Decentralized Intelligent PID based controller tuned by Evolutionary Algorithm for Double Link Flexible Robotic Manipulator with Experimental Validation

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Abstract*—In this paper, a development of decentralized intelligent proportional–integral–derivative (PID) controller for multi input multi output (MIMO) controller of double link flexible robotics manipulator is presented. Simultaneous optimization method is implemented in optimizing the parameters The controllers are incorporated with optimization algorithm that is PSO to find out the parameters of the PID controllers. Numerical simulation was carried out in MATLAB/Simulink to evaluate the system in term of tracking capability and vibration suppression for both links. The optimal values of PID controller parameters that were achieved via off-line tuning using PSO were tested experimentally on the DLFRM experimental test rig. Experimental results show that the proposed control algorithm managed to control the system to reach desired angle for both hub at lower overshoot. Meanwhile, the vibration reduction shows improvement for both link 1 and 2. This signifies that, the PSO algorithm is very effective in optimizing the PID parameters for double link flexible robotics manipulator.

Keywords*—*Flexible Manipulator, Particle Swarm Optimization, Hub Angle ,Vibration suppression, Intelligent PID

I. INTRODUCTION

Despite various advantages shown by flexible manipulator such as offers cost reduction, lower power consumption, improved dexterity, better maneuverability, safer operation and light weight, the undesirable vibration is the common shortcoming occurred in the structure. In order to satisfy the conflicting requirements, number of research on improving the control methods have been carried out.

Among available wide range controllers, PID controller is still the most widely used in the industrial environment for MIMO systems because they are capable of providing a satisfactory performance in spite of their simple structure and intuitiveness. The main issue of PID controllers is to tune the gains. Other than that, PID controller is still significant because of its robustness performance in a wide range of operating condition and easy to implement.

There are few research that consider double link flexible robotic manipulator (DLFRM) using PID controller. The decentralized PI-PID controller for DLFRM have been proposed in [1-2] by employing manual tuning for both PD and PID whereby the parameters of the first link was carried out followed by the second link. The overall system performance has been improved by introducing ILC and adaptive control respectively which were proven in the simulation. Another tuning method that has been implemented in flexible manipulator is simultaneous equation solving method. The Linear matrix inequalities (LMI) based PID control of a nonlinear DLFRM incorporating payload have been presented in [3]. Another researcher proposed a class of stabilizing decentralized proportional integral derivative (PID) controller by incorporating bounding parameters of interconnection terms in LMI formulation for an *n*-link robot manipulator system [4]. Meanwhile, Neural Network (NN) is being utilized to approximate the ZN-PID for each link of DLFRM in [5] which can be categorized under Independent method.

Evolutionary Algorithms have been used in various areas including in developing tuning method of PID controller for flexible manipulator. For instance, hybrid PD-PD/Iterative learning Algorithm (ILA) tuned by Genetic Algorithm for single-link flexible manipulator (SLFM) is presented in [6], a multi-objective optimization using Differential Evolution (MODE) for PID controller of SLFM studied in [7], an improved Bacterial Foraging Algorithms (BFA) to tune the PID controller of SLFM is proposed in [8], Bee Algorithm is used to optimize the hierarchical PID parameter of SLFM in [9] and particle swarm optimization (PSO) algorithm to tune parameter of one PID controller of SLFM in [10].

In this papera decentralized intelligent PID controller is developed for double link flexible robotic manipulator (DLFRM) based on the NARX model plant as elaborated in [11]. The global search of PSO are utilized to optimize all the PID controllers' gains.

II. SYSTEM CONTROLLER

The control scheme is shown in Fig.2. The PID$_{i1}$ controller is developed for hub angle motion while PID$_{i2}$ controller is applied for flexible body motion. The two loops of each link ($i=1,2$) are combined together to give control inputs that work simultaneously for the double link flexible robotic manipulator system.

