

EVOLUTIONARY ALGORITHMS FOR ACTIVE VIBRATION CONTROL OF
FLEXIBLE MANIPULATOR

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

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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 autoregressive 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 diinginkan 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 kerumunan 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

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xi
	LIST OF FIGURES	xiii
	LIST OF ABBREVIATIONS	xvii
	LIST OF SYMBOLS	xx
	LIST OF APPENDICES	xxiii
1	INTRODUCTION	1
	1.1 Background of Study	1
	1.2 Problem Statement	3
	1.3 Objectives of the Research	4
	1.4 Scope of the Research	5
	1.5 Research Contributions	6
	1.6 Research Methodology	7
	1.7 Organization of thesis	10

2	LITERATURE REVIEW	12
2.1	Introduction	12
2.2	Flexible Manipulator Structures	12
2.3	Modeling of Flexible Manipulator	13
2.4	Control Strategies of Flexible Manipulator	17
2.5	Evolutionary Algorithm (EA)	19
2.5.1	Particle Swarm Optimization (PSO) Algorithm	20
2.5.2	Genetic Algorithm (GA)	26
2.6	Active Vibration Control (AVC)	32
2.6.1	PID controller	33
2.6.2	PID controller optimize by PSO and GA algorithms	35
2.7	Research Gap	37
2.8	Summary	39
3	DEVELOPMENT OF EXPERIMENTAL RIG	40
3.1	Introduction	40
3.2	Flexible Manipulator System Rig	40
3.3	Instrumentation System	42
3.3.1	Accelerometer	43
3.3.2	Encoder	44
3.3.3	Piezoelectric Actuator	44
3.3.4	Piezo Actuator Amplifier	46
3.3.5	DC Maxon Motor	47
3.3.6	Maxon Motor Driver	48
3.3.7	Data Acquisition System (DAQ)	48
3.4	System Integration	49
3.5	Results and Discussion	52
3.5.1	Experimental test	52
3.5.2	Impact tests	55
3.5.3	Comparison between experimental and impact test	56
3.6	Summary	57

4	THEORETICAL FRAMEWORKS	58
4.1	Introduction	58
4.2	Particle Swarm Optimization with Explorer (PSOE)	59
4.2.1	Creation of initial set of particles	60
4.2.2	Fitness Evaluation of each Particle	61
4.2.3	Updating particles' velocity and position	63
4.2.4	Termination strategy	64
4.3	Genetic Algorithm with Parameter Exchanger (GAPE)	65
4.3.1	Creation of initial, random population of individuals	66
4.3.2	Fitness evaluation of each chromosome	67
4.3.3	Genetic manipulation	67
4.3.4	Termination strategy	71
4.4	Summary	72
5	SYSTEM IDENTIFICATION	73
5.1	Introduction	73
5.2	System Identification of Flexible Manipulator Structure	73
5.3	Modeling of flexible manipulator structure using PSOE versus PSO	79
5.4	Modeling of flexible manipulator structure using GAPE versus GA	90
5.5	Discussion and Comparative assessment of all algorithms	101
5.6	Summary	104
6	CONTROLLER DEVELOPMENT AND SIMULATION	
	RESULTS	105
6.1	Introduction	105
6.2	Control schemes	106
6.3	Collocated Auto-tuned PID for Rigid Motion Control	110
6.3.1	Simulation result of Rigid Motion Control	111
6.4	PID controller tuning by EA for Flexible Motion Control	114

6.4.1	Particle Swarm Optimization with Explorer (PSOE) for PID tuning	116
6.4.2	Genetic Algorithm with Parameter Exchanger (GAPE) for PID tuning	119
6.4.3	Simulation results of Flexible Motion Control	121
6.4.3.1	PID controller tuned using PSOE and PSO	122
6.4.3.2	PID controller tuned using GAPE and GA	127
6.4.4	Discussion and Comparative Assessment	132
6.5	Summary	136
7	EXPERIMENTAL VALIDATION	137
7.1	Introduction	137
7.2	Implementation of Rigid Motion Control	138
7.2.1	Experimental Results – collocated PID controller	139
7.3	Implementation of Flexible Motion Control	141
7.3.1	Experimental Results – PID tuning using Evolutionary Algorithms	142
7.3.2	Robustness Test	149
7.3.2.1	Position of actuator	149
7.3.2.2	Motor Speed Variation	154
7.3.2.3	Hub Angle Variation	159
7.3.2.4	Added mass	161
7.4	Summary	167
8	CONCLUSION AND FUTURE WORKS	168
8.1	Conclusion	168
8.2	Future works	170
	REFERENCES	172
	Appendices A – L	184 - 200

