Intelligent PID Controller of Flexible Link Manipulator with Payload

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***Abstract*—This paper presents the experimental study of intelligent PID controller with the present of payload. The controllers were constructed to optimally track the desired hub angle and vibration suppression of DLFRM. The hub angle and end-point vibration models were identified based on NNARX structure. The results of all developed controllers were analyzed in terms of trajectory tracking and vibration suppression of DLFRM subjected to disturbance. The simulation studies showed that the intelligent PID controllers have provided good performance. Further investigation via experimental studies was carried out. The results revealed that the intelligent PID control structure able to show similar performance up to 20 g of payload hold by the system. Once the payload increased more than 20 g, the performance of the controller degrades. Thus, it can be concluded that, the controllers can be applied in real application, provided the tuning process were carried out with the existence of the maximum payload which will be subjected in the system. The 20 g payload value can act as uncertainty for the controller performance.**

Keywords*—*flexible manipulator, payload, robotic manipulator, intelligent controller, PSO.

I. Introduction

The flexible plate has been utilized in various industry applications such as aircraft body, automotive structure, robotic arm, electronic board design, bridge decks, and conveyor system [1]. Many researchers have contributed in the study of flexible plate such as in modeling [2-4] and control strategies [5-7].

Recently, the spectrum of applications of flexible plate in robotic arm has become wider and greater. It was used on the land, underwater and outer space. The broader scope of usage shows that the flexible manipulator is practical for real application. It becomes favorable alternative as it is recognized to be exceptionally productive. In opposite to the inflexible structure, it offers lighter in weight, consume less power, require smaller actuators, transportable, higher maneuverability, more secure operation and lower natural affect. However, the structure produces undesirable vibration from the flexible structure which give a lot of effort in controlling the structure. The challenge in control task become intensifies when the flexible multi-link is considered. Aside from the vibration exist in the system, several other factors such as coupling between both links have to be carefully measured. Due to that, the control scheme must be effective and robust.

Flexible Manipulator captures significant interest among researchers in order to accommodate the current industry's needs. The existing researches focused on enhancing the control techniques so that it can comply with all the contradictory needs. In the industrial environment, proportional integral derivative (PID) controller is still a promising choice particularly for multi input multi-output (MIMO) frames. They are frequently showed satisfactory accomplishment despite their simple design. A group of researchers has proposed an easy tuning method. There are three classes of decentralized PID manage method that is detuning of the parameter, in search of on essential gains and acquired controllers through analytic, numerical or graphics methods via taking into accounts the interaction consequences [8]. Meanwhile, additional detail category has been further explained in [9] that is detuning methods, sequential loop closing methods, iterative or trial-and-error methods, simultaneous solving equation or simultaneous optimization methods and unbiased methods.

Several of PID control scheme have been implemented to double link flexible robotic manipulator (DLFRM) system. The work in [10-11] have proposed the PI-PID controller for DLFRM through manual tuning. Then, the overall performance has been elevated by adding ILC which have been verified in the simulation. The linear matrix inequalities (LMI) based PID control of a nonlinear Double link flexible robotic manipulator (DLFRM) incorporating payload have been investigated which is categorized under simultaneous equation optimization method [12]. In [13] PID controller by incorporating bounding parameters of interconnection terms in LMI formulation for an n-link robotic manipulator system was proposed. Another control strategy for DLFRM utilized Neural Network (NN) to approximate the ZN-PID for every link of DLFRM in [14] which can be classified beneath Independent method. Besides, PID tuned by P-type ILA is proposed for DLFRM [15]. The outcome showed a convincing result. Finally, PID tuned by PSO and ABC are offered. The results showed that both the intelligent controllers successfully control the DLFRM but PSO superseded ABC [16].

