva, C. W. D. (Ed.) *Mechatronic System: Devices, Design, Control, operation and Monitoring* (pp.13-1 - 13-14). CRC Press.

Faris, W. F., Ata, A. and Sa'adah, M. Y. (2009). Energy minimization approach for a Two-link Flexible Manipulator. *Journal of Vibration and Control*. 15(4), 497 – 526.

Gerhardt, E. and Gomes, H. M. (2012). Artificial Bee Colony (ABC) Algorithm for Engineering Optimization Problems. *International Conference on Engineering Optimization*, 1-5 July. Rio de Janeiro, Brazil. 1 – 11.

Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley, Reading.

Hadi, M. S., Mat Darus, I. Z. and Mohd Yatim, H. (2013). Modeling Flexible Plate Structure System with Free-Free-Clamped-Clamped (FFCC) Edges using Particle Swarm Optimization, *The Proceeding of the IEEE Symposium on Computers & Informatics (ISCI 2013)*, 7-9 April. Langkawi, Malaysia. 39 – 44.

Hadi, M. S. (2014). *PID Controller using Evolutionary Methods for Vibration Control of Flexible Plate*. Master. Universiti Teknologi Malaysia, Skudai.

Hespanha, J. P. (2007). *System Identification*. Undergraduate Lecture Notes, University of California, California.

Hewit, J. R., Morris, J. R., Sato, K. and Ackermann, F. (1997). Active Force Control of a Flexible Manipulator by Distal Feedback. *Mechanism and Machine Theory*. 32(5), 583 – 596.

Ho, M. T. and Tu, Y. W. (2006). Position control of a Single-link Flexible Manipulator using H-infinity based PID control. *IEEE Proceedings- Control Theory and Applications*. 153(5), 615 – 622.

Hu, Y. R. and Ng, A. (2005). Active Robust Vibration control of Flexible Structures. *Journal of Sound and Vibration*, 288(1-2), 43-56.

Ibrahim, S. M. (2005). *The PID Controller Design using Genetic Algorithm*. Bachelor of Engineering, University of Southern Queensland.

Jaafar, H. I., Mohamed, Z., Abidin, A. F. Z. and Ab Ghani, Z. (2012). PSO-Tuned PID Controller for a Nonlinear Gantry Crane System. *2012 IEEE International Conference on Control System, Computing and Engineering.* 23-25 November. Pulau Pinang, Malaysia. 515 – 519.

Jain, S., Peng, P. Y., Tzes, A. and Khorrami, F. (1996). Neural Network Design with Genetic Learning for Control of a Single link Flexible Manipulator. *Journal of Intelligent and Robotic Systems*. 15(2), 135-151.

Jain, T., Alavandar, S., Radhamohan, S. V. and Nigam, M. J. (2010). Genetically-bacterial swarm optimization: Fuzzy pre-compensated PD control of two-link-flexible manipulator. *International Journal of Intelligent Computing and Cybernetics*, 3(3), 463-494

Jalil, N. A. and Mat Darus, I. Z. (2013). System Identification of Flexible Beam Structure using Artificial Neural Network. *Proceedings of the fifth 2013 IEEE International Conference on Computational Intelligence, Modelling and Simulation.* 24 – 25 September. Seoul, Korea. 3 – 7.

Julai, S., Tokhi, M. O., Mohamad, M. and Abd Latiff, I. (2009). Control of a flexible plate structure using particle swarm optimization. *Proceedings of the IEEE Congress on Evolutionary Computation, CEC 2009*., 18-21 May. Trondheim, Norway. 3183 – 3190.

Julai, S. and Tokhi, M.O. (2010). SISO and SIMO Active Vibration Control of a Flexible Plate Structure using Real-coded Genetic Algorithm. *IEEE 9th International Conference on Cybernetic Intelligent System, CIS*. 1-2 September. United Kingdom. 1 – 6.

Kafader, U. (2014). *Motion Control for Newbies*. Sachseln: Maxon Motor.

Kang, F., Li, J. J. and Xu, Q. (2012). Damage Detection based on Improved Particle Swarm Optimization using Vibration data. *Applied Soft Computing*. 12(8), 2329 – 2335.

Kerem, G., Buckham, B. J. and Park, E. J. (2009). Vibration control of a Single-link Flexible Manipulator using an array of fiber optic curvature sensors and PZT actuators. *Mechatronics*. 19(2). 167-177.

