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Cascade Proportional Derivative Controller for A Flexible Link Robot Manipulator using the Bees Algorithm

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Abstract

In this study, a flexible robot arm model and the design of its controller are introduced. The robot arm consists of a single flexible link. It is desired to control the circular position of the robot arm and the vibration of the tip point. Cascade proportional derivative controller was used to control the position and reduce the tip vibration. Controller gains were found using The Bees Algorithm. The weighted function of system responses such as settling time, maximum overshoot and steady-state error is used as a performance criterion while searching for the best parameters. In addition, controller gains were obtained with the genetic algorithm to evaluate the working performance of The Bees Algorithm. It has been observed that the Cascade PD controller, whose gains are optimized by The Bees Algorithm, successfully controls the flexible robot arm system and reduces the vibration of the tip point.

Keywords: The Bees Algorithm; Flexible Link; Cascade PID

1. INTRODUCTION

In recent years, the use of flexible structures has been increasing in many applications, especially due to their lightweight and lower cost. Especially in the field of aerospace and robotics, many elements are modeled as flexible since structures are desired to be light and quickly movable [1]. Controlling flexible structures is more complicated than rigid systems. Flexible structures require a higher-level control system due to their oscillations. For this reason, studies on the control of flexible structures have gained importance [2, 3].

Different controllers are used in flexible link control [4, 5]. PID controllers are one of the most used structures in controlling systems, thanks to their efficiency and durability [6-9]. It is very important to set the gains correctly in the design of the PID controller [10, 11]. There are many proposed methods for adjusting the coefficients of the PID controller. These methods can be divided into three parts: analytical, empirical, and optimization. Analytical methods try to determine the gains using root-locus curves. On the other hand, empirical methods such as Ziegler-Nichols or Cohen Coon's, try to obtain the gains by making an approach according to the experimentally obtained results [12-14]. However, these methods may be insufficient in some cases in fine-tuning the gains. Generally, in more complex systems, gains are tried to be obtained by using methods such as genetic algorithms and particle swarm optimization [15-18].

The Bees Algorithm is a swarm-based algorithm that mimics the behavior of bees. There are many studies in which the gains of PID controllers are successfully optimized with The Bees Algorithm [19, 20].

There are various approaches proposed for the control of flexible systems in the literature. Generally, open-loop applications cannot provide the desired level of control for flexible systems [21]. Especially depending on the configuration of the system, a more complex control system is needed due to the change of some parameters such as damping or natural frequency [22]. PID [23, 24], LQR [25, 26], and Fuzzy [27] controllers are used to control the flexible systems.

Since there are two output values in the system modeled in this study, it is not appropriate to control the system with a normal PID controller. A hierarchical PID controller was applied to control the flexible link [24]. In addition, a cascade fuzzy controller is also applied to the system [28]. In this study, it is aimed to control the flexible robot arm manipulator with the cascade PD controller. The coefficients of the controller are optimized with The Bees Algorithm. In addition, the controller gains are also found with the Genetic Algorithm in order to observe the performance of The Bees

Algorithm. Response of the system with two proposed controllers were compared.

2. FLEXIBLE LINK SYSTEM

The study was carried out on the linearized state-space model of an experimental flexible link setup designed by Quanser and using frequently in control studies shown in Figure 1.

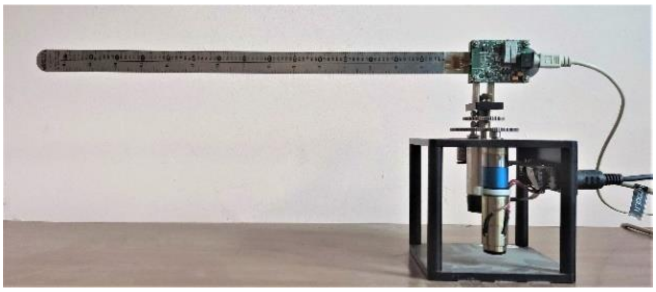

Figure 1. Experimental setup.

A flexible link has been tried to be controlled by using a servo motor. It is assumed that the weight is distributed along its length. An encoder was used to measure the position of the link, and a strain-gage was used to measure the tip vibration of the flexible link. These data are defined as the outputs of the system. The position of the link is defined as "θ" and the tip vibration of the link is defined as "α". The system is shown schematically in Figure 2.

The mathematical model of the system is specified in the user manual of the Quanser flexible link. The dynamic model of the flexible link system can be obtained using the Euler – Lagrange formula [29].