Looking at the wider study dimension of DLFRM, the research on a single link flexible manipulator (SLFM) can be explored. There are quite a number of researches have been conducted for SLFM. Alam, et al. applied hybrid PD-PD/ILA tune by multi-objective Genetic Algorithm optimization for SLFM [17]. Tijani, carried out a multi-objective optimization the use of Differential Evolution (MODE) for PID controller of SLFM [18]. Another researcher has proposed an expanded Bacterial Foraging Algorithms (BFA) to fine-tune the PID controller of SLFM [19]. Bee Algorithm have been successful to optimize the hierarchical PID parameter of

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SLFM in [20]. Finally, PSO is used to fine-tune one of PID parameters of the Hybrid PID-PID controller of SLFM [21]. The literatures disclose that the application of EA is confined to SLFM. However, the survey confirms that unique type of EA provides an effective method in optimizing the PID controller of FLM system in wide- range of control strategy.

Most of the research on control scheme of two-link flexible manipulator stop at simulation and some with limited experimental validations. This paper presents theoretical and experimental investigations of control scheme incorporating payload. A hybrid PID-PSO controller for DLFRM is developed. The controller is further investigated with the presence of payload. The recommended controller is utilized for position tracking and end point vibration suppression. The assessment of the recommended controllers was validated thru experiment to validate the controller's effectiveness in the real application.

II. Double link manipulator system

Double-link flexible robotic manipulator test rig was designed and developed to verify the effectiveness of the proposed control schemes based on the schematic diagram shown in Fig. 1

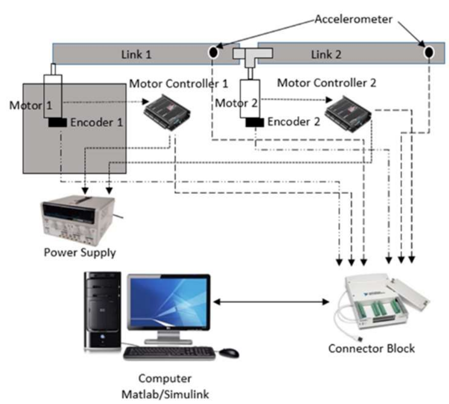


Fig. 1. Schematic diagram of experimental set up

The system set up consists of double-link flexible robotic manipulator, dc motors, motor controllers, accelerometers, power supply, and data acquisition system. DC motors are connected to motor controllers. Meanwhile, motor controllers are linked to connecter block and power supply. The DC motors receive voltage signal from the motor driver and produced torque onto the links which causes an angular displacement that will be detected by the encoders. The vibration of the links due to the input torque or any sudden change in the surroundings will be detected by the accelerometers positioned at the endpoint of the links. For rigid body motion control, the error between the hub angle set point signal and encoder signal from the rig during the experiment will be sent to the controller. Then, the system will produce control signal that generate torque required for trajectory tracking control of the DLFRM. Meanwhile, the vibration at the endpoint of links will be captured by the accelerometer and suppressed by actuators. Encoders and accelerometers are connected to connector block. The connector block will communicate with MATLAB Software via data acquisition card (DAQ) which is fixed to the computer system. A real-time computer control system is established utilizing personal computer. Online monitoring and control algorithm are established within MATLAB/Simulink environment. MATLAB software is appropriate for on-line real-time application where interfacing between computer system and input-output signals can be done easily utilizing National Instrument data acquisition system (NI DAQ). NI DAQ has been utilized to obtain analog input from accelerometer, digital inputs from encoder and send the actuating signal to motor driver. The actual experimental set up is shown in Fig. 2.

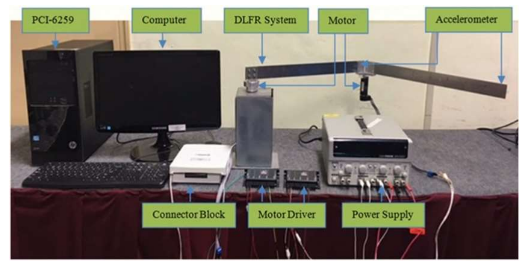


Fig. 2. Experimental set up of double-link flexible robotic manipulator

III. Dynamic Modeling

Modeling via system identification can be classified into two that is parametric modeling and non-parametric modeling. Researchers in [22] develop and discuss both parametric and non-parametric modeling of flexible structure.