Kim, H. K., Choi, S. B. and Thompson, B. S. (2001). Compliant control of a two-link flexible manipulator featuring piezoelectric actuators. *Mechanism and Machine Theory*. 36, 411-424.

Kim, J. S., Kim, J. H., Park, J. M., Park, S. M., Choe, W. Y. and Heo, H. (2008). Auto tuning PID Controller based in Improved Genetic Algorithm for Reverse Osmosis Plant. *World Academy of Science, Engineering and Technology*. 47, 384 – 389.

Kwok, N. M. and Lee, C. K. (2001). Control of a Flexible Manipulator using a Sliding Mode Controller with a Fuzzy-like Weighting Factor. *Proceedings of IEEE International Symposium on Industrial Electronics (ISIE)*. Busan, South Korea. 1, 52 – 57.

Leitch, R. R. and Tokhi, M. O. (1987). Active Noise control systems. *IEEE Proceedings A Physical Science, Measurement and Instrumentation, Managements and Education, Review*. 134, 525 - 546.

Liao, C. -Y, Lee, W. -P, Chen, X. and Chiang C. -W. (2007). Dynamic and adjustable Particle Swarm Optimization. *Proceedings of the 8th Conference WSEAS International Conference on Evolutionary Computing.* Vancouver, Canada. 301 – 306.

Liu, K. and Sun, X. (2001). System identification and Model Reduction for a Single-Link Flexible Manipulator. *Journal of Sound and Vibration*. 242(5), 867-891.

Lin, W. Y., Lee, W. Y. and Hong, T. P. (2003). Adapting Crossover and Mutation Rates in Genetic Algorithm. *Journal of Information Science and Engineering*. 19(5), 889-903.

Ljung, L., (1999). System identification: Theory for the User (2^{nd} Edition), Prentice Hall PTR, New Jersey, USA.

Ljung, L., (2010). Perspectives on system identification. *Annual Reviews in Control*. 34(1), 1-12.

Lueg, P. (1936). *Process of Silencing Sound Oscillations*. U.S. Patent 2 043 416.

Magdalene, M., Yannis, M. and Georgios, E. S. (2011). Vibration control of beams with piezoelectric sensors and actuators using particle swarm optimization. *Journal Expert Systems with Applications*. 38, 6872-6883.

Maouche, A. R. and Attari, M. (2008). Adaptive Neural Control of a Rotating Flexible Manipulator. *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*. 517-522.

Masehian, E. and Sedighizadeh, D. (2011). Multi-objective PSO- and NPSO-based Algorithms for Robot Path Planning. *Advances in Electrical and Computer Engineering*. 10(4), 69 – 76.

Masten, M. K. (1998). Electronics: the intelligence in intelligent control. *Annual Reviews in Control.* 22, 1-11.

Mat Darus, I. Z. and Tokhi, M. O. (2003a). Genetic algorithms based adaptive active vibration control of a flexible plate structure. *Journal of Systems Science.* 29(3), 65-79.

Mat Darus, I.Z. and Tokhi, M. O. (2003b). Genetic Algorithm Identification of a Flexible Plate Structure. *Preprints of ICONS-03: IFAC International Conference on Intelligent Control System and Signal Processing.* 8-11 April. Faro, Portugal. 131-136.

Mat Darus, I. Z. (2004). *Soft computing adaptive active vibration control of flexible structures*. Doctor of Philosophy, University of Sheffield, UK.

Mat Darus, I. Z., Aldebrez, F. M. & Tokhi, M. O. (2004). Parametric Modeling of a Twin Rotor System using Genetic Algorithms. *Proceedings of the 1st IEEE International Symposium on Control Communications and Signal Processing, ISCCSP 2004*, Hammamet, Tunisia, 21-24 March 2004.

Mat Darus, I. Z. and Tokhi, M. O. (2005). Soft Computing – based active vibration control of flexible structure. *Journal of Engineering Application of Artificial Intelligent.* 18, 93-114.

Mat Darus, I. Z. and Al-Khafaji, A. A. M. (2012). Nonparametric Modeling of a Rectangular Flexible Plate Structure, *International Journal of Engineering Application of Artificial Intelligence*. 25, 94-106.

Md Salleh, S., Tokhi, M. O., Julai, S., Mohamad, M. and Abd Latiff, I. (2009). PSO-based Parametric Modeling of a Thin Plate Structure. *Proceedings of the 2009 Third UKSim European Symposium on Computer Modeling and Simulation*. United Kingdom. 43 – 48.

