MODELING AND INTELLIGENT CONTROL OF DOUBLE-LINK FLEXIBLE ROBOTIC MANIPULATOR

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

To my parents,
For raising me to believe everything is possible, taught me to trust in Allah, believe in hard work and that so much could be done with little.

To my husband, my girls and parents in law,
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ABSTRACT

The use of robotic manipulator with multi-link structure has a great influence in most of the current industries. However, controlling the motion of multi-link manipulator has become a challenging task especially when the flexible structure is used. Currently, the system utilizes the complex mathematics to solve desired hub angle with the coupling effect and vibration in the system. Thus, this research aims to develop a dynamic system and controller for double-link flexible robotics manipulator (DLFRM) with the improvement on hub angle position and vibration suppression. A laboratory sized DLFRM moving in horizontal direction is developed and fabricated to represent the actual dynamics of the system. The research utilized neural network as the model estimation. Results indicated that the identification of the DLFRM system using multi-layer perceptron (MLP) outperformed the Elman neural network (ENN). In the controllers' development, this research focuses on two main parts namely fixed controller and adaptive controller. In fixed controller, the metaheuristic algorithms known as Particle Swarm Optimization (PSO) and Artificial Bees Colony (ABC) were utilized to find optimum value of PID controller parameter to track the desired hub angle and supress the vibration based on the identified models obtained earlier. For the adaptive controller, self-tuning using iterative learning algorithm (ILA) was implemented to adapt the controller parameters to meet the desired performances when there were changes to the system. It was observed that self-tuning using ILA can track the desired hub angle and supress the vibration even when payload was added to the end effector of the system. In contrast, the fixed controller degraded when added payload exceeds 20 g. The performance of these control schemes was analysed separately via real-time PC-based control. The behaviour of the system response was observed in terms of trajectory tracking and vibration suppression. As a conclusion, it was found that the percentage of improvement achieved experimentally by the self-tuning controller over the fixed controller (PID-PSO) for settling time are 3.3 % and 3.28 % of each link respectively. The steady state errors of links 1 and 2 are improved by 91.9 % and 66.7 % respectively. Meanwhile, the vibration suppression for links 1 and 2 are improved by 76.7 % and 67.8 % respectively.

ABSTRAK

Penggunaan pengolahan robotik dengan struktur pelbagai-pautan mempunyai pengaruh besar dalam kebanyakan industri semasa. Walau bagaimanapun, mengawal gerakan pengolahan pelbagai-pautan telah menjadi tugas yang mencabar terutama apabila struktur mudah lentur digunakan. Pada masa ini, sistem menggunakan matematik yang kompleks untuk menyelesaikan sudut hub yang dikehendaki dengan kesan gandingan dan getaran dalam sistem. Oleh itu, tujuan penyelidikan ini adalah untuk membentangkan satu sistem dinamik dan kawalan untuk pengolahan robotik mudah lentur (DLFRM) dengan penambahbaikan kedudukan sudut hub dan pengurangan getaran. DLFRM bersaiz makmal yang bergerak dalam arah mendatar dibangunkan dan dihasilkan untuk mewakili dinamik sebenar sistem. Penyelidikan ini menggunakan rangkaian saraf sebagai anggaran model. Keputusan menunjukkan bahawa pengenalan sistem DLFRM menggunakan *perceptron* pelbagai lapisan (MLP) mengatasi prestasi rangkaian neural Elman (ENN). Dalam pembangunan pengawal, penyelidikan ini memberi tumpuan kepada dua bahagian utama iaitu pengawal tetap dan pengawal suai. Dalam pengawal tetap, algoritma metaheuristik yang di kenali sebagai Pengoptimuman Kerumunan Zarah (PSO) dan Koloni Lebah Buatan (ABC) telah digunakan untuk mendapatkan nilai optimum bagi parameter pengawal PID untuk mengesan sudut hub yang dikehendaki dan mengurangkan getaran berdasarkan model yang dikenal pasti yang diperolehi sebelum ini. Untuk pengawal suai, penalaan diri menggunakan algoritma pembelajaran berlelaran (ILA) dilaksanakan bagi menyesuaikan parameter pengawal untuk memenuhi prestasi yang diinginkan apabila terdapat perubahan pada sistem. Daripada pemerhatian, didapati penalaan diri menggunakan ILA dapat menjejaki sudut yang dikehendaki dan getaran dikurangkan walaupun ketika muatan telah ditambahkan ke hujung pautan system. Sebaliknya, penalaan tetap merosot apabila muatan ditambah melebihi 20 g. Prestasi skema kawalan ini dianalisis secara berasingan berasaskan waktu sebenar melalui kawalan komputer. Tingkah laku tindak balas sistem diperhatikan dari segi pengesanan trajektori dan pengurangan getaran. Kesimpulannya, hasil kajian menunjukkan peratus penambahbaikan secara ekperimen yang dicapai dengan kawalan penalaan diri berbanding kawalan secara tetap (PID-PSO) untuk masa penyelesaian 3.3 % dan 3.28 % bagi setiap pautan masing-masing. Ralat keadaan mantap pautan 1 dan 2 dapat diperbaiki sebanyak masing-masing 91.9 % dan 66.7 %. Sementara itu, pengurangan getaran untuk pautan 1 dan 2 diperbaiki masing-masing sebanyak 76.7 % dan 67.8 %.