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	PSO and its algorithm modification applied in identification and control	25
2.2	GA and its algorithm modification applied in identification and control	31
2.3	PID controller optimization using PSO and GA	37
3.1	Properties and dimensions of the aluminum manipulator	41
3.2	Specification of the piezoelectric actuator	45
3.3	Specification of the power amplifier	46
3.4	Specification of the DC motor	47
3.5	Percentage of error for modes of vibration	57
5.1	Comparative results between PSOE and PSO for different number of particles for endpoint acceleration	79
5.2	Comparative results between PSOE and PSO for different number of particles for hub angle	80
5.3	Comparative results between PSOE and PSO for different number of iterations for endpoint acceleration	81
5.4	Comparative results between PSOE and PSO for different number of iterations for hub angle	81
5.5	Comparative results between PSOE and PSO for varying model orders of endpoint acceleration modeling	82
5.6	Comparative results between PSOE and PSO for varying model orders of hub angle modeling	82

5.7	GAPE and GA parameters	90
5.8	Comparative results between GAPE and GA for different number of individuals for endpoint acceleration	91
5.9	Comparative results between GAPE and GA for different number of individuals for hub angle	91
5.10	Comparative results between GAPE and GA for different number of generations for endpoint acceleration	93
5.11	Comparative results between GAPE and GA for different number of generations for hub angle	93
5.12	Comparative results between GAPE and GA for varying model orders of endpoint acceleration modeling	94
5.13	Comparative results between GAPE and GA for varying model orders of hub angle modeling	94
5.14	Performance comparative between all algorithms for endpoint acceleration modeling	101
5.15	Performance comparative between all algorithms for hub angle modeling	102
6.1	Comparison performance of auto-tuned control	113
6.2	PID controller tuning by PSOE and PSO	127
6.3	PID controller tuning by GAPE and GA	132
6.4	Comparison of performances between the four EAs in PID tuning	133
6.5	Others related researches	135
7.1	Control schemes tested in both simulation and experimental environments	138
7.2	PID tuning results by EAs as in Chapter 6	142
7.3	Controller performance in vibration attenuation	148
7.4	Controller performance at different PZT position	154
7.5	Attenuation level under various motor speeds	158
7.6	Attenuation level at various tip payloads	165

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Research Methodology	9
2.1	Two link manipulator (Vakil, 2008)	13
2.2	System identification using EA	15
2.3	Flowchart of PSO algorithm	21
2.4	GA working principle	27
3.1	An orthographic drawing of the flexible manipulator	41
3.2	Isometric model of the experimental rig	42
3.3	Exploded view of the experimental rig	42
3.4	Single axis ICP accelerometer	43
3.5	Accelerometer bonded at endpoint of flexible manipulator	43
3.6	Maxon Encoder HEDL 5540	44
3.7	Details sketch of DuraAct piezoelectric patch	45
3.8	Piezo actuator of P-876.A15 mounted on the manipulator	45
3.9	Piezoelectric actuator amplifier type E-835 OEM	46
3.10	Maxon DC motor of RE 40	47
3.11	Maxon EPOS2 50/5	48
3.12	NI PCI-6259	49
3.13	Connector block SCC-68 series	49
3.14	Schematic diagram of the experimental set up	51
3.15	Maxon DC motor, gearhead, and encoder attached together at hub and connected to motor driver	51
3.16	Complete experimental rig	52