In this study, non-parametric modeling is developed for. NARX is chosen as model structure in this study because it has the simplest structure among non-parametric model. The research makes use of back propagation for multi-layer perceptron (MLP) neural network and Elman neural networks (ENN) for modeling the DLFRM system. All the developed models are validated via Mean Squared Error (MSE). They are further validated via Correlation Test. From the results, it is found that NARX model structure estimated by MLP provides good results. Thus, this controller development utilized those models. The details of system modeling for DLRM can be found in [23].

IV. Control System

The general form of control structure recommended for this work is presented in Fig. 3 and 4. The PID_1 and PID_2 controller is applied for hub angle motion and flexible body motion respectively. The complete PID controllers are tuned by ABC. The two loops of each link *(i*=1,2) are consolidated to allow control inputs to the double link flexible robotic manipulator framework.

A. PID Controller

By referring to Fig. 3, the close loop signal of U_{mi} can be written as;

$$U_{mi}(t) = A_{mi}\left[\left(C_{mi}(t)e_{mi}(t)\right)\right] \qquad i = 1,2 \quad (1)$$

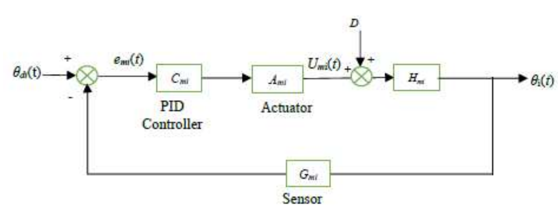


Fig. 3. Block diagram of control rigid body motion.

Therefore, the closed loop transfer function acquired as in Eq. (2);

$$\frac{\theta_i}{\theta_{di}} = \frac{[C_{mi}]A_{mi}H_{mi}}{1+[C_{mi}]A_{mi}G_{mi}H_{mi}} \quad (2)$$

where , and represents reference hub angle and actual hub angle. U_{mi} is PID control input, Ami is motor gain and C_{mi} is PID controller. The controller gains are K_{Pi}, K_{Ii} and K_{Di}.

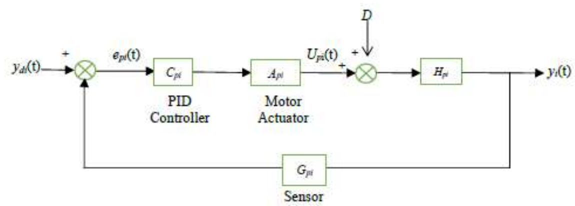


Fig. 4. Block diagram of control flexible body motion

Referring to Fig. 4, the control input is given by;

$$U_{pi}(t) = A_{pi}\lfloor C_{pi}(t)e_{pi}(t)\rfloor \quad i = 1,2 \quad (3)$$

where U_{pi} is PID control input, A_{pi}, are piezoelectric gain, C_{pi} is PID controller. The controller gains are K_{Pi}, K_{Ii} and K_{Di}. The deflection output represents by y_i and the desired deflection y_{di} is set to zero. Therefore, the closed loop transfer function obtained as;

$$\frac{y_i}{y_{di}} = \frac{\lfloor C_{pi}\rfloor A_{pi}H_{pi}}{1+\lfloor C_{pi}\rfloor A_{pi}G_{pi}H_{pi}} \quad (4)$$

The parameters of PID controller, K_{Pi}, K_{Ii} and K_{Di} were tuned accordingly to be fed into the U_{mi} and U_{pi}, thus grant satisfactory accomplishment of DLFRM. The accomplishment of the PID controller was evaluated by minimizing the MSE value.