Md Salleh, S. and Tokhi M. O. (2011). Active Vibration Control on Flexible Plate Structure using Bio-inspired Algorithm. *Third International Conference in Computational Intelligence, Modeling and Simulation (CIMSiM)*. 20 – 22 September. Langkawi, Malaysia. 120 – 126.

Michalewicz, Z. (1996). *Genetic Algorithms + Data Structures = Evolution Program* (3rd Ed), Berlin: Springer-Verlag.

Mohamad, M. (2011). *Swarm Intelligence Modeling and Active Vibration Control of Flexible Structures.* Doctor of Philosophy. University of Sheffield. UK.

Mohamed, Z., Tokhi, M. O. & Azad, A. K. M. (1996). *Finite Difference and Finite Element Simulation of a Flexible Manipulator*. Research Report no. 617, Department of Automatic Control & System Engineering. University of Sheffield, UK.

Mohamed, Z., Martins, J. M., Tokhi, M. O., Da Costa, J. S. and Botto, M. A. (2003). Vibration control of a very flexible manipulator system. *Control Engineering Practice.* 13(3), 267-277.

Mohd Yatim, H., Intan, Z. M. D. and Hadi, M. S. (2013). Particle Swarm Optimization for Identification of a Flexible Manipulator System, *The Proceeding of the IEEE Symposium on Computers & Informatics (ISCI 2013)*. 7-9 April. Langkawi, Malaysia. 112 – 117.

Molter, A., Silveira, O. A. A. D., Fonseca, J. S. O. and Bottega, V. (2010). Simultaneous Piezoelectric Actuator and Sensor Placement Optimization and Control design of Manipulators with Flexible links using SDRE method. *Mathematical Problems in Engineering*. 2010, 1 – 23.

Orszulik, R. R. and Shan, J. (2012). Active vibration control using genetic algorithm-based system identification and positive position feedback. *Smart Material and Structures*, 21(5), 055002-1 – 055002-10.

Panda, S. and Padhy, N. P. (2007). Comparison of Particle Swarm Optimization and Genetic Algorithm for TCSC-based Controller Design. *International Journal of Computer Science and Engineering.*1(1), 305 – 313.

Phan, V. P., Goo, N. S. and Park, H. C. (2009). Vibration Suppression of a Flexible Robot Manipulator with a Lightweight Piezo-composite Actuator. *International Journal of Control, Automation and Systems*. 7(2), 243-251.

Physik Instrumente (PI) GmbH & Co. (2012a). *P-876 DuraAct Patch Transducer*. Karlsruhe, Germany.

Physik Instrumente (PI) GmbH & Co. (2012b). *E-835 DuraAct™ Piezo Driver Module* Karlsruhe, Germany.

Poli, R., Kennedy, J. and Blackwell, T. (2007). Particle Swarm Optimization: An Overview. *Swarm Intelligence Journal*. 1(1), 33-57.

Preumont, A. (2006). Mechatronics: *Dynamics of Electromechanical and Piezoelectric Systems*, Springer.

Qiaorong, Z. and Guochang, G. (2008). Path Planning based on Improved Binary Particle Swarm Optimization Algorithm. *IEEE Conference on Robotics, Automation and Mechatronics*. 21 – 24 September. Chengdu. 462 – 466.

Ramalakshmi, A. P. S., Manoharan, P. S. and Deepamangai, P. (2013). PID Tuning and Control for 2-DOF Helicopter using Particle Swarm Optimization. *Swarm Evolutionary and Memetic Computing.* 662 – 672.

Rovner, D. M. and Franklin, G. F. (1988). Experiments in Load-adaptive Control of a Very Flexible One-link Manipulator. *Automatica*. 24(4), 541-548.

Rudrusamy, B. (2005). *Optimal Input Shaping for Vibration Control of a Flexible Manipulator using Genetic Algorithm.* Master. Universiti Teknologi Malaysia, Skudai.

Ryu, J. H., Kwon, D. S. and Park Y. (2000). A Robust Controller Design Method for a Flexible Manipulator with a Large Time Varying Payload and Parameter Uncertainties. *Journal of Intelligent and Robotic Systems*. 27, 345-361.

Saad, M. S., Jamaluddin, H. and Mat Darus, I. Z. (2012). Implementation PID Controller Tuning Using Differential Evolution and Genetic Algorithms. *International Journal of Innovative Computing, Information and Control*. 8 (11), 1-20.

