Levy Flight Safe Experimentation Dynamics Algorithm for Data-Based PID Tuning of Flexible Joint Robot

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Abstract— **This paper proposes the data-based PID controller of flexible joint robot based on Levy Flight Safe Experimentation Dynamics (LFSED) algorithm. The LFSED algorithm is an enhanced version of SED algorithm where the random perturbation of the updated tuning variable is based on Levy Flight function. By adopting the Levy Flight term to the updated equation of SED, it is expected that a more efficient searching can be performed than the uniform distribution random numbers. The effectiveness of the LFSED algorithm is verified to tune the PID controller of flexible joint robot. In this flexible joint control problem, two PID controllers are utilized to control both rotary angle tracking and vibration of flexible joint robot. The performance of the proposed data-based PID controller is assessed in terms of trajectory tracking of angular motion, vibration reduction and statistical analysis of the pre-defined control objective function. The simulation results showed that the data-based PID controller based on LFSED is able to produce better control accuracy than the conventional LFSED based method.**

I. INTRODUCTION

Data-based control of flexible joint robot has received great attentions by many researchers as compared to model-based control schemes. This is due to huge effort is required to obtain an accurate model of such complex system [1] and further design the model-based controller. Meanwhile, data-based control of flexible joint robot can be divided into two classes, which are feedforward data-driven control and feedback data-driven control. The examples of feedforward data-based control are input shaping and filtering techniques [2,3,4,5]. Here, the techniques utilize the information of vibration frequencies to design the input shaper and filter after generating a bang-bang input torque to the flexible robot system. Meanwhile, in the feedback data-based control, many researchers apply the multi-agent-based optimization tools to tune the feedback control, i.e., PID, based on the input and output data [6,7,8,9]. The advantage of feedforward data-based control is that it only requires one shot of output data to design the input shaping or filtering control schemes as compared to feedback data-driven control, which requires large number of data set. However, the feedforward data-based control is not able to handle any disturbances, while the feedback data-based control scheme can successfully handle any disturbances due to its closed-loop structure.

Recently, in the feedback data-based control schemes, there are various of optimization tools used to tune a pre-defined control structure. For example, Particle Swarm Optimization (PSO) has been widely applied to tune various controller for flexible robot. In [10], they used PSO to tune the dynamic neural network for two-link flexible robot. Specifically, an improved PSO/Bayesian regularization (BR) has been proposed with the integration of extremum response surface method and artificial neural network. In [11], new gains tuning and impedance control method have been applied for flexible base moving robots. Here, a new online PSO for gain tuning of impedance control at the contact moments of end effector has been proposed. In [12], they applied PSO to tune the linear and nonlinear active rejection controller. Meanwhile, Genetic Algorithm (GA) has been used to tune the PID with input shaping controller for input tracking and vibration control of flexible robot [13]. Several similar works on applying GA for tuning controller of flexible robot can be found in [14,15,16]. Furthermore, Evolutionary Algorithm (EA) has been used for system identification of flexible robot and controller tuning [17]. Similarly, Evolutionary Computation (EC) has also been applied for tip position controller of two-link flexible robot [18]. Meanwhile, Bees Algorithm and Artificial Bee Colony have been used to tune the hierarchical PID [19] and intelligent PID [20] of single-link flexible robot, respectively.

Based on the above literature, the main ineluctable limitation in their works is most of the methods requires heavy computation time to obtain the optimal controller parameter. This is because, in the multi-agent-based optimization, the computation times per iteration are proportional to the number of agents. Hence, it motivates us to propose a tuning strategy that requires less computation time, such as single agent-based optimization tools. So far, there are various single agent-based optimization tools that have been applied for data-based control such as Simultaneous Perturbation Stochastic Approximation (SPSA) [21], Simulated Annealing (SA) [22], Random Search (RS) [23] and Safe Experimentation Dynamics (SED) [24]. Based on findings in [24], it is shown that the

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Safe Experimentation Dynamics (SED) is the most significant single-agent based optimization tool as compared to the other single-agent-based optimization tools due to its simplicity, memory based structure and less number of coefficients. Meanwhile, it is worth to point out that Levy Flight is quite efficient in improving the searching mechanism due to its unique generation of random numbers. Hence, it is worth to adopt the Levy Flight function to the SED algorithm instead of using standard uniform random numbers. In addition, there are still no reported works adopt the LFSED based method for controlling the flexible joint robot. So, it is good to see the effectiveness of the LFSED for data-based control of flexible joint robot.

