Intelligent Evolutionary Controller for Flexible Robotic Arm

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Abstract
Robotic is one of the key technologies towards Industrial Revolution 4.0. Robotic system, especially robotic arm have received tremendous demand in various fields especially manufacturing industry. Robotic arm is highly needed to enhance production, improve output, reduce human error and the most importantly, earn more profit with fast return on investment. The current industrial robotic arm, not only they are very expensive and required specialist for maintenance, they are also very heavy and difficult to manoeuvre. These facts are the reason why robotic solution are still unaffordable in most small and medium manufacturing industries in developing countries. Despite all the drawbacks, there is still a pressing need to employ robotics solution with the inherent problems of worker-related issues and output quality. Today, work requires a nimble and versatile robot and yet remain reliable. Operating robots should be simpler, where the learning curve is less steep. The user interface should be friendly and intuitive. Recently, there is a growing interest in employing lightweight, stronger and more flexible robotic arm in various fields. However, lightweight robot arm can be more easily influenced by unwanted vibrations, which may lead to problems including fatigue, instability and performance reduction. These problems may eventually cause damage to the highly stressed structures. This research focused on the development of the intelligent evolutionary controller algorithms for controlling flexible robotic arm manipulator. The controller algorithm has been formulated for trajectory planning control and vibration cancelation utilizing intelligent evolutionary algorithms such as Particle Swarm Algorithm and Artificial Bees Colony. The developed evolutionary algorithms have been implemented and experimentally verified using robotic arm manipulator experimental rig. The performances of these intelligent evolutionary controllers were found to be far better than the conventional method in term of input tracking, trajectory control and vibration cancelation.

1. Introduction

The research on flexible link manipulator (FLM) is reported as early as in 1970's as an alternative to solve problem portray in rigid manipulator. The former studies were initially focused on the dynamic modeling of flexible link such as lumped parameters [1], assumed mode [2]-[3] and finite elements [4]. Apart from that, researchers also investigate the dynamic modeling through system identification [5].

There are another group of researchers investigating and developing dynamic model with both flexible link and joint [6]-[7]. Later, some researcher even explores in difficult mathematical modeling using PDE [8]. Most of the researches described the dynamics of either single link or two link flexible manipulators. The target is to get the modeling as close as possible to the actual plant so that the controller develops for the system will be significant.

Meanwhile, the research on control development of flexible link manipulator (FLM) started in early 80's. There are four main control areas of FLM that is end-effector position regulation, rest to rest end-effector motion in fixed time, trajectory tracking in the joint space and trajectory tracking in the operational space. A review paper written by Benosman and Le Vey [9] revealed that, the study of FLM closed loop arm is quiet shallow. Besides, most of the control development of multi-link FLM was based on open loop structure. However, to date, there are numerous researches published on these areas which cover some of the limitation addressed in previous review papers. The intensive literature on FLM can be found in the latest reviewed paper in [10] and [11]. Though there are many acceptable results accomplished, but there are still problems to be solved due to newer applications and latest technological advancement.

In recent years, the field of robotics and automation has advanced significantly driven by industrial requirements for quicker response times and lower power consumption. These demands have led the changes in robot arm design. Most of the new designs use lightweight materials and the physical configurations of a robot have been modified such that the links are longer and thinner. Flexible manipulator structure is a favorable option in current industries as it is recognized to be very efficient. In opposite to the rigid structure, it offers cost reduction, lower power consumption, improved dexterity, better maneuverability, better transportability, safer operation, light weight and lower environmental impact. However, the system produces undesirable vibration from the flexible structure. The shortcoming become severe when multi-link is involved though it provides a higher degree of freedom. Thus, the drawback received substantial attention in order to cater recent industries demand in various applications. On-going researches focused on improving the control methods in order to fulfill all the conflicting requirements.

Among available wide range controllers, PID controller is still the most widely used in the industrial environment for MIMO systems because they are often 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. In this study dimension, Alam, et al. applied hybrid PD-PD/ILA tune by multi-objective Genetic Algorithm optimization for SLFM [12]. Tijani, performed a multi-objective optimization using Differential Evolution (MODE) for PID controller of SLFM [13]. Another researcher has proposed an improved Bacterial Foraging Algorithms (BFA) to tune the PID controller of SLFM [14]. Bee Algorithm have been successful to optimize the hierarchical PID parameter of SLFM in [15]. Finally, PSO is used to tune one of PID parameters of the Hybrid PID-PID controller of SLFM [16]. The literatures reveal that the application of EA is limited to SLFM. However, the survey confirms that different type of EA can be used effectively in optimizing the PID controller of FLM system in various control strategy.

In this paper, a hybrid PID-PID controller is developed for DLFRM. The global search PSO and ABC are utilized to optimize all the PID controllers' gains. The dynamic model of the system is developed through system identification using Neural Network. NARX model structure based on multi-layer perceptron is employed to obtain the non-parametric modeling in comparison to Elman neural networks [17]. The control structure of PID controllers optimize by PSO and ABC are proposed for position tracking and end point vibration suppression. Performances of the proposed controllers are implemented through simulation in MATLAB/Simulink environment.