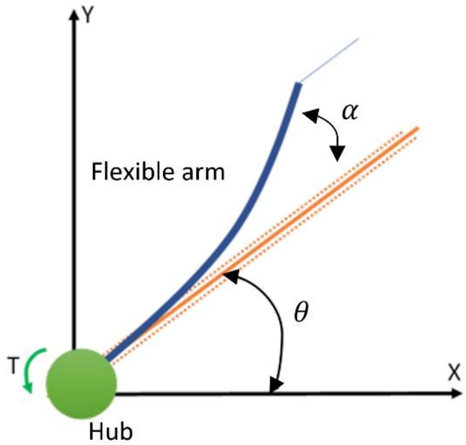

Figure 2. Schematic view of the flexible link

The potential energy and kinetic energy of the system in terms of theta and alpha variables can be defined as shown in Eq. 1 and 2. The stiffness of the link is used in the potential energy equation and the rotational moments of inertia of the hub and the link are used in the kinetic energy equations.

$$V_{P.E} = \frac{1}{2} k_{stiff} \alpha^2 \tag{1}$$

$$\begin{aligned} V_{K.E} &= V_{K.E\,(link)} + V_{K.E\,(hub)} \\ V_{K.E} &= \frac{1}{2} J_{link} (\dot{\theta} + \dot{\alpha})^2 + \frac{1}{2} J_{hub} \dot{\theta}^2 \end{aligned} \tag{2}$$

With these equations, the Lagrange function can be formed as follows.

$$\begin{aligned} L &= V_{K.E} - V_{P.E} \\ L &= \left(\frac{1}{2} J_{link} (\dot{\theta} + \dot{\alpha})^2 + \frac{1}{2} J_{hub} \dot{\theta}^2\right) - \left(\frac{1}{2} k_{stiff} \alpha^2\right) \end{aligned} \tag{3}$$

If partial derivatives are taken according to generalized coordinates, the following equations are obtained. "τ" used in the equations was stated as the output torque of the servomotor, and "b_{eq}" was stated as the equivalent viscous damping coefficient.

$$\frac{\delta}{\delta t}\left(\frac{\delta L}{\delta \dot{\theta}}\right) - \frac{\delta L}{\delta \theta} = \tau - b_{eq} \dot{\theta} \tag{4}$$

$$\frac{\delta}{\delta t}\left(\frac{\delta L}{\delta \dot{\alpha}}\right) - \frac{\delta L}{\delta \alpha} = 0 \tag{5}$$

Using Eq. 4 and 5, the dynamic equations of the system can be obtained as follows.

$$J_{link}(\ddot{\theta} + \ddot{\alpha}) + J_{hub} \ddot{\theta} = \tau + b_{eq} \dot{\theta} \tag{6}$$

$$J_{link}(\ddot{\theta} + \ddot{\alpha}) + k_{stiff} \alpha = 0 \tag{7}$$

The output torque of the servomotor can be expressed as shown in Eq. 8.

$$\tau = \eta_m \eta_g k_t k_g I_m \tag{8}$$

η_m and η_g represent the efficiency of the motor and the gear, respectively. "k_t" is the torque constant, and "k_g" is the gear ratio. "I_m" represents the armature current of the motor. The armature current, on the other hand, can be expressed in terms of controlled voltage using the Kirchhoff rules as shown in Eq. 9.

$$I_m = \frac{V_m - k_t k_m \dot{\theta}}{R_m} \tag{9}$$

"V_m" indicates the voltage supplied to the motor, and "R_m" indicates the electrical resistance of the armature.

Substituting Eq. 8 and 9 into Eq. 6, the dynamic model of the system can be expressed with the following equations.

$$\begin{aligned} J_{link}(\ddot{\theta} + \ddot{\alpha}) + J_{hub} \ddot{\theta} \\ = \eta_m \eta_g k_t k_g \left(\frac{V_m - k_t k_m \dot{\theta}}{R_m}\right) + b_{eq} \dot{\theta} \end{aligned} \tag{10}$$

$$J_{link}(\ddot{\theta} + \ddot{\alpha}) + k_{stiff} \alpha = 0 \tag{11}$$

Arranging Eq. 6 and 7, the state space model of the system can be expressed as shown in Figure 3. The state-space model is arranged as the following equations according to the inputs of the system "u", and the outputs of the system "y" . A, B, C, and D matrices of the system provided in the user manual are shown in Eq. 12.

$$\begin{bmatrix}\dot{\theta}\\ \dot{\alpha}\\ \ddot{\theta}\\ \ddot{\alpha}\end{bmatrix}=\begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & \dfrac{k_{stiff}}{J_{hub}} & \dfrac{-\eta_m\eta_g k_t k_m k_g{}^2+b_{eq}R_m}{J_{hub}R_m} & 0\\ 0 & \dfrac{k_{stiff}(J_{hub}+J_{link})}{J_{hub}J_{link}} & \dfrac{\eta_m\eta_g k_t k_m k_g{}^2+b_{eq}R_m}{J_{hub}R_m} & 0\end{bmatrix}\begin{bmatrix}\theta\\ \alpha\\ \dot{\theta}\\ \dot{\alpha}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ \dfrac{\eta_m\eta_g k_t k_g}{J_{hub}R_m}\\ \dfrac{-\eta_m\eta_g k_t k_g}{J_{hub}R_m}\end{bmatrix}V_m$$

Figure 3. State-space presentation of the flexible link

$$\dot{x}=Ax+Bu$$
$$y=Cx+Du \tag{12}$$

$$A=\begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & 623{,}74 & -40{,}32 & 0\\ 0 & -965{,}34 & 40{,}32 & 0\end{bmatrix}$$

$$B=\begin{bmatrix}0\\ 0\\ 61{,}63\\ -61{,}63\end{bmatrix}, \tag{13}$$

$$C=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix},\quad D=\begin{bmatrix}0\\ 0\end{bmatrix}$$

3. CASCADE PROPORTIONAL DERIVATIVE CONTROLLER

Cascade control consists of the use of two control loops. The first control loop provides the reference point for the second control loop [30].