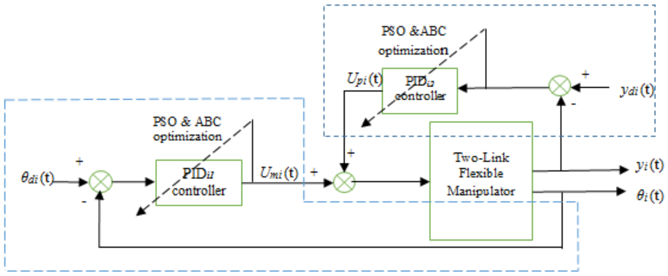


Figure 1: Hybrid controller structure of double link flexible robotic manipulator.

Controller Design

For the hub angle motion, θ_{di} , and $\theta_i(t)$ represents reference hub angle and actual hub angle of the system respectively. By reffering to Fig. 2, the close loop signal of U_{mi} can be written as;

$$U_{mi}(t)=A_{mi}\left[\left(K_{Pi}\left[\theta_{id}(t)-\theta_i(t)\right]+K_{Ii}\int\theta_i dt+K_{Di}\frac{d\theta_i}{dt}\right)\right] \quad (1)$$

where U_{mi} is PID control input, A_{mi}, K_{Pi}, K_{Ii} *and* K_{Di} are motor gain, proportional, integral and derivative gain respectively. The error function of the system defined as in Eq. (2);

$$e_i(t)=\left[\theta_{di}(t)-G_m\theta_i(t)\right] \quad (2)$$

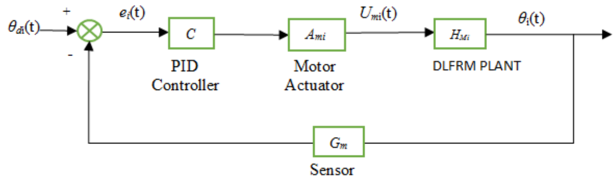


Figure 2: Block diagram of rigid body motion

For the flexible motion, the control input is given by;

$$U_{pi}(t)=A_{pi}\left[\left(K_{Pi}+K_{Ii}\int dt+K_{Di}(d/dt)\right)*e_{vi}(t)\right]i=1,2 \quad (3)$$

where U_{pi} is PID control input, A_{pi}, K_{Pi}, K_{Ii} *and* K_{Di} are piezoelectric gain, proportional, integral and derivative gain respectively. The reference endpoint displacement $y_{di}(t)$ is set to zero. Thus e_i is defined as;

$$e_{vi}(t)=\left[0-G_A y_i(t)\right] \quad (4)$$

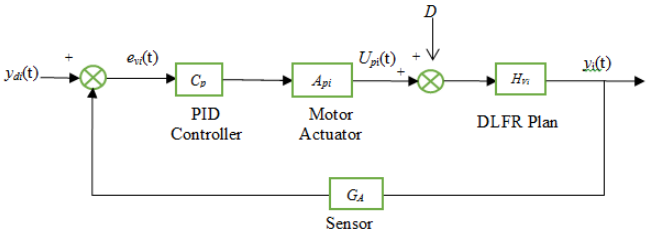


Figure 3: Block diagram of flexible body motion

All the parameters of K_{Pi}, K_{Ii} and K_{Di} were tuned using global optimization method so that U_{Mi} and U_{pi} provide acceptable performance of DLFRM. The performance of the PID controller of hub angle was determined by transient performance such as hub angle settling time, overshoot, rise time and steady state error. Meanwhile, the performance of the PID controller of vibration suppression was determined by means of the MSE value. The lower value of those parameters indicates the good control outcome.

III. OPTIMIZATION METHOD

The proposed control structure using PSO is adopted to tune the PID controllers' parameters. The objective functions of optimization are formulated based on the MSE of the hub angle error and end point vibration suppression.