2. Flexible Robotic Arm

A planar double-link flexible robotic manipulator is developed and fabricated to perform the angular movement of manipulator, thus replicate the vibration at the end of each link.

Double-link flexible robotic manipulator test rig is shown in Figure 1. 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.

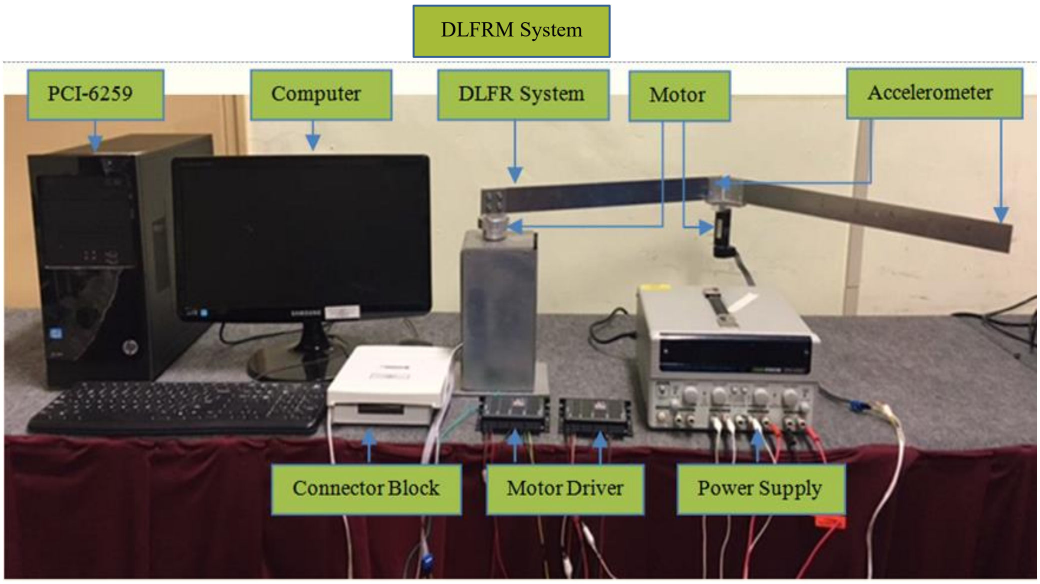


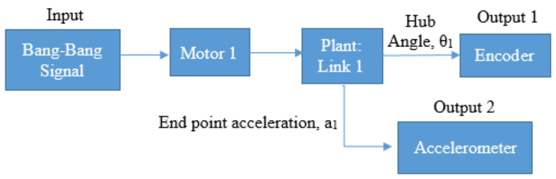
Figure 1. Experimental test-rig of double-link flexible robotic manipulator

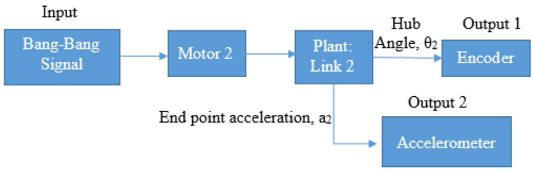
In this study, the National Instrumentation (NI) data acquisition card (PCI-6259) with its input and output connector block (SCC-68) is used as the measurement hardware. PCI-6259 has 16-bit analog outputs and 48 digital input-output. Meanwhile, the SCC-68 connector block has four SCC Module slots, 32 analog input channels, two analog output (AO) channels and 32 bidirectional Digital input output (DIO) channels. It is connected to PCI-6259 through the shielded cable and PCI-6259 is mounted inside the computer on the PCI-bus. The digital input from encoder is obtained through NI DAQ and sent the actuating signal to motor driver. 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.

3. System Identification

System identification (SI) is one of the most fundamental requirements for several scientific and engineering applications. The aim of SI is to build exact or approximate model of a dynamic system based on measured data without knowledge of the actual system physics. After a system model is obtained, it can be utilized to predict the physical system behavior under different operating conditions or to control it. Non-Parametric modeling of double link flexible robotic arm using evolutionary algorithm namely Particle Swarm Algorithm and Artificial Bees Colony are presented in this paper. The aim of the work is to represent the flexible robotic arm behavior utilizing the applied voltage as input and hub-angle as output based on Particle Swarm Algorithm (PSO) and Artificial Bees Colony (ABC).

The double-link flexible robotic manipulator acts as a single-input multiple-output system at each link. The torque is applied at the manipulator hub individually and the results are the movement of hub angle and end-point acceleration. The block diagrams to collect the data were shown in Figure 2 (a)-(b). Bang-bang signals were used to provide required energy to excite the double-link simultaneously. Two encoders and two accelerometers were utilized to accumulate four outputs which represent the hub angle and end-point acceleration of every single link correspondingly.