The outer or primary loop uses the sensor of the variable to be controlled. This is the dominant loop that provides the intended control. The inner or secondary loop uses the second variable sensor to be controlled and drives the second controller to keep this variable at a certain value.

Cascade control is generally advantageous if the dynamics of the inner loop are faster than the dynamics of the outer loop. When the inner loop is not significantly faster than the outer loop, the advantages of cascading control are reduced. Moreover, if the inner loop is set aggressively, it may even cause instability in the system by creating the risk of interaction between the two loops [33].In a single loop PID control system that has low stiffness, it will be difficult to meet the requirements when the level of experimental loads is very high relative to the stiffness of the system. It is therefore unlikely to achieve a very high quality of control [34]. In Cascade control systems, the secondary (internal) circuit is the acceleration loop of the system; the primary (external) circuit can be expressed as a position control loop [35]. In this study, the tip vibration is used as the feedback of the secondary loop, and the position of the link is used as the feedback of the first loop. The primary and the secondary controllers are named as PD-1 and PD-2, respectively. When the reference value is set as the position of the link, the external controller initiates the motion providing a reference to the controller in the secondary loop that controls the tip vibration of the link.

The output of the secondary controller provides the necessary voltage to the motor. The control system block diagram used in the study is shared in Figure 4. In the trials conducted during the study, it was observed that the integration process in the PID controller had not a positive effect on the control of the system. For this reason, the controller was defined as a proportional derivative.

4. CASCADE PD CONTROLLER OPTIMIZATION

4.1. Genetic Algorithm

Genetic algorithms are evolutionary algorithms that optimize functions by modeling the biological process, first introduced by John Holland in 1975 [34]. While GA parameters represent genes in the biology, the aggregated set of parameters constitutes the chromosome. Each individual of the Gas which are the candidates of the solution, is represented in the form of chromosomes. This set of candidate solutions is also called the population. The fitness of the population is maximized or minimized within certain rules. Each new generation is obtained by combining survivors into sequences created by random information exchange [35, 36]. The genetic algorithm is a commonly used method to find controller gains [8, 37-38]. The suitable gains of the PD controller were found by the genetic algorithm using the parameters in Table 1.

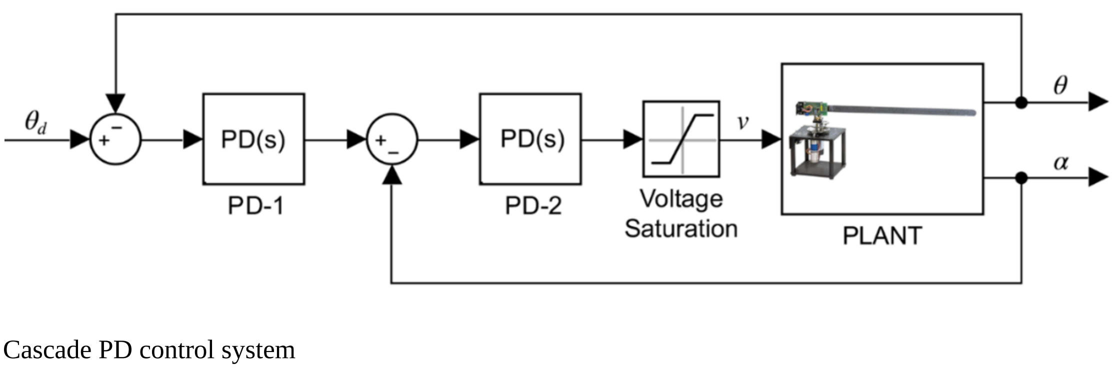

Figure 4. Cascade PD control system

Table 1. Genetic Algorithm parameters

Parameters	Values
Generation number	25
Population size	40
Elite count	10
Crossover fraction	0.6

4.2. The Bees Algorithm

The Bees Algorithm (BA) was first proposed by DT Pham et al. in 2006, the behavior of bees searching for resources such as nectar and water by using swarm intelligence to learn, remember, and transfer the knowledge [39-43]. Pham and Kalyoncu, who designed fuzzy logic and PID controllers with the bees algorithm for the control of a robotic arm, laid the foundations of the studies in this field [24]. Kalyoncu et al. observed that the controllers whose parameters were determined by The Bees Algorithm compared to the traditional methods in position and balance control gave better results [44-47]. Baronti et al. analysed of the search mechanisms of The Bees Algorithm [48]. The flowchart is shown in Figure 5, pseudo code is shown in Figure 6.