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LIST OF ABBREVIATIONS

ABC - Artificial bee colony
AMM - Assumed mode method
ARMAX - Auto-regressive Moving Average Models eXogenous inputs
ARX - Auto-regressive with exogenous input
ARX-BFA - Auto Regressive eXogenous inputs model with bacteria foraging algorithm
ARX-CS - Auto Regressive eXogenous inputs model with cuckoo search
ARX-DE - Auto Regressive eXogenous inputs model with differential evolutionary algorithm
ARX-PSO - Auto Regressive eXogenous inputs model with particle swarm optimization
AVC - Active vibration control
BFA - Bacteria foraging algorithm
BP - Back propagation
CS - Cuckoo search
DAQ - Data acquisition card
DC - Direct current
DCC - Decentralized control
DE - Differential evolution
DLFRM - Double-link flexible robotic manipulator
DOF - Degree of freedom
EA - Evolutionary algorithm
ENN - Elman neural network
FEM - Finite element method

FLC - Fuzzy logic controller
FLM - Flexible link manipulator
GA - Genetic Algorithm
GUI - Graphical user interface
ILA - Iterative learning algorithm
LM - Levenberg-Marquardt
LMI - Linear matrix inequalities
LS - Least square
MIMO - Multiple-input multiple-output
MLP - Multilayer Perceptron Neural Network
MLP-NN-BP - Multilayer perceptron neural network using back propagation
MODE - Multi-objective optimization using differential evolution
MOPSO - Multi-objective PSO
MPC - Model predictive control
MSE - Mean square error
NARMAX - Nonlinear Auto-regressive Moving Average Models eXogenous
NARMAX-RELS - Nonlinear Auto-regressive Moving Average Models eXogenous inputs with recursive extended least square
NARX - Nonlinear auto-regressive with exogenous input
NARX-LS - Auto Regressive eXogenous with least square
NI - National Instrumentation
NN - Neural network
NNARX - Neural network nonlinear Auto Regressive exogenous
OSA - One step ahead
PD - Proportional derivative
PID - Proportional integral derivative
PID-ZN - Proportional integral derivative Ziegler-Nichols
PID-PSO - Proportional integral derivative particle swarm optimization
PID-ABC - Proportional integral derivative artificial bee colony
PID-ILA - Proportional integral derivative iterative learning algorithm
PSO - Particle swarm optimization

PWM	-	Pulse width modulation
PZT	-	Piezoelectric
RGA	-	Relative gain array
RLS	-	Recursive least square
RELS		Recursive extended least square
SDA	-	Spiral dynamic algorithm
SI	-	System identification
SIMO	-	Single-input multiple-outputs
SISO	-	Single-input single-output system
SLFM	-	Single link flexible manipulator
SSE	-	Steady state error
STC	-	Self-tuning controller
SO	-	Single objective
TDL	-	Tapped delay lines
ZN	-	Ziegler-Nichols