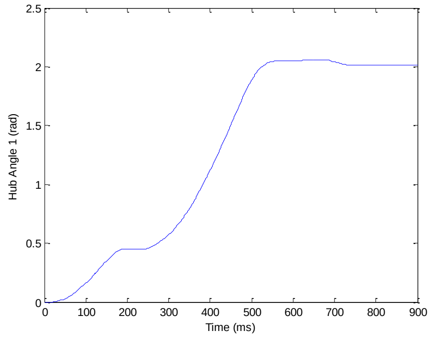




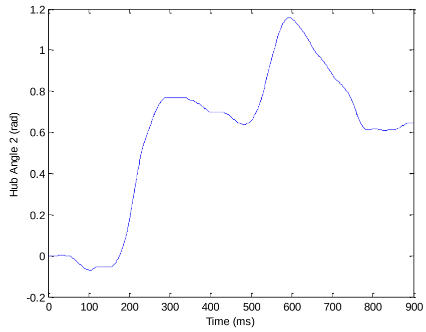
(a) Link 1 (b) Link 2

Figure 2. Block diagram for data collection of DLFRM

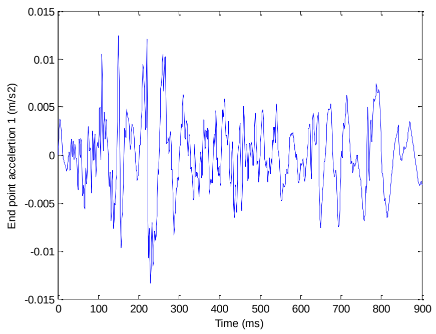
The period of 9 s with sampling time of 0.01 was engaged during the experiment. The time duration is sufficient to move the links to desire angle based on the limitation of the space and links' movement. The experimental hub angles 1 and 2 and end-point accelerations 1 and 2 responses were captured and recorded as in Figure 3.



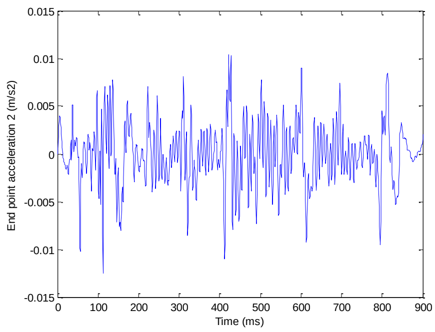
(a) Hub angle 1



(b) Hub angle 2



(c) End-point acceleration 1



(d) End-point acceleration 2

Figure 3. Experimental output response

NARX model is chosen as model structure because of its simplicity. NARX model is rooted from the famous ARX model with the nonlinear simplification. It is established from a customary tool in linear black-box identification.

Model validations were also investigated using mean squared error, one-step ahead prediction and model residual analysis. The performances of the PSO and ABC were compared based on the validation mean- squared error, modeling mean-squared error, correlation tests, and stability. The aim of the identification process in this research is to allow for the design and implementation of controllers based on the identified model for trajectory tracking of the double-link flexible robotic arm.

4. Intelligent Evolutionary Algorithm

Evolutionary algorithm is a generic population-based metaheuristic optimization algorithm. In this research, PID-based controller is tuned by particle swarm optimization (PSO) and artificial bee algorithm (ABC). The developed controller will optimally track the desired hub angle and suppresses the vibration of the DLFRM. These new approaches allow the PID-based parameters to be tuned base on the identified model from a real plant using non-parametric system identification technique, which represents the dynamic characteristic of the system. The performance of PID-based controller tuned by PSO is compared with ABC. The best method is validated experimentally.

Particle Swarm Optimization (PSO) is developed by Kennedy and Eberhart in 1995. It is a population based stochastic optimization technique. PSO is initialized with a group of random particles or solutions and then searches for optimum by updating generations. In iteration, each particle is updated by following two "best" values. The first one is called pbest which is the best solution it has achieved so far. Another "best" value is tracked by the particle swarm optimizer and compared with pbest. This best value is a global best and called gbest. After finding the two best values, the particle updates its velocity and positions with following Eq. (1) and (2).

$$V_{id}^{k+1} = W \times V_{id}^{k} + C_1 \times R_1 \times \left(Y_{id}^{k} - X_{id}^{k}\right) + C_2 \times R_2 \times \left(Y_{id}^{k} - X_{id}^{k}\right) \quad (1)$$

$$X_{id}^{k+1} = Y_{id}^{k} - X_{id}^{k} \quad (2)$$

Where V= particle velocity, X= particle position, W= Inertia weight, R1, R2 = random number and C1, C2 = learning factors. The number of particle *i* is symbolized as the i-th particle in the d-dimensional search space and k is number of iteration. Both are chosen heuristically. The diagram of PSO algorithm is shown in Figure 4. It was found that, the performance of optimization was significantly affected by the number of particles and the number of iteration. The cognitive part C1 encourage the particles to move toward their own best position so far and the social component of C2 represents the collaborative effect of the particles in finding the global optimum solution.