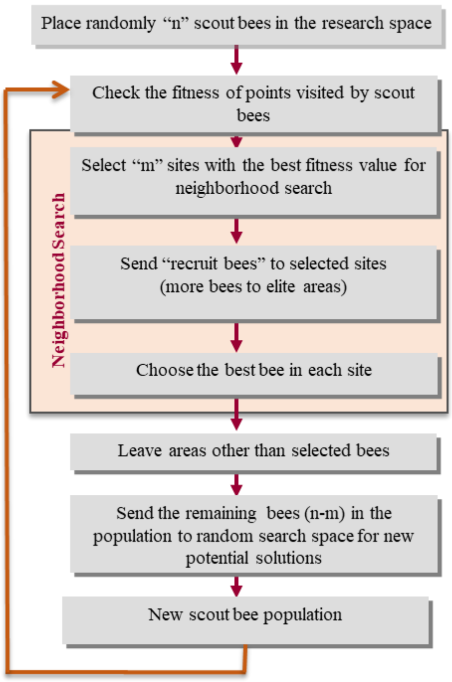

Figure 5. Flowchart of the Bees Algorithm

1. Initialise population with random solutions.
2. Evaluate fitness of the population.
3. While (stopping criteria not met) //Forming new population.
4. Select elite bees.
5. Select sites for neighbourhood search.
6. Recruit bees around selected sites and evaluate fitness.
7. Select the fittest bee from each site.
8. Assign remaining bees to search randomly and evaluate their fitness.
9. End While

Figure 6. Pseudo code of The Bees Algorithm

Table 2. The Bees Algorithm parameters

Parameters	Values
Number of iteration "itr"	25
Number of scout bees "n"	20
Number of suitable regions "m"	8
Number of the best regions "e"	5
Number of bees sent to the best elite region "nep"	10
Number of bees sent to the region "nsp"	7
Region size "ngh"	0.01

The bees algorithm contains many parameters such as the number of scout bees (n), the number of the most suitable regions selected from n visited points (m), the number of the best regions in the m selected regions (e), the number of bees sent to the best elite region (nep), the remaining are the number of bees sent to the region (nsp), the region size (ngh), and the number of iteration (itr). The parameters used in the optimization process are given in Table 2.

4.3. Tuning Cascade PD Controller

The input of the system is the voltage of the servomotor. The proportional controller gains (K_P^1, K_P^2) and derivative controller gains (K_D^1, K_D^2) of the outer and the inner loop of the control system are the parameters that determine the performance of the system. The main goal is to find controller gains that will minimize the performance index for a control input. The performance index was created by considering the weighted summation of rising time (t_r), settling time (t_s), peak time (t_p), maximum overshoot (p_{max}), steady state error (e_{ss}), and matrix norm (α_{norm}) as stated in Eq. 14 [23].

$$\begin{aligned} P &= P_\theta + P_\alpha \\ P_\theta &= 10t_r + 6t_s + 6.5t_p + 0.1|p_{max}| + 4.4|e_{ss}| \\ P_\alpha &= 0.1\alpha_{norm} + 3.3t_s + 50t_p + 0.8|p_{max}| + 1500|e_{ss}| \end{aligned} \quad (14)$$

In this study, the control system and the state-space model of the flexible link are set up in MATLAB/Simulink environment. The related controller coefficients were defined as variables. The response of the system to the control input was evaluated. The range in which the controller gains are sought is given in Table 3. The Bees Algorithm was composed in the MATLAB environment. The system was operated using the parameters suggested by the bees sent in each iteration. The results were stored, and the next iteration was prepared. In this way, the most suitable controller gains that will minimize the fitness function have been obtained with The Bees Algorithm.

Table 3. Optimization ranges of PD controller gains

Gains	Minimum	Maximum
$Kp^{PD\text{-}1}$	0	5
$Kd^{PD\text{-}1}$	0	1
$Kp^{PD\text{-}2}$	0	5
$Kd^{PD\text{-}2}$	0	1

5. STABILITY ANALYSIS

Stability analysis is a standard requirement for control systems to avoid loss of control. Stability can be analyzed by looking at the eigenvalues of A matrix of state-space representation. Many techniques are available for obtaining state-space representations of dynamic systems. MATLAB platform lets you analyze the dynamics of systems and extract system models in the form of the state-space matrices A, B, C, and D according to selected input and outputs. The closed control system shown in Figure 4. including PD controllers is defined as a state-space model by using MATLAB. Obtained *A* matrices including optimized PD controllers by using The Bees Algorithm and Genetic Algorithm are given in Eq. 15 and Eq. 16 respectively.

$$A_{BA} = \begin{bmatrix} -100 & 0 & -0.1763 & 0 & 0 & 0 \\ -13.18 & -100 & -0.3661 & -0.1318 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -4967 & -6163 & -138 & 574.1 & -40.32 & 0 \\ 4967 & 6163 & 138 & -915.7 & 40.32 & 0 \end{bmatrix} \quad (15)$$

$$A_{GA} = \begin{bmatrix} -100 & 0 & -0.3268 & 0 & 0 & 0 \\ -195.7 & -100 & -6.462 & -1.957 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -16100 & -6163 & -531.5 & 462.8 & -40.32 & 0 \\ 16100 & 6163 & 531.5 & -804.4 & 40.32 & 0 \end{bmatrix} \quad (16)$$

Eigenvalues of the obtained *A* matrices are the roots of the characteristic equation [49]. As seen in Table 4. all eigenvalues have negative real parts. This means that all closed-loop poles of the control system which contains optimized PD controllers using The Bees Algorithm and Genetic Algorithm are in the left-half plane. The controlled system is therefore stable.