LIST OF SYMBOLS

A_m - Transfer function of motor gain for hub angle motion

A_p - Transfer function of actuator gain for flexible body motion

C_m - Transfer function of controller for hub angle motion

C_p - Transfer function of controller for flexible body motion

C_1, C_2 - Learning factors

$d(X)$ - Performance derivatives

$dXprev$ - Former adjustment to the weight or bias

$\delta(\tau)$ - Impulse

E - Modulus of elasticity

E_{ss} - Steady state error

$e_p(t)$ - Error of the system for flexible body motion

$e_m(t)$ - Error of the system for hub angle motion

$e(k)$ - System error

ε - Residual

$f(.)$ - Function

$f_{min}(e)$ - Mean squared error

fit_m - Fitness of x_m

G_p - Transfer function of sensor for flexible body motion

$gbest$ - Global best

G_m - Transfer function of sensor for hub angle motion

$\theta(t)$ - Hub angle

$\theta_d(t)$ - Desired hub angle

$\theta_i(t)$ - Hub angle output

i - Number of link

I_{cont} - Output current

j - Number of neuron of MLP

K_P - proportional gain,

K_I - Integral gain

K_D - Derivative gain

K_{cr} - Critical value

$K\ (k)$ - Stored value from the previous iteration (from memory)

$K\ (k+1)$ - Updated value (to memory)

L - Delay time

M_p - Maximum overshoot

N - Number of data

PID_{i1} - PID controller hub angle motion for i link

PID_{i2} - PID controller flexible body motion for i link

P_{cr} - Period

pbest - Best solution PSO has achieved so far

P_m - Profitability of all food sources

R_1, R_2 - Random number

T - Time constant

t_r - Rise time

t_s - Settling time

$\tau(t)$ - Torque

U_{mi} - PID control output for hub angle of i link

U_{pi} - PID control output for flexible body motion of i link

V_{cc} - Operating voltage

v_{mi} - Neighbour food source

V - Particle velocity

ϕ - Regression vector of NNARX

Φ_P - Proportional learning parameter

Φ_I - Integral learning parameter

Φ_D - Derivative learning parameter

W - Inertia weight

w_{ij} - Weight of strength of MLP

X - Particle position

x - Bias

x_m - Initial food sources

x_i - Input layer of MLP

$y_d(t)$ - Desired end-point acceleration

$y_{\mathrm{i}}(t)$ - End-point acceleration output

$y(t)$ - End-point acceleration

$y_d(k)$ - Desired input

$y(k)$ - Actual output

$y_v(t)$ - Disturbance to the system.

$\hat{y}$ - Forecast/predict output

y_j - Output of MLP

Z^N - Training data set

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Robotic manipulators are extensively used in industries and other fields at various level of operation that is from simple pick and place task to the critical operation such as space manipulator, automotive, security, electronic factory, medicine, oil and gas, etc. This is because they are cost effective and proven to be more reliable than humans. In term of design, robotic manipulator structures are generally substantial and heavy that result in rigid arm and stiff joint design. Their usages are limited to light loads and their movement is slow. Hence, the conventional design is not favorable in current industries as it is not efficient in term of speed, productivity and power consumption. Apart from that, many industries require light mechanical structure such as spacecraft and aircraft. Therefore, noteworthy attention has been given to flexible manipulator systems in recent years to fulfill the necessity of industrial applications. There are lots of benefits from the development of the flexible manipulator structure: cost reduction, lower power consumption, improved dexterity, better maneuverability, better transportability, safer operation, light weight and lower environmental impact.

Though flexible structure provides accommodating structure for design, it is known that the systems demonstrate vibration when subject to disturbances forces. The vibration occurs in the light weight manipulators cannot be avoided whenever they maneuver from one point to another. The vibration can be very severe to the extent that results in noise, disturbances and discomfort. Vibration may cause performance degradation, tracking errors, long idle period between tasks, undermining accuracy and safety. In the worst-case, vibration may cause premature deterioration of the system. Therefore, it is vital to control the vibration of flexible structures.

Ongoing researches of flexible structure focused on improving the control methods to fulfill all conflicting between benefits, drawbacks and industries requirements. In suppressing the vibration, there are two different techniques that are hitherto utilised, namely passive control techniques and active control techniques. Though there is research on passive control in flexible manipulator (Feliu *et al.*, 2014; Emiliano *et al.*, 2007; Forbes and Damaren, 2012), but most of the researches concentrated on using active vibration technique. Active control uses the principle of wave interference by artificially generating a destructive anti source that interferes with the disturbances and reduces the level of vibration. In other word, a suitable control will process the detected vibration in the system, then superimpose disturbance signals to free the system from the actual disturbance force. Meanwhile, a passive control requires additional weight embedded to the system as an absorber which is simpler, but it is applied to the system with high frequency which is more than 200 Hz. Besides, engaging passive control may contradict with the objective to reduce the weight of mechanical structures. Furthermore, the flexible manipulator system is found to be categorized under low frequency system. Thus, in comparison, active control is found to be more suitable and practical to be applied to the system. It has been widely used by many researchers and is still the prominent approach till today.