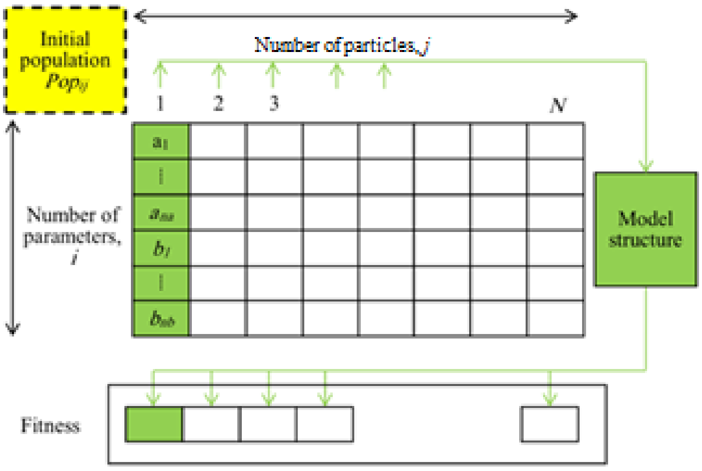


Figure 4. Diagrammatic representation of the initial population generation

Artificial Bee Colony (ABC) is inspired by intelligent behavior of honey bees developed by Dervis Karabogain in 2005. Three types of bees: employed bees, onlooker bees, and scout bees. ABC system combines local search methods, carried out by employed and onlooker bees, with global search methods, managed by onlookers and scouts, attempting to balance exploration and exploitation process. In the ABC algorithm, the first half of the swarm consists of employed bees, and the second half constitutes the onlooker bees. It uses common control parameters such as colony size and maximum cycle number. The number of employed bees or the onlooker bees is equal to the number of solutions in the swarm. The ABC generates a randomly distributed initial population of SN solutions (food sources), where SN denotes the swarm size. Each employed bee generates a new candidate solution in the neighbourhood of its present position. The fitness is calculated by the following Eq. (3) after that a greedy selection is applied between xm and vm.

$$fit_m(x_m) = \frac{1}{1+f_m(x_m)},\ f_m(x_m) > 0, \quad fit_m(x_m) = 1 + |f_m(x_m)|,\ f_m(x_m) < 0 \quad (3)$$

where, fm (xm) is the objective function value of xm. The quantity of a food source is evaluated by its profitability and the profitability of all food sources. Pm is determined by the Eq. (4);

$$P_m = \frac{fit_m(x_m)}{\sum_{m=1}^{SN} fit_m(x_m)} \quad (4)$$

where, fitm (xm) is the fitness of xm. After all, employed bees have completed the search processes, they share the information of their food sources with the onlooker bees through waggle dances. An onlooker bee evaluates the nectar information taken from all employed bees and chooses a food source with a probability related to its nectar amount. Onlooker bees search the neighborhoods of food source. If a position cannot be improved over a predefined number (called limit) of cycles, then the food source is abandoned. The scout bee discovers a new food source to replace the abandon food source. The procedure of ABC algorithm is illustrated in the diagram in Figure 5.

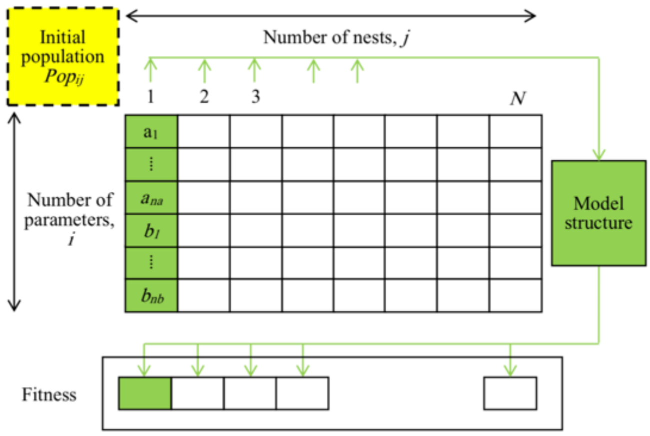


Figure 5. Diagrammatic representation of generation the initial population

5. Controller Development

For the hub angle motion, and represents reference hub angle and actual hub angle of the system respectively. By referring to Figure 6, the close loop signal of U_{mi} can be written as;

$$U_{mi}(t) = A_{mi}\left[\left(K_{Pi}\left[\theta_{id}(t)-\theta_i(t)\right]+K_{Ii}\int\theta_i dt + K_{Di}\frac{d\theta_i}{dt}\right)\right] \quad (5)$$