Table 4. Eigenvalues of *A* matrices.

Eigenvalues of A_{BA}	Eigenvalues of A_{GA}
$-99.8487 + 1.4641i$	$-98.1218 + 7.6902i$
$-99.8487 - 1.4641i$	$-98.1218 - 7.6902i$
$-8.9633 + 21.9158i$	$-8.4908 + 21.2097i$
$-8.9633 - 21.9158i$	$-8.4908 - 21.2097i$
-19.2677	-3.4269
-3.4285	-23.6679

6. SIMULATION RESULTS

Controller gains found by The Bees Algorithm and Genetic Algorithm are shown in Table 5. The gains of the proportional controller were very close to each other. However, a difference was observed between the gains of the derivative controller gains.

The responses of the systems found with two different algorithms are shared in Table 6. The settling and rising times of the system for theta angle were very close to each other. However, when the tip point vibrations are evaluated, it is observed The Bees Algorithm achieves better results.

Table 5. GA and BA optimization results

Gains	Genetic Algorithm	The Bees Algorithm
Kp^{PD-1}	2,9752	2,6019
Kd^{PD-1}	0,0033	0,0018
Kp^{PD-2}	0,6547	0,6741
Kd^{PD-2}	0,0196	0,0013

Table 6. Performance criteria of controllers

Time Responses	GA Controller	BA Controller
θ, Rise Time (t_r) [s]	0.6846	0.6968
θ, Settling Time (t_s) [s]	1.1891	1.2310
θ, Maximum Peak [%]	0	0
θ, Steady State Error (e_{ss})	0	0
α, Norm	14.9806	10.6592
α, Settling Time (t_s) [s]	0.8473	0.9444
α, Peak Time (t_p) [s]	0.0609	0.0805
α, Maximum Peak [deg]	3.5952	2.6088
α, Steady State Error (e_{ss})	0	0

The convergences of two different algorithms in the iterations are shown in Figure 7. When the curves are examined, it is seen that while the Genetic Algorithm converges faster, the fitness value obtained by The Bees Algorithm is more successful than the Genetic Algorithm.

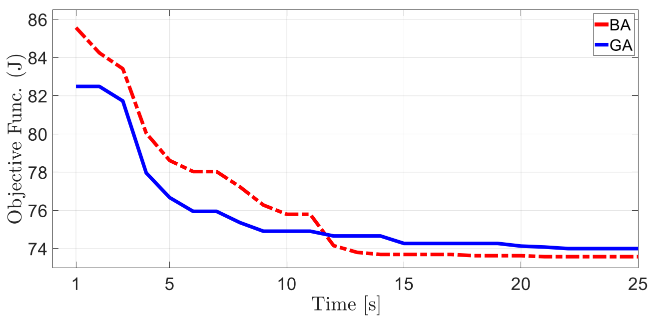

Figure 7. Convergence performance of GA, BA

In addition, according to the supplied voltage of the motor shown in Figure 8 and Figure 9, it is seen that the controller obtained with BA provides a more efficient control with less energy consumption.

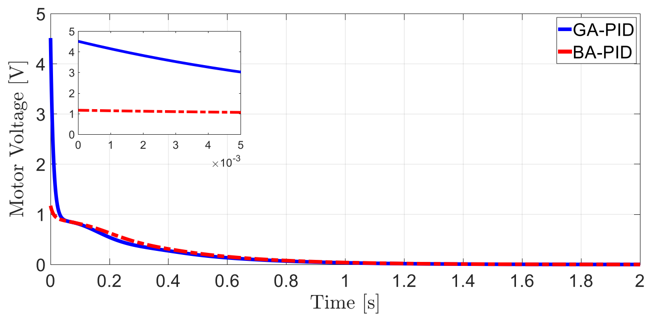

Figure 8. Motor voltages for 30º reference position.

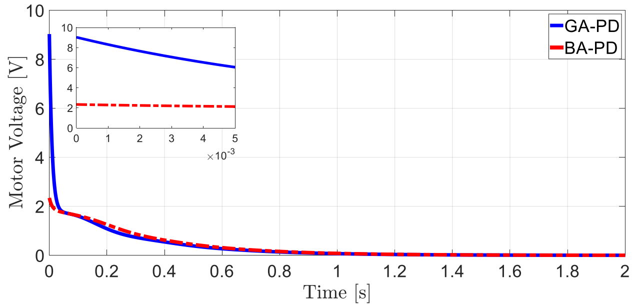

Figure 9. Motor voltages for 60° reference position.

It is seen that BA and GA have obtained close results in position control in Figure 10 and Figure 11, but BA is more successful in tip vibration shown in Figure 12 and Figure 13.