Saad, M. S., Jamaluddin, H. and Mat Darus, I. Z. (2013). Active vibration control of a Flexible beam using System Identification and Controller tuning by Evolutionary Algorithm. *Journal of Vibration and Control*. 1-16.

Sedighizadeh, D. and Masehian, E. (2009). Particle Swarm Optimization Methods, Taxonomy and Applications. *International Journal of Computer Theory and Engineering*. 1(5), 486-502.

Selvi, V. and Umarani, R. (2013). Hybridization of Evolutionary Computation Techniques for Job Scheduling Problem. *International journal of Computer Applications*. 62(5), 24-29.

Settles, M. (2005). *An Introduction to Particle Swarm Optimization*. University of Idaho, Moscow. 1-8.

Shaheed, M. H., Azad, A. K., Tokhi, M. O. (2006). Intelligent Modeling of Flexible Manipulator Systems. In *Climbing and Walking Robots*. Springer Berlin Heidelberg, 607 – 614.

Shan, J. (2007). Comparison of Two Vibration Control Methods for Flexible Manipulator with PZT actuators. *International Conference on Mechatronics and Automation*. 3220-3225.

Shen, X., Wei, K., Wu, D., Tong, Y., and Li, Y. -X. (2007). An Dynamic Adaptive Dissipative Particle Swarm Optimization with Mutation Operation. *IEEE International Conference on Control and Automation, ICCA 2007*. 30 May- 1 June. Central China Normal University, China. 586 – 589.

Shi, Y. H. and Eberhart, R. (1998). Parameter selection in particle swarm optimization. *Evolutionary Programming VII: Proceedings of the Seventh Annual Conference on Evolutionary Programming*. 591-600.

Shi, Y. H. and Eberhart, R. (1999). Empirical study of Particle Swarm Optimization. *Proceeding Congress on Evolutionary Computation*. 6-9 July. Washington, DC, USA. 1945-1950.

Shi, Y. H. and Eberhart, R. (2001). Fuzzy adaptive Particle Swarm Optimization. *Proceedings of the 2001 Congress on Evolutionary Computation 2001*. USA. 101 – 106.

Siddique, M. N. H., and Tokhi, M. O. (2002a). GA-based Neural Fuzzy Control of Flexible-link Manipulators. *IEEE International Conference on Control Applications*. 471-476.

Siddique, M. N. H. and Tokhi, M. O. (2002b). GA-Neuro-Fuzzy Control of Flexible-link Manipulators. *15th Triennial World Congress*, Barcelona, Spain. 15(1), 967-972.

Solihin, M. I., Legowo, A. and Akmeliawati, R. (2010). Comparison of LQR and PSO-based State Feedback Controller for Tracking Control of a Flexible Link Manipulator. *The 2nd IEEE International Conference on Information Management and Engineering (ICIME)*. 16 – 18 April. Chengdu. 354 – 358.

Solihin, M. I., Tack, L.F. and Kean, M. L. (2011). Tuning PID controller using Particle Swarm Optimization. *Proceeding of the International Conference on Advanced Science, Engineering and Information Technology 2011*. 14-15 January. Putrajaya, Malaysia. 458-461

Spears, W. (1995). Adapting crossover in evolutionary algorithms. In McDonnell, J.R., Reynolds, R.G. and Fogel, D.B. (Eds.), *Proceeding of the 4th Annual Conference on Evolutionary programming* (pp.367 – 384). Cambridge, MA: MIT Press.

Sun, D. and Mills, J. K. (1999). Study on Piezoelectric Actuators in Control of a Single-link Flexible Manipulator. *IEEE International Conference on Robotics and Automation*. 2, 849-854.

Sun, D., Mills, J. K., Shan, J. and Tso, S. K. (2004). A PZT actuator control of a Single-link Flexible Manipulator based in Linear Velocity Feedback and Actuator Placement. *Mechatronics*, 14(4), 381-401.

Supriyono, H. and Tokhi, M. O. (2012). Parametric Modeling Approach using bacterial foraging algorithms for modeling of flexible manipulator systems. *Engineering Applications of Artificial Intellignece.* 898-916.

Syswerda, G. (1989). Uniform crossover in genetic algorithms. In J. D. Schaffer (Ed.), *Proceedings of the Third International conference on genetic algorithms*, San Mateo (CA): Morgan Kaufmann Publishers.