PSO is initialized with a group of random particles and then searches for optimum by updating generations. The particle updates its velocity and positions with following Eq. (5) and (6).

$$V_{id}^{k+1}=W\ *V_{id}^{k}+C1*R1*\left(Y_{id}^{k}-X_{id}^{k}\right)+C2*R2*\left(Y_{id}^{k}-X_{id}^{k}\right) \quad (5)$$

$$X_{id}^{k+1} = Y_{id}^{k} - X_{id}^{k} \qquad (6)$$

where V= particle velocity, X= particle position, W= Inertia weight, R_1, R_2 = random number and C_1, C_2 = learning factors. In this research, $C_1 = C_2$ is chosen as 2 and R_1, R_2 is between 0 and 1. The starting and end point of inertia weight, W set as 0.9 and 0.25.

IV. EXPERIMENTAL SET UP

The DLFRM was studied by moving the manipulator to 0.3 rad and 0.5 rad respectively. The angle was recorded by the encoder sensor at each hub. As the link moved, the vibration would occur at the end of the links. The accelerometers were employed to record the behaviour of the vibration at each of end-point links. The analog signals of the accelerometers were passed to the signal conditioning device (SCC-ACC01) to regulate the signal into voltage. The PZT actuators (P-876.A15) were mounted on the surface of the DLFRM links for end-point vibration suppression. The controller outputs from the NI PCI-6259 analog/digital converter determined from PID were supplied to actuator through amplifier E-835 in order to actively suppress the end-point vibration. The time sample was maintained at 0.01 s.

The trajectory tracking control and vibration suppression of DLFRM using PID control structure in experimental mode are shown in Fig. 4 and 5 respectively. The best PID controllers from simulation were verified in real-time computer control system. The performances of PID control structure for hub angle and end-point acceleration of DLFRM were monitored on-line via computer screen and the data was further analyzed using MATLAB software.

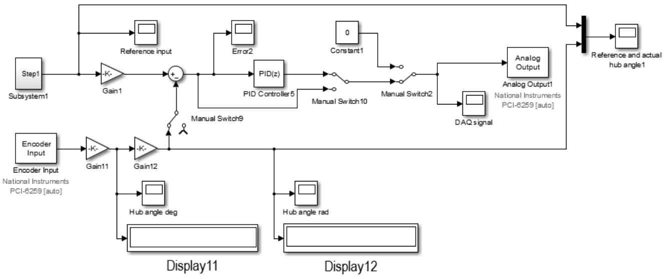


Figure 4. Simulink model for hub angle control of DLFRM using PID controller

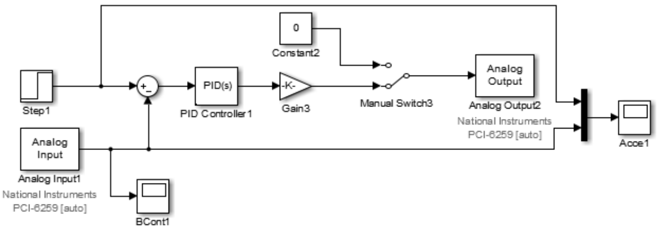


Figure 5. Simulink model for end-point acceleration control of DLFRMM using PID controller.

V. RESULTS AND DISCUSSION

A. *Simulation Results*

The hub angles were controlled by the collocated PID controller individually. 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 shows the PID parameters along with the the rise time, steady state error and overshoot value of the PID-PSO controller for both link.

Table I: Parameters and Performance of hub input tracking for DLFRM system

		Parameters			Rise Time (s)	Sett. Time (s)	Over shoot (%)	SSE
		K_P	K_I	K_D				
PSO	L1	3.65	57.9	3.46	0.058	1.16	0.89	0.003
	L 2	2.19	88.2	0.79	0.043	0.59	1.64	0.002

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

Table II: Parameters and Performance of vibration suppression for DLFRM system.