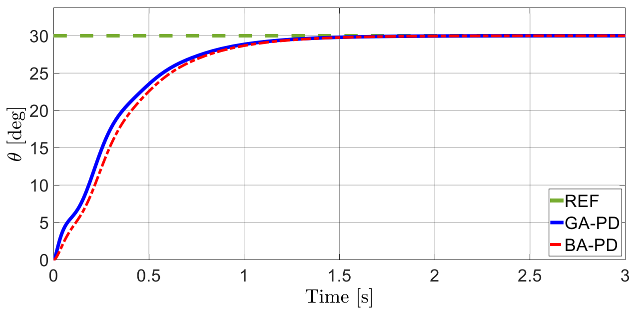

Figure 10. Position result for 30° reference position.

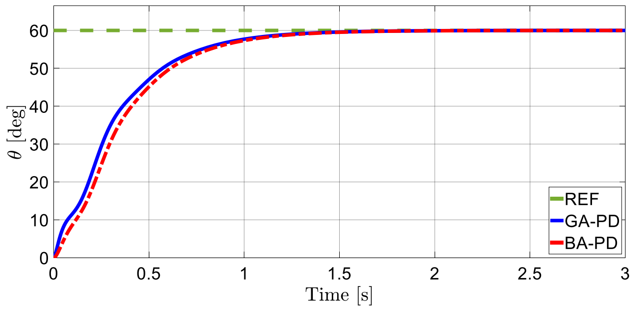

Figure 11. Position result for 60° reference position.

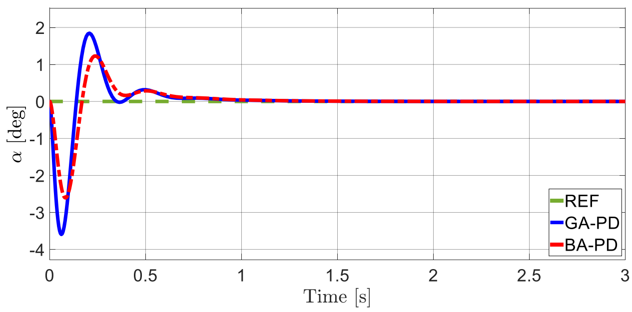

Figure 12. Tip vibration result for 30° reference position.

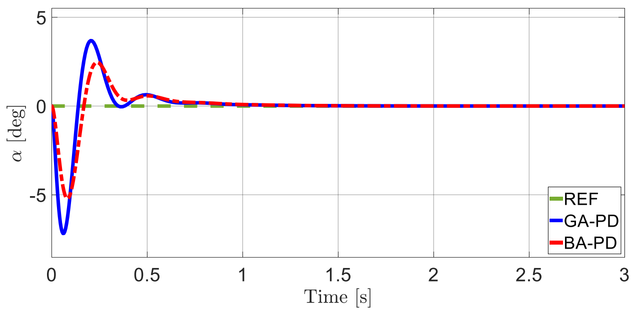

Figure 13. Tip vibration result for 60° reference position.

7. CONCLUSION

In this study, a model of a flexible robot manipulator arm was created. A cascade PD controller was used to control the position and tip point vibration. The gains of the proposed PD controller have been successfully found by Genetic Algorithm and The Bees Algorithm. It has been observed that The Bees Algorithm founds the controller gains with better fitness values than the Genetic Algorithm. When the response of the systems suggested by different algorithms was examined, it was observed that the tip point vibration level was reduced. In addition, the decrease in the motor voltage with The Bees Algorithm leads to lower energy consumption. I was observed that the tip point vibration level was successfully suppressed with a sufficient position control.

Author Contributions: Gumus M.S. performed the analysis and wrote the paper. Cakan A. designed the model and made the stability analysis. Kalyoncu M. conceived the study and contributed to the optimization.
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REFERENCES

[1] S. Xu, G. Sun, and Z. Li, "Finite frequency vibration suppression for space flexible structures in tip position control," International Journal of Control, Automation, and Systems, vol. 16, no. 3, pp. 1021-1029, 2018.

[2] B. Altıner, A. Delibaşı, and B. Erol, "Modeling and control of flexible link manipulators for unmodeled dynamics effect," Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, vol. 233, no. 3, pp. 245-263, 2019.

[3] X. Lang, C. J. Damaren, and X. Cao, "Hybrid frequency domain control for large flexible structures," Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, vol. 233, no. 11, pp. 4272-4283, 2019.

[4] Bhaskarwar T, Hawari HF, Nor NBM, Chile RH, Waghmare D, Aole S, “Sliding Mode Controller with Generalized Extended State Observer for Single Link Flexible Manipulator,” Applied Sciences, vol 12, no 6, 3079, 2022.

[5] Zhou X, Wang H, Tian Y, “Adaptive boundary iterative learning vibration control using disturbance observers for a rigid–flexible manipulator system with distributed disturbances and input constraints,” Journal of Vibration and Control, vol 28 no.11-12, pp. 1324-1340, 2022.

[6] M.-T. Ho and Y.-W. Tu, "PID controller design for a flexible-link manipulator," in Proceedings of the 44th IEEE Conference on Decision and Control, 2005: IEEE, pp. 6841-6846.

[7] A. Izadbakhsh and S. Khorashadizadeh, "Single-loop PID controller design for electrical flexible-joint robots," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 42, no. 2, pp. 1-12, 2020.