Tavakolpour A.R. (2010). *Mechatronic Design of Intelligent Active Vibration Control Systems for Flexible Structures*. PhD. Universiti Teknologi Malaysia, Skudai, Malaysia.

Tavakolpour, A. R, Mat Darus, I. Z., Mailah, M., M.O. Tokhi (2010), Genetic Algorithm-based Identification of transfer function parameters for a Rectangular Flexible Plate System. *Engineering Application of Artificial Intelligence*, 23, 1388 – 1397.

Toha, S. F. and Tokhi, M. O. (2009). Real-coded Genetic Algorithm for Parametric Modeling of a TRMS. *IEEE Congress on Evolutionary Computation CEC'09*. 18-21 May. Trondheim. 2022-2028.

Tokhi, M. O., Azad, A. K. M., Poerwanto, H., Kourtis, S. and Baxter, J. (1996). A Simulink environment for Simulation and Control of Flexible Manipulator systems. *UKACC International Conference on Control '96*. 427(1), 210-215.

Tokhi, M. O., Mohamed, Z. and Shaheed, M. H. (2001). Dynamic Characterization of a Flexible Manipulator System, *Robotica*. 19, 571-580.

Tripathi, P. K. and Gangadharan, K. V. (2012). Design and Implementation of Active Vibration Control in Smart Structures. *International Journal of Research and Reviews in Mechatronic Design and Simulation*. 2 (1), 92-98.

Tumari, M. Z.M, Ahmad, M. A., Saealal, M. S., Zawawi, M. A., Mohamed, Z. and Yusop, N. M. (2011). The Direct Strain Feedback with PID control approach for a Flexible Manipulator: Experimental Results. *11th International Conference on Control, Automation and Systems.* 26-29 October. Gyeonggi-do, Korea. 7-12.

Vakil, M. (2008). *Dynamics and Control of Flexible Manipulators.* Doctor of Philosophy, University of Saskatchewan, Saskatoon, Canada.

Vincent, P. (2001). Finite Element Modeling of Piezoelectric Active Structures. Doctor of Philosophy, Université Libre de Bruxelle.

Virk, G. S. and Al-Dmour, A. S. (1999). Real-Time Vibration Suppression in a Flexible Cantilever Rig. *Microprocessors and Microsystems*. 23 (6), 365-384.

Vrajitoru, D. (1998). Crossover Improvement for the Genetic Algorithm in Information Retrival. *Information Processing and Management*. 34(4), 405 – 415.

Wang, Q. G., Zou, B., Lee, T. H., and Bi, Q. (1997). Auto-tuning of Multivariable PID controllers from decentralized relay feedback. *Automatica*. 33(3), 319 – 330.

Wei, J. J., Qiu, Z. -C, Han, J. -D and Wang, Y. -C. (2010). Experimental Comparison Research on Active Vibration Control for Flexible Piezoelectric Manipulator using Fuzzy Controller. *Journal of Intelligent and Robotic Systems*. 59(1), 31-56.

Zain, B. A. M., Tokhi, M. O. and Toha, S. F. (2009). PID-based Control of a Single-Link Flexible Manipulator in Vertical Motion with Genetic Optimisation. *Third UKSim European Symposium on Computer Modeling and Simulation*. 25-27 Nov. Athens, Greece. 355-360.

Zhou, Y. (2006). *Study on Genetic Algorithm Improvement and Application*. Master, Worcester Polytechnic Institute, Worcester.

Zhu, H., Zheng, C., Hu, X. and Li, X. (2008). Adaptive PSO using Random Inertia Weight and its Application in UAV path planning. *International Society for Optics and Photonics*. 7128, 712814-1 – 712814-5.

Zoric, N. D., Simonovic, A. M., Mitrovic, Z. S., Obradovic, A. M. and Lukic, N. S. (2014). Free Vibration Control of Smart Composite Beams using Particle Swarm Optimized Self-Tuning Fuzzy Logic Controller. *Journal of Sound and Vibration*. 333(21), 5244 – 5268.

APPENDIX A

LIST OF PUBLICATIONS

International Journals:

1. **Hanim Mohd Yatim** and Intan Z. Mat Darus (2014), Self tuning Active Vibration Controller using Particle Swarm Optimization for Flexible Manipulator System, *WSEAS Transactions on Systems and Control*, Vol 9, pp.55-66. (Indexed in SCOPUS)

2. **Hanim Mohd Yatim** and Intan Z. Mat Darus (2013), Intelligent Parametric Identification of Flexible Manipulator System, *International Review of Mechanical Engineering*, 8(1), pp.11-21. (Indexed in SCOPUS).