This paper presents the data-based PID controller of flexible joint robot using Levy Flight Safe Experimentation Dynamics (LFSED) algorithm. In the new version of SED, the random perturbation of updated tuning variable is enhanced by using the Levy Flight function. The effectiveness of the LFSED algorithm is verified for finding the optimal PID controller of flexible joint robot. Specifically, two PID controllers are utilized to control both angular tracking and vibration of elastic joint robot. The performance of the proposed data-based PID controller is assessed in terms of trajectory tracking of angular motion, vibration reduction and statistical analysis of the pre-defined control objective function. The results of the simulation showed that the data-based PID controller based on LFSED algorithm could exhibit slightly improvement in the control accuracy than the standard SED algorithm.

II. RESEARCH METHOD

The synthesize of data-based PID controller of flexible joint robot using Levy Flight Safe Experimentation Dynamics is explained in this section. Firstly, the problem setting of data-based PID controller of flexible joint robot is presented. Here, the structure of conventional PID controller and its parameter are explained. Secondly, we show the procedure to find the optimal PID parameters using LFSED such that the given control objective function is minimized.

A. Problem Setting of Data-Based PID Controller

Fig. 1 shows block diagram of the PID control system for flexible joint robot. In the figure, the symbols G, $Y_R(t)$, $Y(t)$, $V(t)$, and $\theta(t)$ are defined as flexible joint robot plant, reference, rotary angle, control input and oscillation angle, respectively. Note that the flexible joint robot is a class of underactuated system since only one control input is used to regulate both rotary angle and oscillation angle.

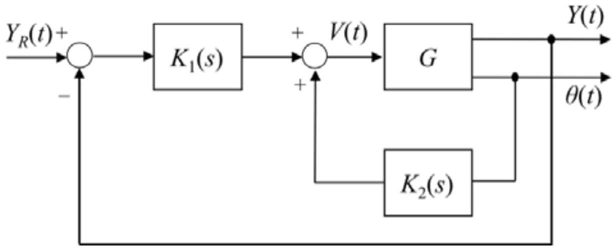

Figure 1. Control system block diagram of flexible joint robot

Furthermore, two PID controllers, which are denoted by the symbols $K_1(s)$ and $K_2(s)$ are fed back from the rotary angle and the oscillation angle, respectively. The detailed expression of both PID controllers are given by

$$K_1(s) = P_1\left(1 + \frac{1}{I_1 s} + \frac{D_1 s}{1+\left(D_1/N_1\right)s}\right) \tag{1}$$

$$K_2(s) = P_2\left(1 + \frac{1}{I_2 s} + \frac{D_2 s}{1+\left(D_2/N_2\right)s}\right) \tag{2}$$

where $P_1, P_2 \in \mathbf{R}$, $I_1, I_2 \in \mathbf{R}$, $D_1, D_2 \in \mathbf{R}$ and $N_1, N_2 \in \mathbf{R}$ are the proportional gains, integral gains, derivative gains and filter coefficients, respectively. Our aim is to design data-based PID controller such that the rotary angle follows the desired reference trajectory with minimum oscillation angle. Therefore, the control objective function is designed as follow

$$J(\boldsymbol{P}, \boldsymbol{I}, \boldsymbol{D}, \boldsymbol{N}) = w_1\hat{E} + w_2\hat{\theta} + w_3\hat{V} \tag{3}$$