[8] S. K. Pradhan and B. Subudhi, "Position control of a flexible manipulator using a new nonlinear self-tuning PID controller," IEEE/CAA Journal of Automatica Sinica, vol. 7, no. 1, pp. 136-149, 2018.

[9] P. Sarkhel, N. Banerjee, and N. B. Hui, "Fuzzy logic-based tuning of PID controller to control flexible manipulators," SN Applied Sciences, vol. 2, pp. 1-11, 2020.

[10] A. Urbaś, J. Kłosiński, and K. Augustynek, "The influence of the PID controller settings on the motion of a truck-mounted crane with a flexible boom and friction in joints," Control Engineering Practice, vol. 103, p. 104610, 2020.

[11] H. Açikgöz, Ö. F. Keçecioğlu, M. Güneş, And M. Şekkeli, "Öz Ayarlamalı Bulanık-Pid Denetleyici İle Hidrolik Türbinin Benzetim Çalışması," Academic Platform Journal Of Engineering And Science, Vol. 3, No. 1, Pp. 7-15, 2015.

[12] R. Aisuwarya and Y. Hidayati, "Implementation of ziegler-nichols PID tuning method on stabilizing temperature of hot-water dispenser," in 2019 16th International Conference on Quality in Research (QIR): International Symposium on Electrical and Computer Engineering, 2019: IEEE, pp. 1-5.

[13] K. S. Chia, "Ziegler-nichols based proportional-integral-derivative controller for a line tracking robot," Indonesian journal of electrical engineering and computer science, vol. 9, no. 1, pp. 221-226, 2018.

[14] J. Fišer and P. Zítek, "PID controller tuning via dominant pole placement in comparison with ziegler-nichols tuning," IFAC-PapersOnLine, vol. 52, no. 18, pp. 43-48, 2019.

[15] N. I. M. Azmi, N. M. Yahya, H. J. Fu, and W. A. W. Yusoff, "Optimization of the PID-PD parameters of the overhead crane control system by using PSO algorithm," in MATEC Web of Conferences, 2019, vol. 255: EDP Sciences, p. 04001.

[16] M. A. Ibrahim, A. K. Mahmood, and N. S. Sultan, "Optimal PID controller of a brushless DC motor using genetic algorithm," Int J Pow Elec & Dri Syst ISSN, vol. 2088, no. 8694, p. 8694, 2019.

[17] H. Suwoyo, Y. Tian, C. Deng, and A. Adriansyah, "Improving a wall-following robot performance with a PID-genetic algorithm controller," in 2018 5th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI), 2018: IEEE, pp. 314-318.

[18] Z. Xiang, D. Ji, H. Zhang, H. Wu, and Y. Li, "A simple PID-based strategy for particle swarm optimization algorithm," Information Sciences, vol. 502, pp. 558-574, 2019.

[19] M. Arif Şen, M. Tinkir, and M. Kalyoncu, "Optimisation of a PID controller for a two-floor structure under earthquake excitation based on the bees algorithm," Journal of Low Frequency Noise, Vibration and Active Control, vol. 37, no. 1, pp. 107-127, 2018.

[20] E. A. Esleman, G. Önal, and M. Kalyoncu, "Optimal PID and fuzzy logic based position controller design of an overhead crane using the Bees Algorithm," SN Applied Sciences, vol. 3, no. 10, pp. 1-13, 2021.

[21] C. Conker, H. Yavuz, and H. H. Bilgic, "A review of command shaping techniques for elimination of residual vibrations in flexible-joint manipulators," Journal of Vibroengineering, vol. 18, no. 5, pp. 2947-2958, 2016.

[22] D. K. Thomsen, R. Søe-Knudsen, O. Balling, and X. Zhang, "Vibration control of industrial robot arms by multi-mode time-varying input shaping," Mechanism and Machine Theory, vol. 155, p. 104072, 2021.

[23] T. Mansour, A. Konno, and M. Uchiyama, "Modified PID control of a single-link flexible robot," Advanced Robotics, vol. 22, no. 4, pp. 433-449, 2008.

[24] D. Pham, E. Koç, M. Kalyoncu, and M. Tınkır, "Hierarchical PID controller design for a flexible link robot manipulator using The Bees Algorithm," Methods (eg. genetic algorithm), vol. 25, p. 32, 2008.

[25] H. H. Bilgic, M. A. Sen, A. Yapici, H. Yavuz, and M. Kalyoncu, "Meta-heuristic tuning of the LQR weighting matrices using various objective functions on an experimental flexible arm under the effects of disturbance," Arabian Journal for Science and Engineering, pp. 1-14, 2021.

[26] Ü. Önen, A. Çakan, and I. Ilhan, "Performance comparison of optimization algorithms in LQR controller design for a nonlinear system," Turkish Journal of Electrical Engineering & Computer Sciences, vol. 27, no. 3, pp. 1938-1953, 2019.

[27] C. Sun, H. Gao, W. He, and Y. Yu, "Fuzzy neural network control of a flexible robotic manipulator using assumed mode method," IEEE Transactions on Neural Networks and Learning Systems, vol. 29, no. 11, pp. 5214-5227, 2018.