		Parameters			MSE	Attenuation of amplitude at natural frequency (dB)		
		K_P	K_I	K_D		1st	2nd	3rd
PSO	L1	2.07	498.1	2.04	3.948e-08	45.77	27	12
	L2	8.06	817.9	1.03	4.315e-08	43.3	44.4	32.6

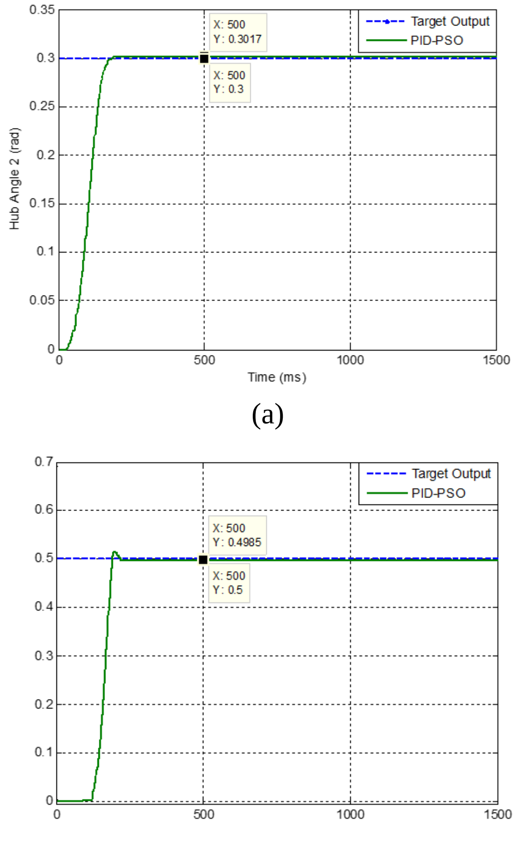
The details of this simulation results can be obtained former paper [12].

The simulation results obtained here were the best simulated controllers of PSO-PID for the DLFRM system. Therefore, the optimal values of PID controller parameters that were achieved via off-line tuning using PSO were tested experimentally on the DLFRM experimental test rig, and their performances was evaluated.

B. *Experimental Results*

i. *Hub angle control*

The controller was applied in a real-time computer control system using MATLAB/Simulink with a sampling rate of 0.01 s. Figure 6 showed the experimental hub angle responses of PID controller using the controller parameters obtained in simulation work. It can be noted from figures that the proposed controllers achieved an acceptable hub angle response.



(a)

(b)

Figure 6: Experiment validation of tracking trajectory using PSO (a) Input tracking for Hub 1 (b) Input tracking for Hub 2

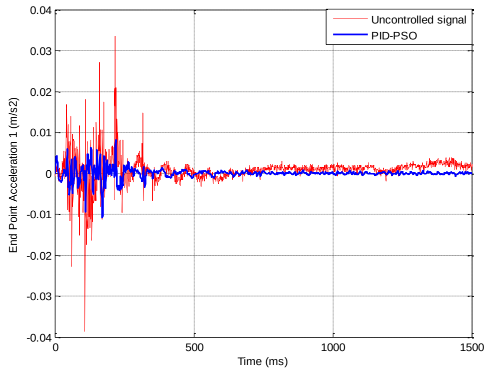
The numerical values are tabulated in Table III. From the table, the results showed that the response with the PSO based control has acceptable rise time, settling time and steady state error. Besides, the controllers provide zero overshoot for link 1. However, for link 2 there is slight overshoot. Since both links are connected, thus link 2 would receive additional force from link 1. Consequently, it can be concluded that PID controller parameters tuned by PSO significantly track the desired angle of DLFRM system. Based on the overall results, it is proven that the metaheuristic optimization technique such as PSO is effective in finding the PID controller parameters for trajectory tracking of the DLFRM.

Table III: Performance of PID-PSO controllers for hub angle of DLFRM system.