To date, a number of control strategies are available for double-link flexible robotic manipulator (DLFRM) such as Passivity-based velocity feedback and strain-feedback schemes (Peza-Solís *et al.*, 2010), hybrid collocated proportional derivative (PD) and non-collocated proportional integral derivative (PID) (Mahamood and Pedro, 2011a), global terminal sliding mode (Chu *et al.* 2009), a genetic algorithm (GA) based hybrid fuzzy logic control strategy (Zebin and Alam, 2010), decoupling controller based on the cloud model (Lingbo *et al.*, 2006), decentralized controller based on linear matrix inequalities (Khairudin and Husain, 2014; Leena and Ray, 2012). The strategies include both conventional and intelligent schemes. Some of them combine both intelligent and conventional scheme to compensate the drawback of each controller.

1.2 Statement of the Problem

The advancements in various field of life inclusive of domestic and industries create a great demand for flexible robot manipulator. Many robot manipulator applications are categorized as multiple-input-multiple-output (MIMO) systems due to multi-link structure. The design and tuning of multi-loop controllers to meet certain specifications are often the pullback factor because there are interactions between the controllers. The system must be decoupled first to minimize the interaction or to make the system diagonally dominant. Moreover, the reduction of vibration on flexible structure of robot manipulator must be treated at the same time. The continuous stress produced by the vibration can lead to structural deterioration, fatigue, instability and performance degradation. Thus, the reduction of vibration on flexible structure of robot manipulator is of paramount importance. Though many researchers have successfully produced the controllers for multi-link flexible manipulator, the control scheme developed involves complex mathematics to solve the coupling effect and vibration simultaneously. As a result, it consumes a lot of time in numerical computation which leads to higher computational cost.

In the attempt of providing a better control performance, the preferable option for control strategy that involves MIMO system is decentralized control strategy because it reduces the system into single-input single-output system (SISO). Simultaneous optimization method is an alternative of optimizing the parameters without go through the complex mathematical calculation to decouple the system. Meanwhile, AVC is opted to optimally reduce vibration. For implementing AVC in flexible manipulator, smart material is embedded to the system.

Thus, this thesis aims to manage the MIMO system along with the existence of vibration in them. In this research, the hybrid PID-PID controller is developed for hub motion and end point vibration suppression of each link respectively. The optimization procedure of PID control parameters are tackled using EA and ILA. Two EAs are implemented, namely, Particle Swarm Optimization (PSO) and Artificial Bees Colonial Algorithm (ABC). Meanwhile, for adaptive controller, self-tuning of P-Type ILA employed to the system. The PID control tuning method using EAs and ILA are implemented on the identified model through system identification acquisition of the real plant using neural network structure based on NARX model. The performance of EA and ILA is then analyzed via experimental validation. Self-tuning using iterative learning algorithm (ILA) was implemented to adapt the controller parameters to meet the desired performances when there were changes to the system.

1.3 Objectives of the Study

This research focuses on the control strategies of the double-link flexible robotic manipulator. The objectives are as such;

1. To model the dynamic of double-link flexible robotic manipulator with actual experimental input-output data using non-parametric system identification (SI) utilizing Neural Network Non-linear Auto Regressive exogenous (NNARX) structure.

2. To develop conventional and intelligent hybrid PID controllers that can achieve desired angle of each link together with the suppression of the unwanted tip vibration on the double-link flexible robotic manipulator based on the identified model.

3. To develop, simulate and analyze the performance of real time self-tuning PID controller in controlling the angle and vibration of double-link flexible robotic manipulator.

4. To analyze, verify and validate the best intelligent hybrid PID and self-tuning PID controllers experimentally and to perform the comparative assessment between those controllers.

1.4 Scope of the Study

The scope of the research is as follows;

1. Development and fabrication of a laboratory scale size of double-link flexible robotic manipulator to move in horizontal planar direction only and gravity effect is neglected.

2. The non-parametric model approach is used to model the dynamic of double-link flexible robotic manipulator limited to multilayer perceptron neural network (MLP) and Elman neural network (ENN) based on Nonlinear auto-regressive with exogenous input (NARX) structure. All the developed models are validated via mean square error (MSE), one step ahead (OSA) prediction and correlation tests only.

