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Modelling of Flexible Manipulator System via Ant Colony Optimization for Endpoint Acceleration

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Abstract. The application of flexible manipulators has increased in recent years especially in the fourth industrial revolution. It plays a significant role in a diverse range of fields, such as construction automation, environmental applications, space engineering and many more. Due to the lightweight, lower inertia and high flexibility of flexible manipulators, undesired vibration may occur and affect the precision of operation. Therefore, development of an accurate model of the flexible manipulator was presented prior to establishing active vibration control to suppress the vibration and increase efficiency of the system. In this study, flexible manipulator system was modelled using the input and output experimental data of the endpoint acceleration. The model was developed by utilizing intelligence algorithm via ant colony optimization (ACO), commonly known as a population-based trail-following behaviour of real ants based on autoregressive with exogenous (ARX) model structure. The performance of the algorithm was validated based on three robustness methods known as lowest mean square error (MSE), correlation test within 95% confidence level and pole zero stability. The simulation results indicated that ACO accomplished superior performance by achieving lowest MSE of 2.5171×10^{-7} for endpoint acceleration. In addition, ACO portrayed correlation tests within 95% confidence level and great pole-zero stability.

1. Introduction

The remarkable benefits of a rigid robotic arm have proven its worth in the industry since decades ago. However, the safety of operators in the working environment is threatened due to its heavy and bulky size of the rigid machine. Based on newspaper reading, in the year 2015, a contractor was struck in the chest by the machine and pressed against a metal plate during the installation which resulted with fatality [1]. Furthermore, from The Sun newspaper in 2018, a factory worker was impaled with ten steel spikes from a falling malfunctioned robotic arm. Fortunately, he survived the horrific incident as one of the rods missed an artery by just 0.1mm [2].

Hence, to prevent these accidents, flexible manipulators are applied in most industries as it is lightweight, lower in cost, inertia and power consumption compared with rigid ones. It plays a significant role in a diverse range of fields, such as construction automation, environmental applications, space engineering and many more. However, because of its flexible structure system, it is dealing with high amount of vibration that affects the efficiency and performance as vibration will cause fatigue to the machine [3].



Thus, to resolve this problem, efforts and alternatives are introduced by researchers as it is an alarming issue in the industry. The application of active vibration control method is widely applied to minimize exertion of the vibration in recent years compared to passive vibration control as feedbacks of AVC can be obtained. AVC uses sensors and actuators to measure vibration and to introduce an equal and opposite forces to diminish the undesired vibration. Before designing the controller, development of an accurate dynamic modelling is crucial to ensure the effectiveness of the control [4,5]. Therefore, this study presents the development of flexible manipulator model using evolutionary swarm algorithm via ant colony optimization for end point acceleration.

2. Ant colony optimization

Ant colony optimization (ACO) is a metaheuristic algorithm where the search space is explored comprehensively by population of solutions in their own process rather than using a fixed answer from classical methods. The most fascinating aspect of the ants' behavior is its capability to distinguish routes between nest and food source by traversing pheromone traces. The ants then select a direction to follow with a potential pheromone level-based decision [6,7].

The initial population and fitness values are randomly created. Every solution obtained was therefore inclusive of n variables. The number of solutions that were kept in the archive are known as k . The j th solution with Sol symbol is represented as Equation (1). Beginning from initial variable, each ant choose a point in the domain, $x_i \in [X_{min}^i, X_{max}^i]$ of each variable. Then, a path that corresponds to a solution vector X is completed after n choices of ant. Equation (2) represents one route solution and Equation (3) denotes the equation share's value. The fitness function or known as objective function is presented as in Equation (4). Meanwhile, the fitness values signified the objective function in this study which was known as MSE is represented in Equation (5).

$$Sol_j = (S_j^1, S_j^2, \dots, S_j^i, \dots, S_j^n) \quad (1)$$

$$Sol_j = X_{min}^n + k \times h_k \quad (2)$$

$$h_i = \frac{X_{max}^i - X_{min}^i}{k} \quad (3)$$

$$f_i = F(Sol_j) \quad (4)$$

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (5)$$

The parameter of P_j that defines the probability of choosing any of the variables based on their fitness can be calculated using Equation (6).