3.17	Input torque bang-bang	53
3.18	Hub angle	53
3.19	Endpoint acceleration in time and frequency domain	54
3.20	Impact test in time domain	55
3.21	Impact test in frequency domain	56
4.1	Swarm of particles	60
4.2	Inserted pseudocode of PSOE	62
4.3	A PSOE procedure	65
4.4	Binary encoded of four parameters	67
4.5	Single-point crossover operator	68
4.6	Parameter crossover operator	70
4.7	Mutation operator	70
4.8	A GAPE procedure	71
5.1	Implementation of system identification	74
5.2	PSOE procedure for SI	76
5.3	Binary encoded of SI parameters	77
5.4	GAPE procedure for SI	78
5.5	Parameter convergence (a) in PSO (b) in PSOE (c) Explorer Convergence in PSOE	84
5.6	PSOE algorithm convergence of endpoint acceleration	85
5.7	The outputs between actual and PSOE modeling	86
5.8	Normalized error of the output	87
5.9	Correlation tests	87
5.10	Poles-zeros map	87
5.11	PSOE algorithm convergence of hub angle	88
5.12	The outputs between actual and PSOE modeling	89
5.13	Normalized error of the output	89
5.14	Correlation tests	89
5.15	Convergence profile of model parameter (a) in GA (b) in GAPE	95
5.16	GAPE algorithm convergence for endpoint acceleration	96
5.17	The outputs between actual and GAPE modeling	97

5.18	Normalized error of the output	98
5.19	Correlation tests	98
5.20	Poles-zeros map	98
5.21	GAPE algorithm convergence for hub angle	99
5.22	The outputs between actual and GAPE modeling	100
5.23	Normalized error of the output	100
5.24	Correlation tests	100
5.25	Average value of minimum fitness function for endpoint acceleration modeling	102
5.26	Average value of minimum fitness function for hub angle modeling	103
6.1	Control structure for flexible manipulator system	108
6.2	Block diagram of control schemes	109
6.3	PID control schemes	110
6.4	SIMULINK model for rigid motion control	112
6.5	Simulation results of hub angle with auto-tuned control	113
6.6	Block diagram of flexible motion control	115
6.7	PSOE algorithm for PID tuning	118
6.8	Binary encoding representing the PID parameters	119
6.9	GAPE algorithm for PID tuning	120
6.10	SIMULINK model for flexible motion control	121
6.11	PSOE convergence	123
6.12	PSO convergence	123
6.13	PID-PSOE parameter convergence	124
6.14	PID-PSO parameter convergence	124
6.15	PID-PSOE controller for vibration suppression	125
6.16	PID-PSO controller for vibration suppression	126
6.17	GAPE convergence	128
6.18	GA convergence	128
6.19	PID-GAPE parameter convergence	129
6.20	PID-GA parameter convergence	129

6.21	PID-GAPE controller for vibration suppression	130
6.22	PID-GA controller for vibration suppression	131
6.23	Vibration attenuation by each approach	133
7.1	Experimental results of hub angle	140
7.2	Experimental time response	143
7.3	Enlarged view during link movement and stopping for both controllers	145
7.4	Enlarged view after 15 seconds link stopped for both controllers	146
7.5	Experimental frequency response	147
7.6	Flexible manipulator in 10 segments	149
7.7	Vibration responses at the tip for different PZT actuator position	151
7.8	Frequency response for different PZT actuator position	153
7.9	Time response at the tip under various motor speeds	156
7.10	Enlarged view of frequency response under respective motor speeds	158
7.11	Time response under various position set points	160
7.12	Enlarged view of frequency response under various position set points	161
7.13	Hub angle response at various tip loads	162
7.14	Endpoint acceleration response at various tip loads	164
7.15	Frequency response at respective tip payload	166

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 optimization
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	-	Proportional-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
$y_I(t)$	-	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
ζ	-	Precision constant
$\Delta Fitness$	-	Error function of particle fitness
Δt	-	Time step
Δx	-	Length of segment

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	List of publications	184
B	Technical specification of accelerometer	186
C	Technical specification of accelerometer input module	187
D	Technical specification of encoder	188
E	Technical specification of piezoelectric actuator	189
F	Technical specification of piezoelectric actuator amplifier	190
G	Technical specification DC motor	191
H	Technical specification of motor gearhead	192
I	Technical specification of motor driver	193
J	Technical specification of data acquisition system (DAQ)	194
K	Analysis for motor, gearhead and encoder selection	195
L	Heuristic Method	197

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.