3. Rigid and flexible motion controls of DLFRM are conducted using two different control loops respectively based on decentralized control strategy only. The rigid motion is evaluated via the input tracking only and the performance of the flexible motion is assessed through vibration attenuation at the first mode of vibration.

4. The intelligent controls are designed and simulated by applying PID controller tuned via offline, limited to particle swarm optimization (PSO) and

artificial bee colony (ABC) and compared with conventional fixed Ziegler-Nichols (ZN) PID controller. The best control scheme of fixed controller obtained from the simulation is validated experimentally via the developed DLFRM rig.

5. The real time self-tuning PID control schemes limited to P-type iterative learning algorithm (ILA). The controller is implemented for input tracking and vibration suppression via the developed DLFRM experimental rig.

6. The robustness test for the PID control scheme on the experimental rig is limited to angle variation and end point payload.

1.5 Significant Contribution to Knowledge

The contributions of the research are focused on four main areas that is in the development of model using experimental data from the rig, the development of controllers via decentralized control strategies, the implementation of simultaneous optimization method via evolutionary algorithm in solving the parameter of hybrid PID MIMO system and real time self-tuning PID based controllers. The details are elaborated herein;

1. This research contributes in developing the dynamic model of the double-link flexible robotic manipulator using non-parametric system identification approach. Most of the previous researches used model-based mathematical modeling such as assumed mode method (AMM), finite element method (FEM) and lump parameters and quite a number implement non-model based such as using neural network (NN), fuzzy and neuro-fuzzy. In this research, the model is developed using both input and output data from the experiment of double-link flexible robotic manipulator system based on NARX model structure model. Two types of parameter estimation were used for the model development that is multilayer perceptron neural network using back

propagation as training algorithm (MLP-NN-BP) and Elman neural network. The models were verified through mean squared error, one step ahead and correlation tests to determine the best model that represents the system. Thus, the controller was designed based on NNARX model which represent the nonlinear model of the system. Number of research in this area control the system via linear model of the system which is not preferable because it does not represent the real plant.

2. This research contributes in developing a new method using hybrid PID controller on DLFRM with decentralized control strategy via simultaneous optimization method. Problem arises as the systems consist of single-input multiple-outputs (SIMO) as a separate system and become MIMO system as the system merge. The simultaneous optimization method is implemented to the MIMO system. Despite the fact that many researches had implemented this method, most of them has pre-calculated the decouple gain and use the optimization method on decoupled matrix. Whereas, in this research, the optimization is implemented directly on the obtained models from system identification for all the PID controllers. Thus, the novelty of this research is that the dynamic models of DLFRM are separated in the modeling stage. By that, the characteristics of DLFRM are defined in each model and the coupling effect is assumed to be minimized. There is no study yet to implement this approach. Besides, the intelligent Hybrid PID controllers tuned by PSO and ABC have not been reported previously to control the rigid and flexible motion of DLFRM. Thus, in this study, the simultaneous optimization method using PSO and ABC are developed to observe the mathematical burden in calculating the decouple gain due to coupling effect.

3. This research contributes in investigating the implementation of controlling MIMO system using decentralized control strategies in the actual plant. The models are controlled within the simulation environment to pre-determine the appropriate gains for PID controllers before the experimental work is employed. Later, the performances of the simulated controllers are validated

experimentally. All the four controllers are run simultaneously on the real plant which has not been conducted previously.

4. The real time self-tuning iterative learning algorithm PID based controllers is simulated and validated experimentally. The system is controlled concurrently by all the four controllers in real time. Besides, the study provides details implementation of new control structure in controlling DLFRM under variation of payloads via online which has not been reported in any research. From the experiment, these controllers are proven to be robust in term of the input tracking and vibration suppression though there is a change of payloads at the end-effector. This is a great advantageous of the controllers and it is very important characteristics to be implemented in the real application.

1.6 Research Methodology

The extensive literature review on the subject matter was carried out to properly decide the direction of the study. The research consists of several phases: system identification, controller design and experimental validation as shown in Figure 1.1. Before that, the experimental rig was developed and fabricated. The fabrication of the rig was aimed to replicate the dynamics of the actual systems. The instrumentation and data acquisition system were setup and integrated with the DLFRM rig.