$$P_j = \frac{w_j}{\sum_m w_m^\alpha} \quad (6)$$

where α is applied to increase or decrease probabilities and w_j is the weighting coefficients to each of the variables, as seen in Equation (7). It is worth mentioning that the larger the average distance from others, the bigger the scope of the solution will be examined.

$$w_j = \frac{1}{qk\sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{j-1}{qk}\right)^2\right) \quad (7)$$

3. Results and Discussions

System identification (SI) of flexible manipulator was presented via ARX structure that will replace the actual system with mathematical expression. Ant colony optimization (ACO) algorithm was applied to determine the best ARX model parameters for end point acceleration. The selection of the best ARX model were based on verification of several robustness methods which were lowest mean squared error in testing data (MSET), high stability and correlation tests within 95% confidence level. A total number of 45,000 data points were collected during experiment for endpoint acceleration where 20,000 data out of 45,000 were used as training data while the remaining 25,000 data were utilized in data testing. On the other hand, the input-output data collected for hub angle were 6,400 data points where only 1750 data out of the total were employed in data training and 4,650 were used for data testing.

Due to no specific method of tuning flexible structures, heuristic approach was applied in tuning the parameters of ACO algorithm to acquire the best fit models for endpoint acceleration. To achieve the global optimum model, there were seven parameters of ACO that affect the performance and efficiency of the model. However, only five parameters were required to be tuned appropriately and the other two parameters known as upper and lower boundary, and deviation-distance ratio, ζ were fixed based on literature review. The modelling of endpoint acceleration implemented heuristic method of tuning by varying the intensification factors, q , archive sizes, sample sizes, number of iterations and number of model order. The best parameters to be used in ACO algorithm in obtaining best fit model of endpoint acceleration are tabulated in Table 1.

Table 1. The set of parameters used in ACO algorithm to obtain best fit model of endpoint acceleration.

Parameters	Value
Upper and Lower Boundary	-0.01, 0.01
Deviation-distance ratio, ζ	1.0
Intensification Factor, q	0.00001
Archive Size	20
Sample Size	20
Number of iterations	100
Model Order	2
Number of Parameters	4

The best model seen is model order 2 based on verification of robustness method where its MSET is the lowest among others with the value of 2.5171×10^{-7} . Figures 1 depicts the actual and ACO modelling outputs of endpoint acceleration in time and frequency domains, respectively. The developed model efficiency can be assessed by observing time and frequency domains' response of ACO modelling overlapping with the actual response that was measured experimentally. It is essential for the developed model to overlap to ensure an accurate representation of the actual flexible manipulator structure characteristics. Besides that, Figure 2 shows the normalized error of the output between actual and LS modelling on the distinction between measured and predicted data. The optimized model parameters of ACO can be expressed in the transfer function based on discrete time form in Equation (8).

$$\frac{-0.01173z^{-1} + 0.1758z^{-2} - 0.1415z^{-3} + 0.06039z^{-4}}{1 - 1.876z^{-1} + 1.681z^{-2} - 0.8007z^{-3} + 0.1626z^{-4}} \quad (8)$$

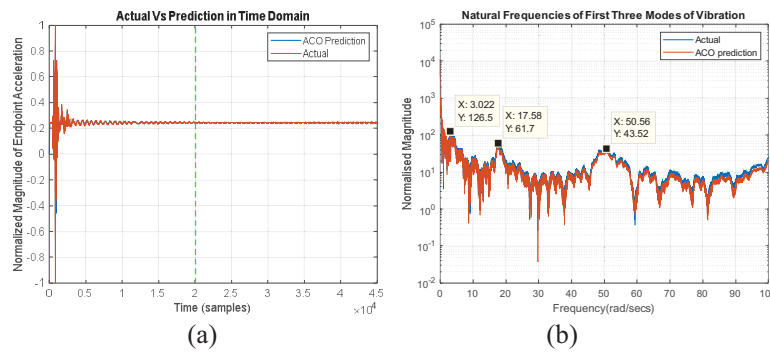


Figure 1. Actual and ACO Modelling Outputs of Endpoint Acceleration. (a) Time Domain. (b) Frequency Domain.