where

$$\hat{E} = \int_{t_0}^{t_f} \left|Y_R(t) - Y(t)\right|^2 dt, \tag{4}$$

$$\hat{\theta} = \int_{t_0}^{t_f} \left|\theta(t)\right|^2 dt, \tag{5}$$

$$\hat{V} = \int_{t_0}^{t_f} \left|V(t)\right|^2 dt, \tag{6}$$

for the time duration of $[t_0, t_f]$. In (3), the symbols $\boldsymbol{P} = [P_1\ P_2]^T$, $\boldsymbol{I} = [I_1\ I_2]^T$, $\boldsymbol{D} = [D_1\ D_2]^T$, and $\boldsymbol{N} = [N_1\ N_2]^T$, which contribute to 8 tuning variables in PID controllers. In order to properly regulate this kind of multi-objective function in (3), several weight coefficients are introduced, which is denoted by the symbols $w_1 \in \mathbf{R}$, $w_2 \in \mathbf{R}$ and $w_3 \in \mathbf{R}$. Finally, the problem setting for data-based PID controller is given by:

Problem 1. Based on the given plant G with PID controller structure in Fig. 1 and the available input and output data, find the PID controllers $K_1(s)$ and $K_2(s)$ such that the objective function in (3) is minimized.

B. Data-based PID utilizing Levy Flight Safe Experimentation Dynamics

In this section, the proposed LFSED algorithm is used for finding the optimal PID controller of flexible joint control problem. Initially, the conventional SED algorithm that was firstly introduced by Marden et. al., [25] is reviewed. Next, the enhanced version of SED, which is called LFSED is presented. Ultimately, the procedure to utilize the Adaptive SED algorithm in finding the optimal PID controller of flexible joint robot is shown.

Since our aim is to minimize the objective function in (3), we consider the minimization optimization problem as follow

$$\min_{z\in\mathbf{R}^n} L(\boldsymbol{z}), \tag{7}$$

where L: $\mathbf{R}^n \rightarrow \mathbf{R}$ is an unknown loss function with the tuning variable vector $\boldsymbol{z} \in \mathbf{R}^n$. The SED algorithm [25] updates $\boldsymbol{z} \in \mathbf{R}^n$ to find an optimal solution $\boldsymbol{z}^* \in \mathbf{R}^n$ of (7). The updated equation of SED algorithm is expressed by

$$z_i(k+1) = \begin{cases} h\left(\bar{z}_i - K_g r_1\right) & \text{if } r_1 \leq E, \\ \bar{z}_i & \text{if } r_1 > E, \end{cases} \tag{8}$$

where $k = 0,1,\ldots,$ is iteration number, $z_i \in \mathbf{R}$ is the ith element of $\boldsymbol{z} \in \mathbf{R}^n$, and $\bar{z}_i \in \mathbf{R}$ is the ith iteration of $\bar{\boldsymbol{z}} \in \mathbf{R}^n$. The symbol $\bar{\boldsymbol{z}}$ is denoted as the current best value of the tuning variable. The symbol K_g is the size of interval to determine the random steps on $z_i \in \mathbf{R}$, the symbol E is the probability to change the element of the tuning variable and $r_1 \in \mathbf{R}$ is the random value that is generated uniformly between 0 and 1. In (8), the function h is given by

$$h(.) = \begin{cases} Z_{max}, \ \bar{z}_i - K_g r_2 > Z_{max}, \\ \bar{z}_i - K_g r_2, \ \ Z_{min} \leq \ \bar{z}_i - K_g r_2 \leq Z_{max}, \\ Z_{min}, \ \bar{z}_i - K_g r_2 < Z_{min}, \end{cases} \tag{9}$$

where the pre-determined minimum and maximum of tuning variable are denoted by Z_{min} and Z_{max}, respectively, and r_2 is another random number that is generated independently from r_1. The step-by-step procedure to execute the SED algorithm are given by:

S1: Determine the values of Z_{min}, Z_{max}, K_g and E. Set the initial conditions of the tuning variable $\boldsymbol{z}(0)$. Calculate the loss function $L(\boldsymbol{z}(0))$ and set $\bar{\boldsymbol{z}} = \boldsymbol{z}(0)$ and $\bar{L} = L\big(\boldsymbol{z}(0)\big)$.
S2: Execute $\bar{\boldsymbol{z}} = \boldsymbol{z}(k)$ and $\bar{L} = L\big(\boldsymbol{z}(k)\big)$ when the value $L\big(\boldsymbol{z}(k)\big) < \bar{L}$. Otherwise, go to **S3**.
S3: Generate random numbers r_1 and r_2 independently and execute the updated equation in (8).
S4: Calculate the loss function $L\big(z_i(k+1)\big)$.
S5: If the pre-defined termination criterion (such as based on the designated maximum number of iteration k_{max}) is satisfied, the algorithm terminates with the optimum tuning variable $\boldsymbol{z}^* \coloneqq \arg\min_{z\epsilon\{z(0),z(1),\ldots,z(k+1)\}} L(\boldsymbol{z})$. Otherwise, repeat **S2**.

Based on our preliminary study in the controller tuning process, there is a probability that the obtained control tuning parameter converges too early which may degrade the overall control performance accuracy. It clarifies that the conventional SED algorithm is still not enough to achieve good convergence accuracy. This is because the updated tuning variable in (8) is only depends uniformly distributed numbers r_2, which make it similar to basic random search strategy. Therefore, in order to solve the above issue, we improve the conventional SED by adopting the Levy Flight function instead of using uniformly distributed numbers r_2. Then, it is used as the optimization tool for data-based PID controller of flexible joint robot. In particular, the updated equation in (8) is modified as follow

$$z_i(k+1) = \begin{cases} h\left(\bar{z}_i - K_g Levy(\beta)\right) & \text{if } r_1 \leq E, \\ \bar{z}_i & \text{if } r_1 > E, \end{cases} \tag{10}$$

where $Levy(\beta)$ is Levy flight function which provide random walks that is drawn from Levy distribution for large number of iterations

$$Levy \sim u = k^{-1-\beta} \tag{11}$$

which has an infinite variance with an infinite mean. Note that the value of is selected between $0 < \beta < 2$. By using the new updated equation in (10), it is expected to increase the search efficiency with more chances of finding better updated solution.

Furthermore, by using the new updated equation in (10), the procedure to implement LFSED for data-based PID controller of flexible joint robot is given as follow

Step 1: Determine the maximum iteration k_{max} and consider $L(\boldsymbol{z}) = J(\boldsymbol{P},\boldsymbol{I},\boldsymbol{D},\boldsymbol{N})$ and $z_i = \log\psi_i$. Note that $\psi = [P_1 \ \ I_1 \ \ D_1 \ \ N_1 \ \ P_2 \ \ I_2 \ \ D_2 \ \ N_2]^{\mathrm{T}}$ is the tuning variable vector and $\psi_i = 10^{z_i} (i = 1,2,\ldots,8)$.
Step 2: Execute the LFSED algorithm.
Step 3: After k_{max} is achieved, obtain the optimal tuning variable $\boldsymbol{z}^* = \bar{z}$. Then, implement to PID controller $\psi^* = [10^{\bar{z}_1} \ \ 10^{\bar{z}_2} \ \ \cdots \ \ 10^{\bar{z}_8}]^{\mathrm{T}}$ in Fig. 1.

III. RESULTS AND ANALYSIS

The efficacy of the LFSED algorithm in finding the optimal PID controller flexible joint robot is demonstrated in this section. In particular, the convergence curve response of the objective function in (3), the rotary angle, oscillation angle and input responses, and the statistical analysis of objective function, integral square error and integral square input are presented and analyzed. In this study, 30 trials are considered to evaluate the statistical performances of LFSED.

In this study, the model of the flexible joint plant G is taken from [26]. The reference $Y_R(t)$ is expressed by

$$Y_R(t) = \begin{cases} 50t, & 0 \leq t \leq 1, \\ 50, & 1 \leq t \leq 4. \end{cases} \tag{12}$$

Here, the objective is to find the optimal PID controller such that the rotary angle can follow the pre-defined trajectory in (12) with minimum oscillation angle. The coefficients of SED are given as $K_g = 0.02$, $E = 0.66$, $Z_{min} = -3$, $Z_{max} = 3$. Meanwhile, the coefficients of LFSED are same with SED, except for $\beta = 1$. The weighting coefficients are set as $w_1 = 400$, $w_2 = 400$ and $w_3 = 1$. The initial values of the tuning variable is given as $\boldsymbol{z}(0) = [0.5 \ \ 1.0 \ \ 0.0 \ \ 1.0 \ \ 0.0 \ \ 1.0 \ \ 0.0 \ \ 2.0]^{\mathrm{T}}$. Note that the initial values are selected after performing several preliminary experiments by guaranteeing a stable response is obtained.