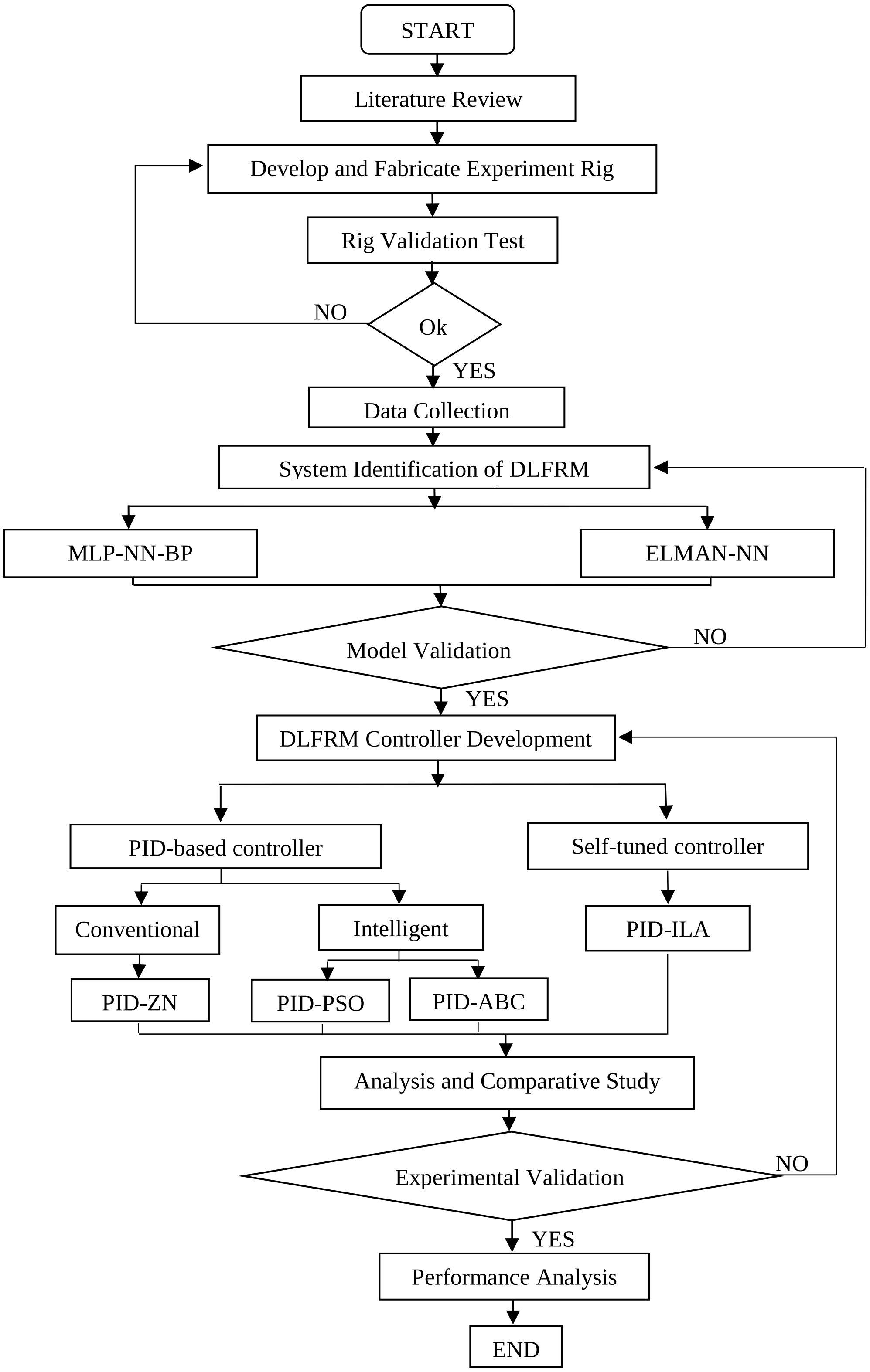

Figure 1.1 Flowchart of Research

The impact test was executed to the DLFRM system to validate the rig. The first three modes of vibration were identified from the findings. This is an important element in vibration control. The results were to be compared with the experimental studies. From there, the validity of the developed model could be confirmed.

Then the model of double-link flexible robotic manipulator was identified through SI. The input-output data required for the modeling process were collected experimentally using the DLFRM test rig. Simulink program was developed as the tool for collecting the data. Four outputs were collected from two encoders and two accelerometers which represent the hub angles and end point accelerations of each link respectively. Nonlinear auto-regressive with exogenous input model structure was used to define the relationship between input and output data. The model was estimated using neural network that is multi-layer perceptron and Elman neural network. The model was validated through MSE, OSA and correlation tests. The fittest model was selected as the platform or plant for the PID controller design in the simulation environment.