[28] İ. H. Akyüz, Z. Bingül, And S. Kizir, "Cascade fuzzy logic control of a single-link flexible-joint manipulator," Turkish Journal of Electrical Engineering & Computer Sciences, vol. 20, no. 5, pp. 713-726, 2012.

[29] I. Tijani, R. Akmeliawati, A. A. Muthalif, and A. Legowo, "Optimization of PID controller for Flexible link system using a Pareto-based Multi-Objective differential (PMODE) evolution," in 2011 4th International Conference on Mechatronics (ICOM), 2011: IEEE, pp. 1-6.

[30] W. Bolton, Instrumentation and control systems. Newnes, 2021.

[31] Y. Hu, C. Chen, H. Wu, and C. Song, "Study on structural optimization design and cascade PID control of maglev actuator for active vibration isolation system," Journal of Vibration and Control, vol. 24, no. 10, pp. 1829-1847, 2018.

[32] J. Liu, Y. Li, Y. Zhang, Q. Gao, and B. Zuo, "Dynamics and control of a parallel mechanism for active vibration isolation in space station," Nonlinear Dynamics, vol. 76, no. 3, pp. 1737-1751, 2014.

[33] B.-J. Yang, A. Calise, J. Craig, and M. Whorton, "Adaptive control for a microgravity vibration isolation system," in AIAA guidance, navigation, and control conference and exhibit, 2005, p. 6071.

[34] H. John, "Holland. genetic algorithms," Scientific american, vol. 267, no. 1, pp. 44-50, 1992.

[35] P. J. Angeline, "Evolution revolution: An introduction to the special track on genetic and evolutionary programming," IEEE Intelligent Systems, vol. 10, no. 03, pp. 6-10, 1995.

[36] A. Sadık, A. Kahraman, And R. Şahin, "Determination Of Optimum Pinch Point Temperature Difference Depending on Heat Source Temperature and Organic Fluid with Genetic Algorithm," Academic Platform Journal of Engineering and Smart Systems, vol. 10, no. 1, pp. 19-29..

[37] J. Zhang, J. Zhuang, and H. Du, "Self-organizing genetic algorithm based tuning of PID controllers," Information Sciences, vol. 179, no. 7, pp. 1007-1018, 2009.

[38] A. Mirzal, S. Yoshii, and M. Furukawa, "PID parameters optimization by using genetic algorithm," arXiv preprint arXiv:1204.0885, 2012.

[39] D. Karaboga, "An idea based on honey bee swarm for numerical optimization," Technical report-tr06, Erciyes university, engineering faculty, computer …, 2005.

[40] D. Karaboga and B. Akay, "A comparative study of artificial bee colony algorithm," Applied mathematics and computation, vol. 214, no. 1, pp. 108-132, 2009.

[41] D. Pham, A. Ghanbarzadeh, E. Koc, and S. Otri, "Application of the bees algorithm to the training of radial basis function networks for control chart pattern recognition," in Proceedings of 5th CIRP international seminar on intelligent computation in manufacturing engineering (CIRP ICME'06), Ischia, Italy, 2006, pp. 711-716.

[42] D. Pham, A. J. Soroka, A. Ghanbarzadeh, E. Koc, S. Otri, and M. Packianather, "Optimising neural networks for identification of wood defects using the bees algorithm," in 2006 4th IEEE International Conference on Industrial Informatics, 2006: IEEE, pp. 1346-1351.

[43] D. T. Pham, A. Ghanbarzadeh, E. Koç, S. Otri, S. Rahim, and M. Zaidi, "The bees algorithm—a novel tool for complex optimisation problems," in Intelligent production machines and systems: Elsevier, 2006, pp. 454-459.

[44] V. Bakırcıoğlu, M. Şen, and M. Kalyoncu, "Dört Ayaklı Robotun Bir Bacağı İçin PID Kontrolcü Tasarımı ve Arı Algoritması Kullanarak Optimizasyonu," Uluslararası katılımlı 17. Makina Teorisi Sempozyumu (UMTS 2015), pp. 661-665.

[45] D. Pham and M. Kalyoncu, "Optimisation of a fuzzy logic controller for a flexible single-link robot arm using the Bees Algorithm," in 2009 7th IEEE International Conference on Industrial Informatics, 2009: IEEE, pp. 475-480.

[46] M. A. Şen, V. Bakırcıoğlu, and M. Kalyoncu, "Performances comparison of the bees algorithm and genetic algorithm for PID controller tuning," in Proceedings of the 5th International Conference on Mechatronics and Control Engineering, 2016, pp. 126-130.

[47] M. A. Sen and M. Kalyoncu, "Optimisation of a PID controller for an inverted pendulum using The Bees Algorithm," in Applied Mechanics and Materials, 2015, vol. 789: Trans Tech Publ, pp. 1039-1044.

[48] Baronti, L., Castellani, M., & Pham, D. T. “An analysis of the search mechanisms of the bees algorithm,” in Swarm and Evolutionary Computation, 2020, vol. 59, 100746.

[49] K. Ogata, “Modern Control Engineering,” in Prentice Hall, Vol. 5, 2010.