B. PID controller tuned by PSO

The recommended control structure using ABC was embraced to tune the PID controllers. Fig. 5 and 6 present a block diagram of the closed loop system for rigid body and flexible motion control respectively. The objective functions of optimization are expressed based on the MSE of the hub angle error and end-point vibration concealment. This was applied to both algorithms.

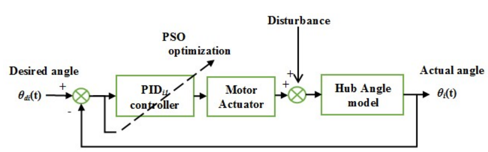


Fig. 5. PID control structure for hub angles 1 and 2.

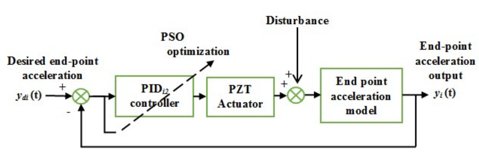


Fig. 6. PID control structure for end-point accelerations 1 and 2.

The simulation study was conducted offline to explore the execution of ABC algorithm in tuning the PID controllers' parameters. The controller parameters which are K_P, K_I and K_D were assigned to the closed-loop PID controller in MATLAB/Simulink. The error for each sample was computed and the MSE is assessed. MSE was set as fitness value in the algorithm. The objective is to continuously revise the PID controller parameters until the minimum fitness value is accomplished.

V. IMPLEMENTATION AND RESULTS

A. Simulation Results

The hub angles were individually controlled by the collocated PID controller. The DLFRM system is required to follow a step input of 2.1 rad and 1.1 rad to test the hub tracking input of link 1 and 2, respectively. Table I lists the PID parameters along with the rise time, steady-state error and overshoot value of the PID-PSO controller for both links.

TABLE I. PARAMETERS AND PERFORMANCE OF HUB INPUT TRACKING FOR DLFRM SYSTEM

	Parameters			Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error
	KP	**KI**	**KD**				
Link 1	3.65	57.9	3.46	0.058	1.16	0.89	0.003
Link 2	2.19	88.2	0.79	0.043	0.59	1.64	0.002

The non-collocated PID controllers were implemented in DLFRM system to actively suppress the vibration at the endpoint of link 1 and 2 individually. Table II illustrates the PID parameters of the PID-PSO controller for both links.

TABLE II. PARAMETERS AND PERFORMANCE OF VIBRATION SUPPRESSION FOR DLFRM SYSTEM.

	Parameters			MSE	Attenuation of the amplitude at a natural frequency (dB)		
	KP	**KI**	**KD**		1st	2nd	3rd
Link 1	2.07	498.1	2.04	3.948e-08	45.77	27	12
Link 2	8.06	817.9	1.03	4.315e-08	43.3	44.4	32.6

The details explanation of this simulation results can be obtained in former paper [24].

B. System with Payload

The results from the simulation were tested experimentally on the DLFRM experimental test rig to further investigate the existence of payload in the system. This is to imitate the real case scenario whereby the robot manipulator will carry the payload in their operation. The controller was applied in a real-time computer control system using MATLAB/Simulink with a sampling rate of 0.01 s.

In this section, various payloads of up to 50 g weight were added at the end effector in order to demonstrate the effects of payload with applied PID-PSO. Fig.7 and 8 indicated the hub angles response respectively when the load at the tip of a flexible manipulator changes from 2 g, 10 g, 20 g, 30 g and 50 g, respectively.