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. (6);

$$e_i(t) = \left[\theta_{di}(t) - G_m\theta_i(t)\right] \quad (6)$$

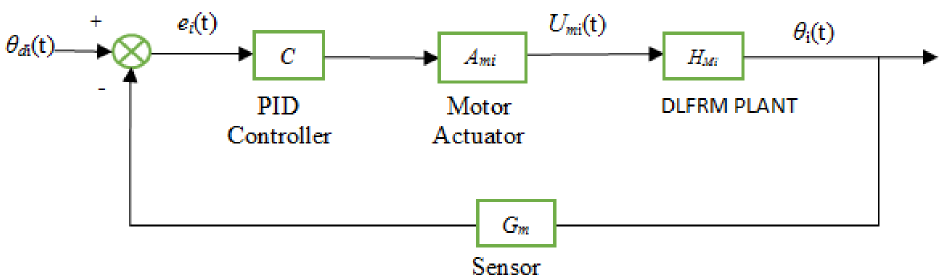


Figure 6. Block diagram of rigid body motion

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

$$U_{pi}(t) = A_{pi}\left[\left(K_{Pi} + K_{Ii}\int dt + K_{Di}(d/dt)\right) * e_{vi}(t)\right] i = 1,2 \quad (7)$$

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_{vi} is defined as;

$$e_{vi}(t)=[0-G_A y_i(t)] \quad (8)$$

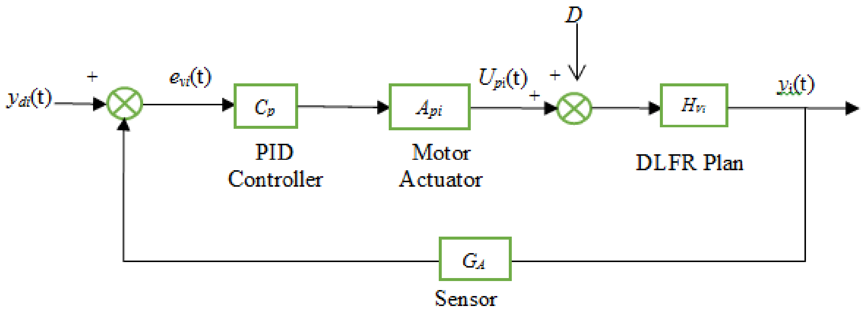


Figure 7. Block diagram of flexible body motion

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

Based on the proposed controller design, the simulation study was conducted offline to investigate the performance of PSO and ABC algorithm to tune the PID controllers' parameters. The corresponding controller parameters which are K_P, K_I and K_D were fed to the closed-loop PID controller in MATLAB/Simulink. The error for each sample was calculated and the MSE is evaluated. MSE was set as fitness value in the algorithm. The objective is to adjust the PID controller parameters in order to minimize the fitness value. The schematic diagram of the closed loop system utilizing PID controller with identified hub angle models and end-point vibration models are shown in Figure 8 and 9 respectively.