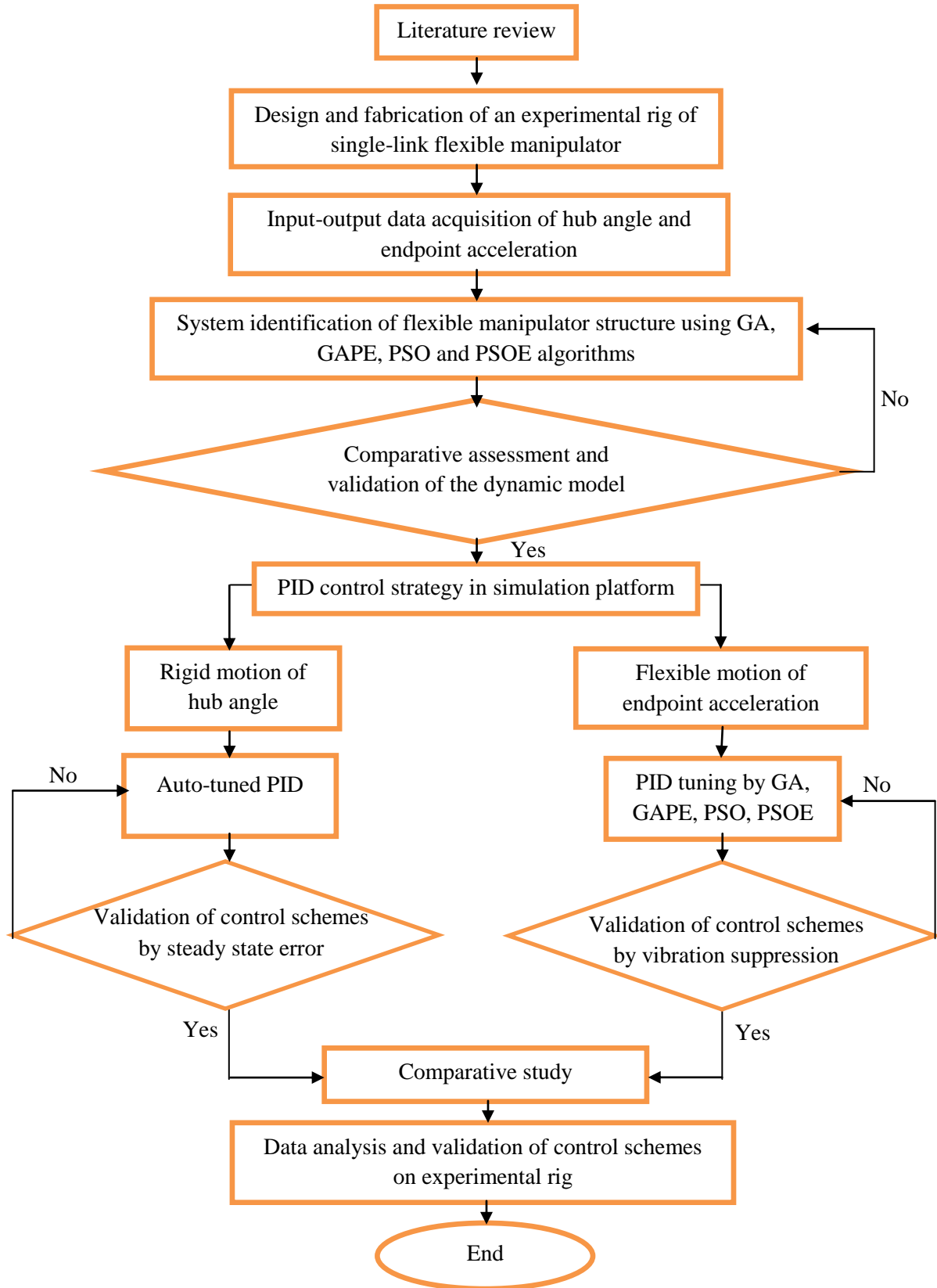


Figure 1.1: Research Methodology

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.

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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 Algorithm, *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.