Fig. 2 shows the response of the objective function convergence after 400 iterations to produce the best tuning variable $\boldsymbol{z}^* = [0.7894 \quad -1.4397 \quad -0.1125 \quad 2.6471 \quad -0.7519 \quad 1.4668 \quad 0.3649 \quad -0.3804]^{\mathrm{T}}$ that corresponds to $\psi^* = [6.1577 \quad 0.0363 \quad 0.7718 \quad 443.7389 \quad 0.1771 \quad 29.2979 \quad 2.3170 \quad 0.4165]^{\mathrm{T}}$. Note that the convergence response in Fig. 2 is the best convergence response out of 30 trials. It shows that the LFSED based method is able to minimize the objective function in (3) and produce better output and input responses, which can be clearly seen in Figs. 3, 4 and 5. Here, the red-dotted line corresponds to the response of the controller based on initial PID parameters (k = 0), while the straight black line refers to optimal PID parameters (k = 400). In Fig. 3, it shows that the data-based PID utilizing LFSED successfully improves the rotary angle tracking, with very minimal overshoot and almost zero steady state error. In terms of oscillation angle (in Fig. 4), the optimal PID controller can minimize the oscillation angle faster than the initial PID controller, which is within 2 seconds. Furthermore, it produces slightly lower magnitude of oscillation angle, which is from -1.9 degree to 2.2 degree, as compared to the initial PID controller. Similarly, the control input of the optimal PID controllers produces lower settling time but with higher magnitude of input as compared to the initial PID parameter.

Furthermore, the control performances of the data-based PID based on LFSED are also compared with the data-based PID based on standard SED, in terms of the statistical analysis of the objective function, integral square error and integral square input. Table 1 depicts the performance comparison for both methods after 30 trials. Here, the numerical values with bold in Table 1 indicate the best performance. It shows that the LFSED produce slightly better statistical values (in terms of mean and best) in the objective function, tracking error and control input than the standard SED. Moreover, the LFSED also yields slightly lower worst and standard deviation values in the tracking error analysis than the standard SED. Therefore, it justifies that the proposed LFSED can yield improvement in the PID control accuracy, especially on the objective function and the tracking error than the standard SED.

TABLE I. STATISTICAL PERFORMANCES BETWEEN STANDARD SED AND LFSED

Algorithm		**Standard SED**	**LFSED**
$J(\boldsymbol{P},\boldsymbol{I},\boldsymbol{D},\boldsymbol{N})(\times 10^3)$	Mean	4.1007	**4.0761**
	Best	4.0790	**3.9304**
	Worst	4.1499	**4.1057**
	Std.	**0.0138**	0.0281
$\hat{E} + \hat{\theta}$	Mean	3.4709	**3.4372**
	Best	3.3601	**3.2960**
	Worst	3.6193	**3.5416**
	Std.	0.0590	**0.0522**
$\hat{V}(\times 10^3)$	Mean	2.7123	**2.7012**
	Best	2.6782	**2.5137**
	Worst	**2.7578**	2.7743
	Std.	**0.0215**	0.0405