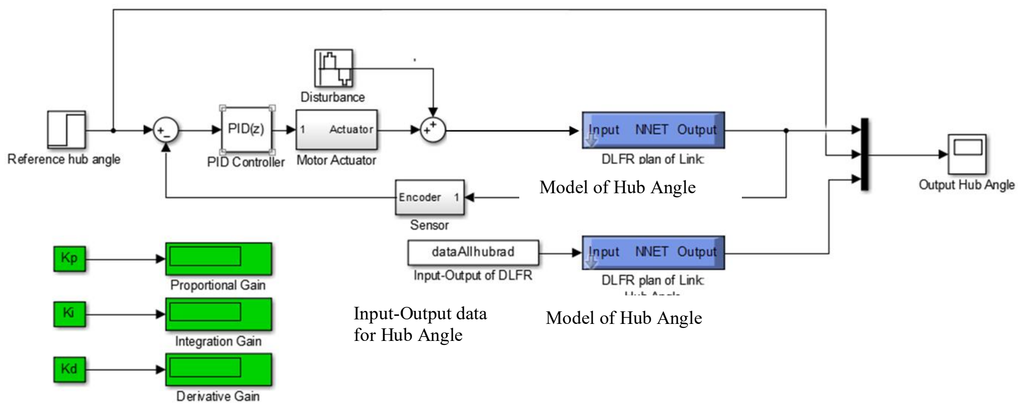


Figure 8. Simulink model for hub angle tuning by PSO and ABC

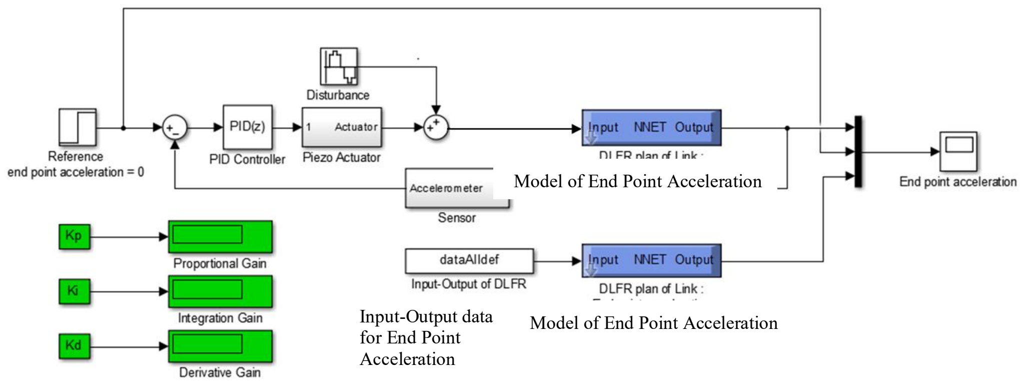


Figure 9. Simulink model for end-point acceleration tuning by PSO and ABC

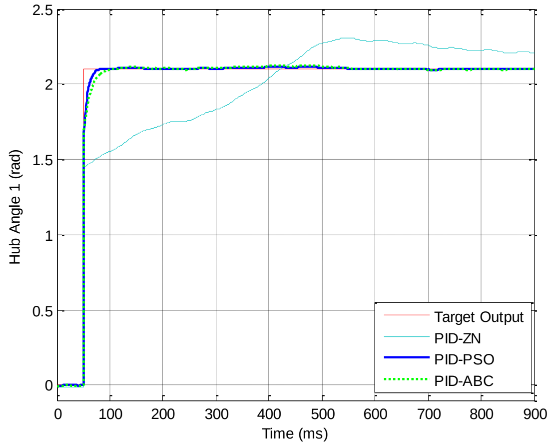
Step input was used as input reference. The performance of PID controllers for hub angle models were observed in terms of *tr*, *ts*, *Mp* and *Ess*. Meanwhile, the performances of vibration suppression were observed in terms of the attenuation of the first three mode of vibration. The comparative assessments of the performance of the hub angle and end-point vibration reduction are conducted to find the best controller. The best PID controller will be tested experimentally using DLFRM test rig.

6. Results and Discussion

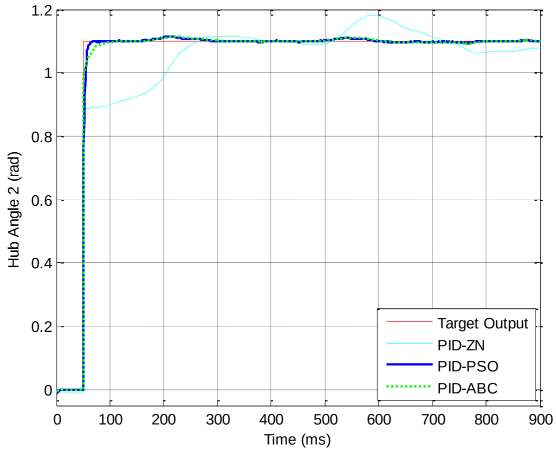
The control parameters of K_P, K_I and K_D obtained through simulation automatically fed in PID controller' parameters in MATLAB/Simulink environment. The DLFRM was moved from the actual state to a desired angle of 2.1 rad and 1.1 rad respectively.

The results for closed-loop hub angles 1 and 2 response of both controllers are shown in Figure 10 (a) and (b). The details of these results are presented in Tables 1. It is noted that PID tuning through ABC and PSO have provided better performance than those obtained by the ZN method. It can be observed from Figure 10 (a) that the responses from ABC and PSO tuning methods nearly coincided with each other. Numerical results presented in Table 1 shows that the rise time, steady state error and overshoot value of the PID-PSO controller are recorded at the lower value compared to ABC-based control. Though ABC-based control provides slightly lower settling time, the overshoot value is almost double the overshoot value of PSO-based control.

The same pattern was observed for hub angle 2 responses shown in Figure 10 (b). ABC-based controls and PSO-based control provided better performance than those obtained by the ZN method. The tracking trajectory of ABC and PSO tuning methods almost overlapped with each other. Overall, the results showed PSO-based controller supersede ABC-based controller in all aspect of system response. From these results, it can be concluded that PID tuned by evolutionary algorithms such as ABC and PSO have significantly improved the trajectory tracking of both hub angle of the DLFRM system. The PID-PSO controller was taken as the best controller of hub angle 1 because it gave better performance with lower steady state error and acceptable overshoot and settling time. For hub angle 2, the performance of PID-PSO controller showed better outcome.