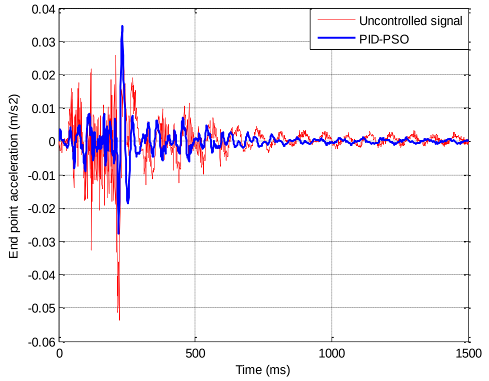
	Rise Time (s), t_r	**Settling Time (s), t_s**	**Overshoot (%), M_p**	**SSE, E_{ss}**
Link 1	0.8468	1.6692	0	0.0017
Link 2	0.4958	1.8691	3.3516	0.0015

ii. Flexible motion control

Figure 7 presented the experimental vibration suppression responses of PID controllers using the parameters obtained from offline PSO. The results are presented in time and frequency domain. It can be noted from Figures 7 (a) and (b) that the controller used in this work achieved acceptable vibration suppression for both link 1 and 2. The results are supported by the frequency domain graphs presented in Figures 8 (a) and (b) for each link respectively.

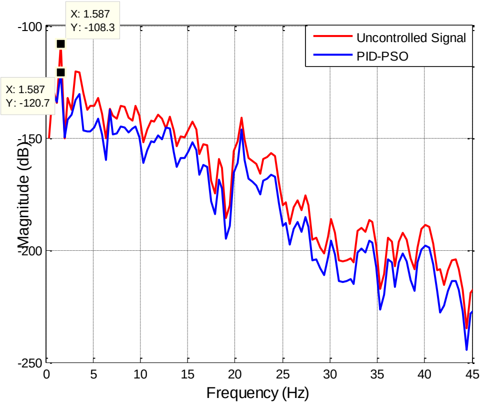


(a) Link 1

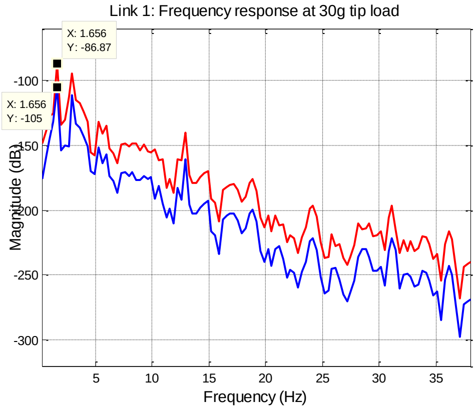


(b) Link 2

Figure 7: Experiment validation of end-point vibration suppression using PSO in Time Domain.



(a) Link 1



(b) Link 2

Figure 8: Experiment validation of end-point vibration suppression using PSO in Frequency Domain.

The numerical values of the results are tabulated in Table IV. It is noted from the table that the response with the PSO based control has acceptable attenuation value. Consequently, it can be concluded that PID controller parameters tuned by PSO were able to suppress significantly the vibration of DLFRM system. Based on the overall results, it is proven that the metaheuristic optimization technique such as PSO is effective in finding the PID controller parameters for end-point acceleration of the DLFRM.

Table IV: Parameters and Performance of vibration suppression for DLFRM system.

	Parameters			MSE	Attenuation of amplitude at natural frequency (dB)		
	K_P	K_I	K_D		1st	2nd	3rd
Link 1	2.07	498.1	2.04	1.19×10^{-7}	12.40	9.70	9.40
Link 2	8.06	817.9	1.03	2.05×10^{-7}	18.13	16.61	16.70

(a)

CONCLUSION

In this work, the decentralized intelligent PID controllers have been developed for DLFRM. PSO were applied to optimize and tune the controller parameters offline. For hub angle error the performance was determined by transient performance such as hub angle settling time, overshoot, rise time and steady state error. Meanwhile, the performance of the PID controller of vibration suppression was determined by means of the MSE value. Simulation study was conducted using MATLAB/Simulink to tune the PID controller gains, K_P, K_I and K_D offline. The simulation studies showed that the PID tuning through PSO had provided good performance. Then, the best tuned parameters achieved from simulation for DLFRM system was tested experimentally using DLFRM test rig. The experimental studies showed that PID tuned by PSO offer good transient response.

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