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Flower Pollination for Rotary Inverted Pendulum Stabilization with Delay

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Abstract

Flower pollination is a single objective optimization technique which as a unconstrained optimization method is applied for the stabilization of the rotary inverted pendulum system. It was observed that the flower pollination method gave better sensitivity in control of the pendulum about its upright unstable equilibrium position with less time and definitely indicated that the method is an energy efficient method when compared with other methods like direct pole placement. This method yielded results under the influence of time delay and have proven that the influence of time delay is significantly felt and would cause loss of energy, however the presence of flower pollination for optimization minimizes the loss incurred due to time delay and makes the system significant in terms of sensitivity.

Keywords: flower pollination, rotary inverted pendulum, stabilization, time delay, optimization

1. Introduction

The present technological advancements in the field of humanoid robots require analysis and knowledge of robotic programming synthesis. Synthesis in the case of systems with delay is an area which is not found much in literature. The synthesis can be declassified into various actuator movements. The study of the dynamics can be elaborated by taking an exploded image of the humanoid by itself. Some of the state of the art areas in humanoid mainly include bipedal locomotion, perception, human-robot interaction, learning and adaptive behavior, manipulation. These areas are one major application where the studies on inverted pendulum systems play a key role. Rotary Inverted Pendulum (RIP) is a control problem with typical applications in the field of systems and control, robotic manipulators and various levels of machine control which use vivid dynamic systems. The rotary inverted pendulum is also called the furuta pendulum and dynamics describe a circular trajectory [1]. Studies on dead time of systems which mainly results as a sum of dead times from the sensor and the actuator unit [2] plays key role in system performance. Flower pollination is a nature inspired algorithm which has emphasis on a single objective unconstrained optimization [3] is widely applied in control domain.Flowering plant has been evolving for at least more than 125 million years [4] whose evaluation is considered.The classical Indian Rope trick wherein a rope is made to stand in thin air without support is the origin for these kind of control problems. The plant model has been studied and applied for analysis of dynamics and also for extending the model to suit to industry requirements by researchers. Yan [5] have discussed methods to overcome the drawbacks in control using combined application of nonlinear backstepping and differential flatness. Yubai [6] discusses a design of suboptimal weights using iterative schemes that maximizes robust stability using h-infinity norms. Slavka [7] have discussed the prototype model design of the pendulum system using toolboxes. Mahindrakar et al [8] have discussed the system analysis with perturbations. Pan et al [9] have elaborated on a method of using fractional order approach which yields better precision in control. XU [10] et al have investigated the aspects of delay compensation using sliding mode controller. Abhishek [11] have discussed a fusion technique for control of the pendulum using fuzzy logic. Yogesh et al [12] have obtained better tracking using ANFIS based controller.

The rotary pendulum is also called the furuta pendulum and dynamics of the Furuta pendulum are somewhat more complicated because the pendulum joint describes a circular trajectory instead of a straight line. The Furuta pendulum is a system consisting of an inverted pendulum connected to a horizontal rotating arm acted upon by a direct dc motor drive. Pan [16] have worked on a special robust control method the sliding mode variation control that has solved the control problem of uncertain non-linear system effectively; it is suitable for stabilization and motion tracking. Singh [17] discuss about rule number explosion and adaptive weights tuning which are two main issues in the design of fuzzy control systems. Kumar [18] developed fuzzy method for control of the rotary inverted pendulum (RIP) using linear fusion function based on LQR mapping. Feng [19] proposed a fractional order improvement by simulating on rotary double inverted pendulum system, the result's comparison indicates that fractional-order method has obvious superiority, like overshoot decreasing, adjusting time shortening, and vibration weakening. Eker [20] designed a nonlinear observer for the inverted pendulum which uses standard structure of the linear observer with the linear model replaced by a nonlinear model. Nominal gains are determined from a linearized model. The model is also used to find a compromise between robustness and performance.Hanafy et al [21] has indicated the rule base for the inverted pendulum system and Heng et al [22] has indicated how sliding mode control. Although much work is done in the inverted pendulum type of system not much work is done combining latest algorithms like flower pollination combined with the issues of time delay. The story of evolution of various flowering plants is an example by itself on indicating the efficiency of evolutionary process.