(a)



(b)

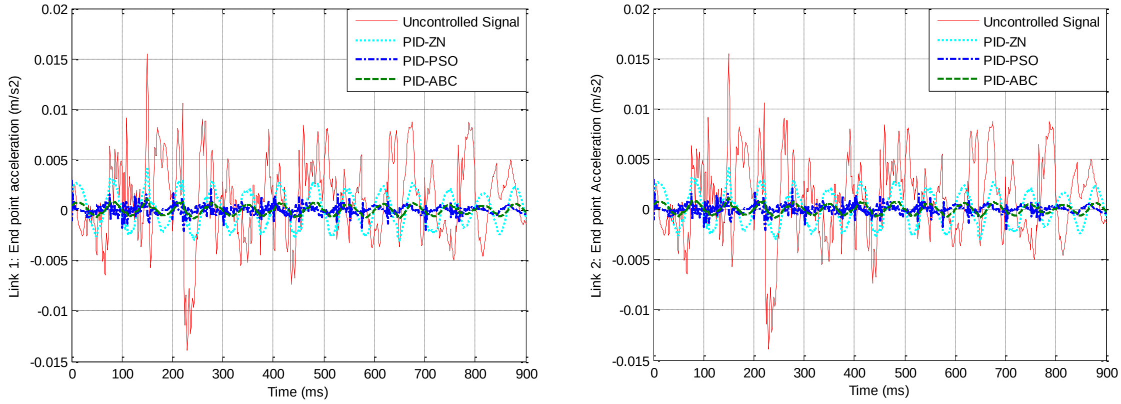
Figure 10. (a) Input tracking for Hub 1 (b) Input tracking for Hub 2

Table 1. Parameters and Performance of hub input tracking for DLFRM system

		Parameters			Rise Time (s)	Settling Time (s)	Overshoot (%)	SSE
		K_P	K_I	K_D				
ABC	L 1	6.54	20.5	49.43	0.076	1.08	1.94	0.007
	L 2	5.48	28.3	13.72	0.099	5.64	3.19	0.002
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
ZN	L1	2.09	0.54	2.01	2.97	7.15	4.69	0.681
	L2	4.15	1.3	3.32	1.46	5.45	5.45	0.284

The desired end-point vibration is set to zero. The closed-loop results for vibration suppression of links 1 and 2 of both controllers are shown in Figure11 (a) and (b). The vibration attenuations using PSO-based control and ABC-based control in time and frequency domains are tabulated in Tables 2. The results show that PID tuning through ABC and PSO managed to improve the performance of vibration suppression than those obtained by the ZN method. It can be observed from Figure 11 that the responses from ABC and PSO tuning methods have about the same amplitude of vibration. Numerical results presented in Table 3 shows that the MSE value of the PSO-based control is recorded at the lower value in comparison to ABC-based control. This could be further investigated from frequency domain results. PSO-based control provides the highest attenuation value of mode 1, meanwhile ABC-based control gives highest attenuation value of mode 2 and 3. However, the first mode is dominant and contributes substantial effect to the system.

The vibration suppression for link 2 showed the similar pattern of link 1 response. The ABC-based control and PSO-based control provided better performance than those obtained by the ZN method. The vibration suppression response of ABC and PSO tuning methods have about the same amplitude. The MSE value of the PSO-based control is recorded slightly at the lower value in comparison to ABC-based control. From the frequency domain results, PSO-based controls provide a higher attenuation value of mode 1. Meanwhile, ABC-based control gives significant difference attenuation value of mode 2 and 3. However, mode 2 and 3 are considerably much lower magnitude when compared to mode 1, thus they do not have much effect on the system directly.



(a) (b)

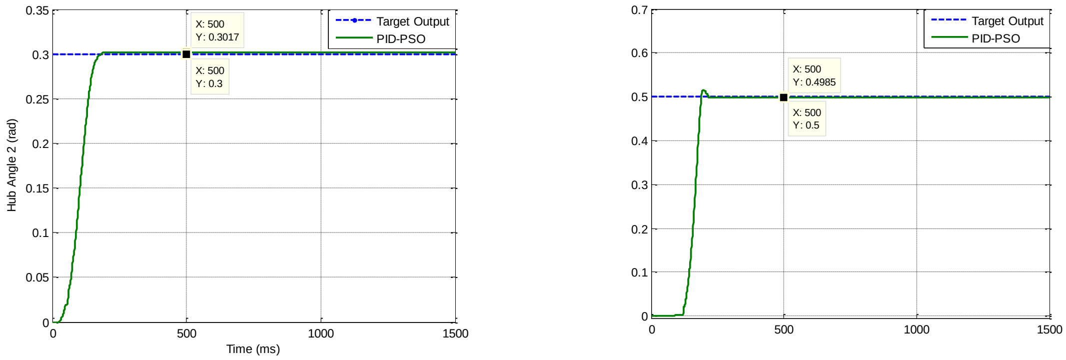
Figure 11. (a) End point vibration suppression of Hub 1(b) End point vibration suppression of Hub 2

Table 2. Parameters and Performance of vibration suppression for DLFR system.

		Parameters			MSE	Attenuation of amplitude at natural frequency (dB)		
		K_P	K_I	K_D		1st	2nd	3rd
ABC	L1	30.03	56.07	88.95	7.919e-07	35.27	67.7	67.6
	L2	50.1	46.96	23.62	8.432e-08	39.8	82.2	83.4
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
ZN	L1	7.2	21.176	0.612	2.822e-06	8.9	41	40.9
	L2	16	55.082	1.281	7.564e-07	11.8	53.3	54.4

Overall, ABC and PSO had shown to be effective for PID controller tuning in vibration control of the DLFRM system. However, those optimization methods are not a universal solution. The execution of each technique depends on the control parameters that need to be appropriately set. For the case on research, PSO manage to suppress the vibration better than ABC based on the attenuation value of mode 1.