3. Intan Z. Mat Darus, Ameirul A. Mustadza, **Hanim Mohd Yatim** (2013), Harnessing Energy from Mechanical Vibration Using Non-Adaptive Circuit and Smart Structure, *International Review of Mechanical Engineering*, 7(5), pp. 832-840 (Indexed in SCOPUS).

International Conferences:

1. **Hanim Mohd Yatim,** Intan Z. Mat Darus, Muhamad Sukri Hadi, Modeling of Flexible Manipulator Structure using Particle Swarm Optimization with Explorer, *IEEE Symposium on Industrial Electronics and Applications (ISIEA 2014)*, Kota Kinabalu, Sabah, Malaysia, 29 September – 1 Oktober 2014.

2. M. Sukri Hadi, Intan Z. Mat Darus, Rickey Ting Pek Eek, **Hanim Mohd Yatim**, Swarm Intelligence for Modeling a Flexible Plate Structure System with Clamped-Clamped-Free-Free Boundary Condition Edges, *IEEE Symposium on Industrial Electronics and Applications (ISIEA 2014)*, Kota Kinabalu, Sabah, Malaysia, 29 September – 1 Oktober 2014.

3. Rickey Ting Pek Eek, **Hanim Mohd Yatim**, Intan Z. Mat Darus, Shafisshuhaza Sahlan, Development of Controller Graphical User Interface for Vibration Supression of Flexible Beam, *IEEE Symposium on Industrial Electronics and Applications (ISIEA 2014)*, Kota Kinabalu, Sabah, Malaysia, 29 September – 1 Oktober 2014.

4. Muhammad Sukri Hadi, Intan Z. Mat Darus and **Hanim Mohd Yatim**, Active Vibration Control of Flexible Plate with Free-Free-Clamped-Clamped (FFCC) Edges using Genetic Algrithm, *Australian Control Conference (AUCC 2013)*, Perth, Australia, 4-5 November 2013, pp.109-114.

5. **Hanim Mohd Yatim**, Intan Z. Mat Darus and Sukri M. Hadi, Modeling of Flexible Manipulator Structure Using Genetic Algorithm with Parameter Exchanger, *The proceeding of IEEE the 5th International Conference of Computational Intelligence, Modelling and Simulation (CimSIM 2013)*, Seoul South Korea, 24-26 September 2013, pp.37-42.

6. **Hanim Mohd Yatim**, Intan Z. Mat Darus and Muhammad Sukri Hadi, Particle Swarm Optimization for Identification of a Flexible Manipulator System, *The Proceeding of the IEEE Symposium on Computers & Informatics (ISCI 2013)*, Langkawi, Malaysia, 7-9 April 2013, pp.112-117.

7. Muhammad Sukri Hadi, Intan Z. Mat Darus and **Hanim Mohd Yatim**, Modeling Flexible Plate Structure System with Free-Free-Clamped-Clamped (FFCC) Edges using Particle Swarm Optimization, *The Proceeding of the IEEE Symposium on Computers & Informatics (ISCI 2013)*, Langkawi, Malaysia, 7-9 April 2013, pp. 39-44.

8. **Hanim Mohd Yatim** and Intan Z. Mat Darus, Swarm Optimization of an Active Vibration Controller for Flexible Manipulator, *13th WSEAS International Conference on Robotics, Control and Manufacturing Technology*, Kuala Lumpur, 2–4 April 2013, pp.139-146.

9. Intan Z. Mat Darus, Ameirul A. Mustadza, **Hanim Mohd Yatim**, Comparative Analysis of Piezoelectric Energy Harnessing from Micro Vibration Using Non-Adaptive Circuit, *13th WSEAS International Conference on Robotics, Control and Manufacturing Technology*, Kuala Lumpur, 2 – 4 April 2013, pp. 165-171.

10. **Hanim M. Yatim**, I. Z. Mat Darus and Maziah Mohamad, Parametric Identification and Dynamic Characterisation of Flexible Manipulator System, *Proceedings of 2012 IEEE Conference of Control, System and Industrial Informatics (ICCSII 2012)*, Bandung Indonesia, 22 - 26 September 2012, pp. 16 – 21.