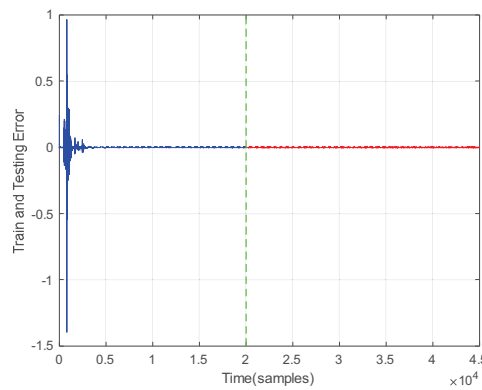


Figure 2. ACO Modelling Normalized Error of the Output of Endpoint Acceleration.

One of the correlation tests in Figure 3 which is auto correlation resulted with biased where it does not pass the percentage of confidence level. When the correlation is low, it shows no relation between the two variables. However, the cross correlation test is within the 95% confidence level which indicates that the degree of similarity between developed model and actual data are alike. This model has good stability since the position of all poles are located inside the circle in the pole-zero stability diagram as illustrated in Figure 4.

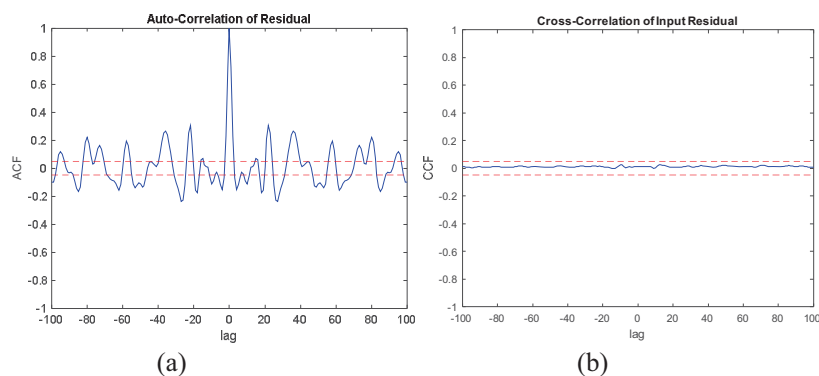


Figure 3. Correlation Tests of Endpoint Acceleration Using ACO Modelling. (a) Auto Correlation (b) Cross Correlation.

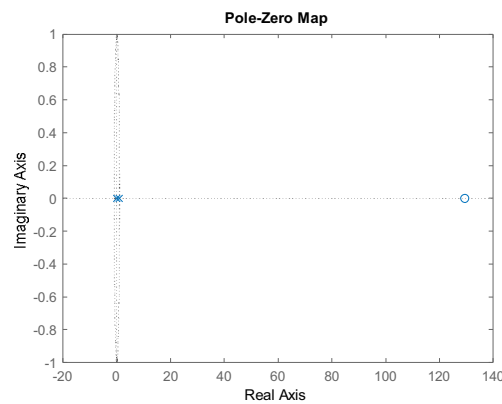


Figure 4. Pole-Zeros Stability Diagram for Endpoint Acceleration Using ACO Modelling.

4. Conclusions

In this study, end point acceleration of flexible manipulator system was modelled properly via ant colony optimization based on input-output vibration data acquired experimentally. A precise structure modelling is necessary prior to developing the PID controller as it represents real characteristics of flexible manipulator. The best model was chosen best on lowest mean squared error, good correlation test which the correlation between input and error within 95 % confidence level and high stability. ACO was seen to achieve lowest mean squared error value with 2.5171×10^{-7} , acceptable correlation tests and great root locus stability. This proves that ACO is capable in producing remarkable result in modelling of end point acceleration as the algorithm meet the validations mentioned. Therefore, the aim of this study which was to develop an accurate model of flexible manipulator system for end point acceleration based on system identification (SI) method via ACO was fulfilled. This model will be used as a platform of controller development for vibration cancellation of the system.

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