The results from the previous section showed that the PSO-based controls were the best simulated controllers 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. The controller was applied in a real-time computer control system using MATLAB/Simulink with a sampling rate of 0.01 s. Figures 12 (a) and (b) 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. The numerical values are tabulated in Table 3. 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. 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.



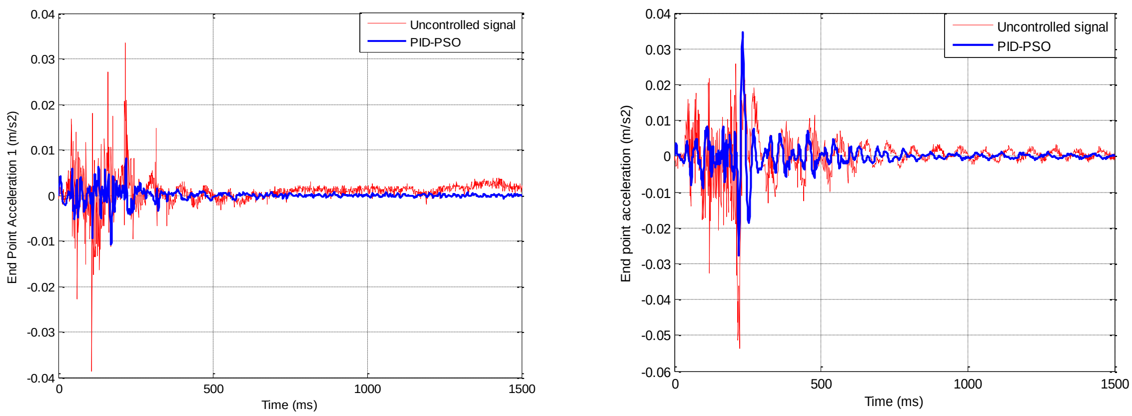
(a) Link 1 (b) Link 2

Figure 12. Experiment validation of hub angle using PSO

Table 3. Performance of PID-PSO controllers for hub angle of DLFRM system.

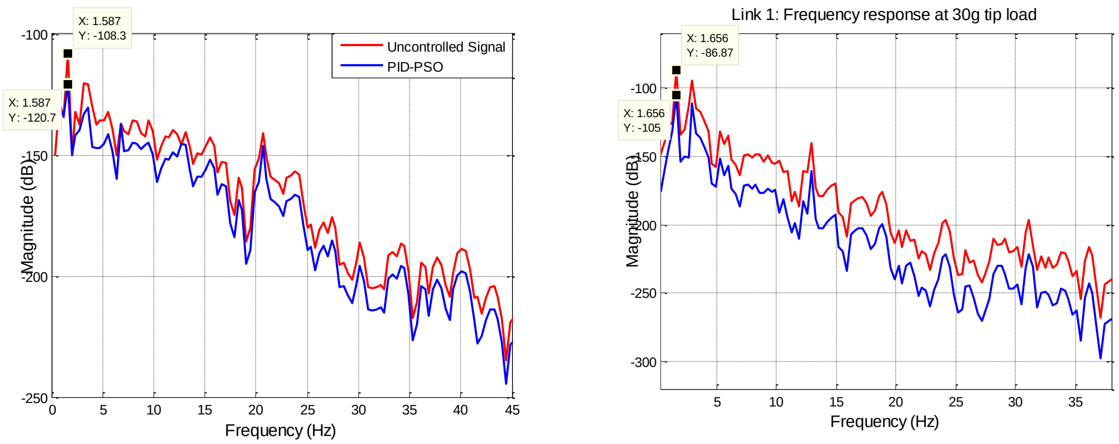
	Rise Time (s), t_r	Settling Time (s), t_s	Overshoot (%), M_p	SSE, E_{ss}
Link 1	0.8468	1.6692	0	0.0017
Link 2	0.4958	1.8691	3.3516	0.0015

Figures 13 (a) and (b) 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 that the controller used in this work achieved acceptable vibration suppression. The results are supported by the frequency domain graphs presented in Figures 14 (a) and (b).



(a) Link 1 (b) Link 2

Figure 13. Experiment validation of end-point vibration suppression using PSO (Time Domain)



(a) Link 1 (b) Link 2

Figure14. Experiment validation of end-point vibration suppression using PSO (Frequency Domain)

The numerical values of the results are tabulated in Table 5. 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 4. Performance of PID-PSO controllers for vibration suppression of DLFRM system

Controller	**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

7. Conclusion

In this work, the intelligent evolutionary PID controllers have been developed for DLFRM. PSO and ABC 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 as compared to ABC. 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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