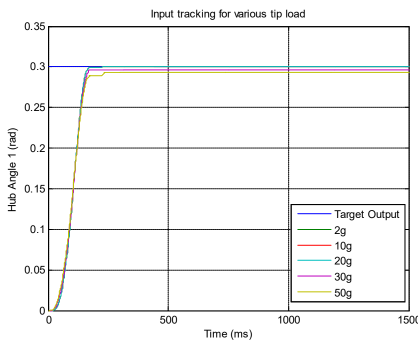


Fig. 7. Experiment validation of tracking trajectory of hub angle 1 using PSO

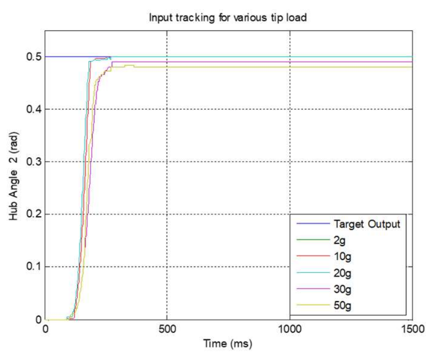


Fig. 8. Experiment validation of tracking trajectory of hub angle 2 using PSO.

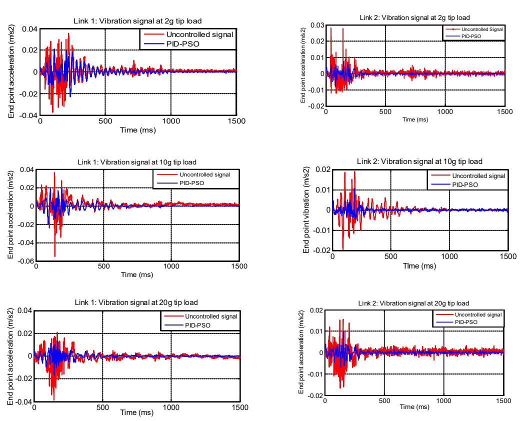
The performance of hub angle response has precisely tracked the input motion up to 20 g. However, the link could not reach the desired output when the mass payload added is more than 20 g. The time responses of hub angles have shown significant changes whereby the system exhibits higher rise time and settling times with increasing payload. The results were more noticeable in link 2. This happened due to the first link failure to reach the desired output, thus the second link performance also gets affected. The results show that the link 2 was very much influenced by link 1. Therefore, it can be concluded the performance of fixed controller is limited whereby it is able to control up to certain payloads only.

Fig. 9 (a) - (e) illustrate the end-point acceleration response with the variations of payload for both ink 1 and 2.

a.

b.

c.



d.

e.

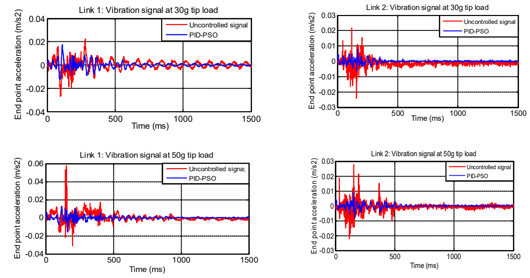


Fig. 9. Vibration suppression with variation of payloa

It is noted that payload attached at the end effector has increased the total mass of the system. The flexibility of the link reduces as the payload increases. Hence, the increasing mass has significant effect on the performance of controller since the dynamic model of the system may change. From Fig. 5.43, it can be observed that the maximum disturbance magnitude is reduced as the weight of load is increased. This is due to the mass payload that compensated for the vibration overshoot. At 2 g, 10 g and 20 g loads attached, the vibration signal was found to have almost zero acceleration towards the end of observations. Meanwhile, it is observed that the amplitude vibration for 30 g yet to settle even after 15 s. The disturbance takes longer time to settle down as higher persistent oscillations can be seen with increased mass payload attached. The condition applies for both links. However, the pattern of the amplitude vibration for the mass payload at 50 g follows the first 3 payloads. This pattern may be due to the contribution of the mass payload at 50 g as a passive damper which increases the suppression level.

VI. Conclusion

The simulation studies showed that PID tuned by PSO offer good transient response. However, the experimental results indicate that the intelligent PID controller has their limitation when the payload exist in the system. The performance of the controller reduces when the payload increases more than 20 g. In the real application, this finding is crucial to estimates the presence of uncertainty in the controllers. Notably, the controllers are fit to be used in real application subjected to how the tuning process is carried out in the system. It is advisable and practical to tune the controllers with the presence of the maximum payload in the system.

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