Once the model has been selected, the controllers were developed. Three types of controllers were designed that is conventional controller, intelligent PID controller and self-tuned controller. Conventional controller acts as the experiment control of the controller design. The algorithm was used to compute the amount of torque (motor voltage) required for trajectory tracking and the amount of voltage from actuator to suppress the vibration for DLFRM system. The PID control scheme was tuned offline by intelligent tuning methods using ABC and PSO. Meanwhile, the conventional tuning method implemented Ziegler-Nichols method. The performance of the intelligent fixed PID control schemes were compared with a conventional, fixed PID control scheme.

The best performances of fixed PID controllers obtained from the simulation evaluations were validated experimentally using the developed DLFRM rig. For self-tuning PID control scheme, the ILA was incorporated with the PID controller to update its parameters iteratively. P-Type ILA was used to tune the PID controller parameters for both trajectory tracking and end point acceleration control of

DLFRM. The real time self-tuning PID control scheme was executed through the developed experimental rig for trajectory tracking control and end point acceleration. Finally, a comparative study between fixed and self-tuning PID control schemes were conducted and reported. The objective of the comparative study was to observe the differences in their performance simultaneously. From there, the researchers can exploit the benefits of using the proposed strategies. Figure 1.1 shows the flow chart of the proposed research strategy considered in this study.

1.7 Structure of Research

This thesis is organized into seven chapters. A brief outline of contents of the thesis is as follows:

Chapter 1 presents an introduction of the research problem. It comprises the research background and problem statement. Besides, the research objectives, contributions and methodology are highlighted and elaborated. The structure and the flow of the thesis are also outlined in this chapter.

Chapter 2 focuses on the literature review of modeling and control for the flexible manipulators. Firstly, a brief overview on modeling approaches and control schemes of the flexible manipulators was highlighted. Then, the recent proposed model schemes were reviewed. This was followed by the review on the numerous proposed control schemes and their various applications. The gaps between the earlier researches and the proposed modeling and control schemes were recognized and discussed.

Chapter 3 describes the development of experimental test rig to perform the planar movement of double-link flexible robotic manipulator. The rig design, the hardware use in the experiment set up and the system integration were elaborated in details. Besides, the method of data acquisitions was elucidated. The chapter also clarified the reliability of the developed experimental rig through the experimental and impact test carried out on the system.

Chapter 4 presents the implementation of SI in modeling the hub-angle and end point vibration of the DLFRM. The NARX model structure was selected to characterize the actual system. The MLP neural network and Elman neural network techniques were utilized to estimate and obtain the model of the system. This chapter starts with brief explanation of neural network and NARX model structure in general. Then, the details of model estimation were discussed which involved the incorporation of NARX model structure and neural network. The comparative study among the developed models in terms of MSE, OSA and correlation tests were carried out. The best model among the developed models was utilized as a system plant in the development of control via simulation environment.

Chapter 5 presents new tuning methodologies of the conventional PID controller by using metaheuristic algorithms. The algorithm is expected to optimally track the desired hub-angle together with vibration suppression of the DLFRM. This chapter starts with simulation studies of three types of PID based controller configurations that implemented and tuned the controller based on Ziegler Nichols method. The performance of the hub angle control and end point acceleration of DLFRM are evaluated. The best among the controllers is to be compared with the proposed controllers. Next, the implementation of tuning the PID-based controller offline on the identified hub-angle model and end point acceleration to obtain the controllers parameters are discussed. The optimization process uses the metaheuristic algorithms that are ABC and PSO by targeting the position of the hub angle and vibration suppression. PID-based parameters are validated experimentally and the performance of PID-based controller tuned by ABC was compared with PSO. Lastly, the robustness tests were carried out to evaluate the effectiveness of the controller.

Chapter 6 presents the development of real time self-tuning PID control scheme based on ILA for DLFRM. The proposed controllers were observed via simulation environment before executed on experimental rig. The self-tuning PID controller performance was validated experimentally and compared with the fixed control schemes. The effectiveness of the controller was validated through robustness tests.

Chapter 7 summarizes the work presented and draws significant conclusions. Suggestion on the possible future works for modeling and control of DLFRM are also discussed.

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