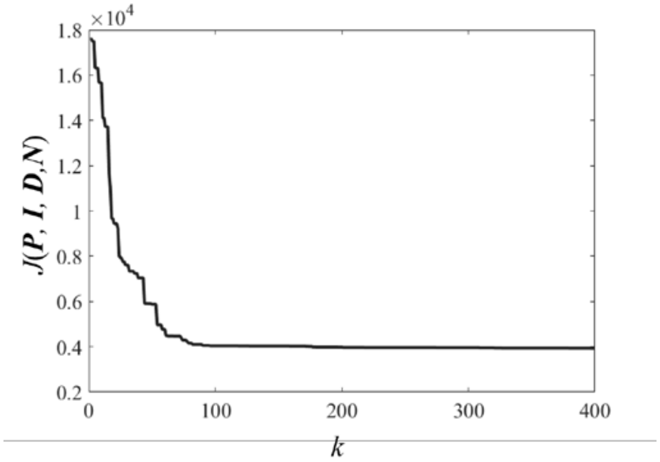

Figure 2. Convergence curve response

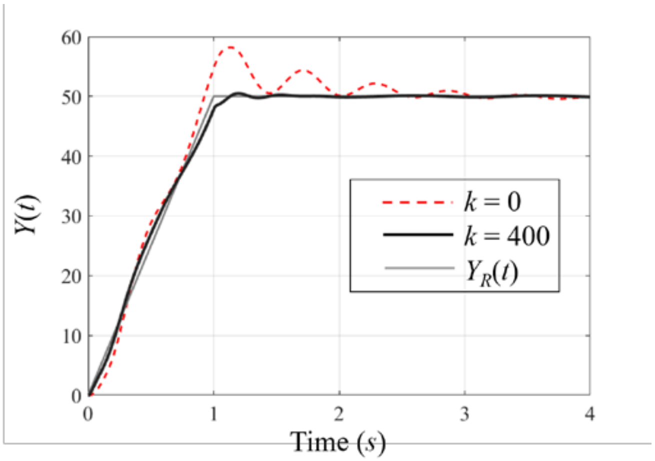

Figure 3. Rotary angle responses

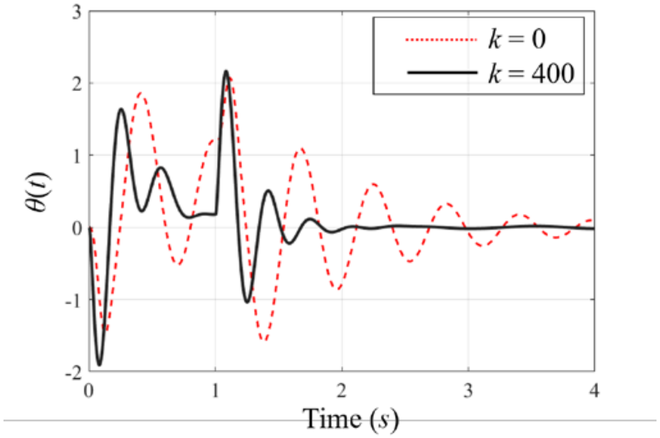

Figure 4. Oscillation angle responses

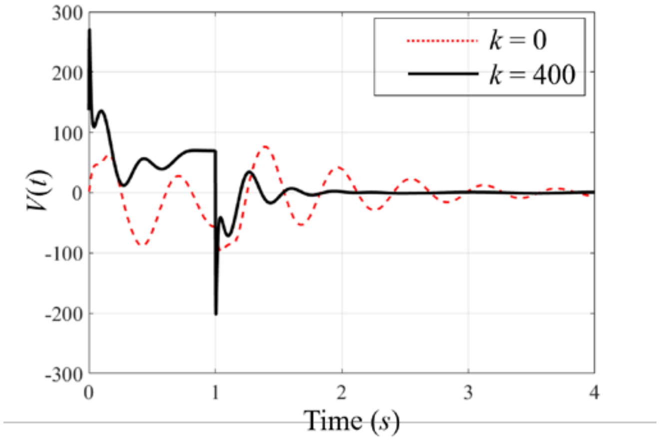

Figure 5. Input responses

IV. CONCLUSION

In this study, a data-based PID utilizing Levy Flight Safe Experimentation Dynamics (LFSED) algorithm for flexible joint robot has been presented. The results demonstrated that the proposed LFSED based method has a good capability in the improvement of the PID control accuracy. Specifically, it is shown that the proposed LFSED based method is able to produce lower values of objective function, integral square error and integral square input as compared to the standard SED based method. The findings also can be justified through the responses of the rotary angle tracking and the oscillation angle. In the future, the LFSED algorithm can be extended to tune various types controller such as fuzzy logic controller and neural network controller.

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