The sensitivity of such a system when influenced by parameters like time delay with an optimization analysis done using flower pollination is not studied in literature. In view of the vivid advantages that have been outlined, this paper investigates the methods for control and stabilization of the rotary inverted pendulum using flower pollination which is a work which was not carried so far. It definitely paves way to new domains of research in the context of the analysis under the influence of time delays.

2. Plant Dynamics and Implications Due to Time Delay

As seen in the literature search, research procedure in the form of algorithms or Pseudocode or other, the effect of time delay can be verified scientifically [2], [4]. The plant that needs to be controlled can be represented as in Figure 1 with various variables as tabulated in appendix A and with the dynamics of the rotary inverted pendulum can be given using Equations 1 and 2. The nonlinear model of the mechanical part of the system has been derived using Newton or the Euler Lagrange formalism. The torque acts as the only control input. Based on the linearized system model, trajectory tracking approach to the problem of changing the angular position of the horizontal arm between an initial and final value while keeping the pendulum around its unstable equilibrium position.
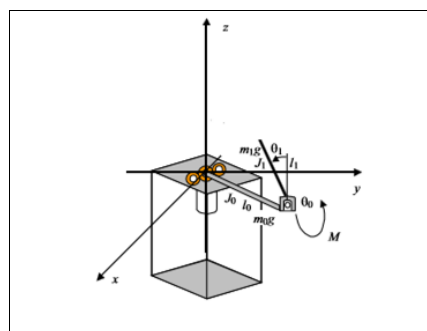

Figure 1. Rotary Inverted Pendulum Model

The dynamics of the rotary inverted pendulum are given as [1] and the notations used are same as explained in the work on the same plant.

$$M_0 \ddot{\theta}_0 + M_1 \theta_1 Cos\theta_0 \ddot{\theta}_1 - M_2 \sin\theta_0 \cos\theta_0 \dot{\theta}_1^2 - M_3 g \sin\theta_0 = 0 \qquad (1)$$

$$M_1 Cos\theta_0 \ddot{\theta}_1 + M_4 + (M_3 \sin^2\theta_0)\ddot{\theta}_1 - M_1 \sin\theta_0 \dot{\theta}_0^2 + 2M_2 \sin\theta_0 \cos\theta_0 \dot{\theta}_0 \dot{\theta}_1 = \tau \quad (2)$$

Where τ in equation 2 refers to the control input which is applied to the shaft of the arm. M_i (i= 0, 1, 2, 3, 4) in equations 1 and 2 are positive system parameters determined as:

$$M_0 = I_1 + l_1^2 m_1 \qquad (3)$$

$$M_1 = m_1 l_1 L_2 \qquad (4)$$

$$M_2 = l_1^2 m_1 \qquad (5)$$

$$M_3 = l_1 m_1 \qquad (6)$$

$$M_4 = I_2 + l_2^2 m_2 + L_2^2 m_1 \qquad (7)$$

The plant equations considered under state space representation are as follows:

$$\begin{bmatrix} \ddot{\theta}_0 \\ \ddot{\theta}_1 \\ \dot{\theta}_0 \\ \dot{\theta}_1 \end{bmatrix} = \begin{bmatrix} bd/E & -CG/E & 0 & 0 \\ qd/E & -bG/E & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_0 \\ \dot{\theta}_1 \\ \theta_0 \\ \theta_1 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ A_1 \\ A_2 \end{bmatrix} u \qquad (8)$$

Where $a = J_{eq} + mr^2$;　$b = mLr$; $C = 4/3ML^2$; $d = mgL$; $E = ac - b^2$;

　　　　The dynamics of the plant are modified to accommodate the time delay influence on the system. So, taking the four states that represent as follows a fifth state is added which will influence the system parameter and the effect of the state is considered as time delay. A transport delay was incorporated into the system which would be τ_1. The time delay parameter would dynamics would involve an additional state defined from the following:

$$\bar{x}_m (1 + \frac{s\Gamma}{2}) = \bar{x}_1 (1 - \frac{s\Gamma}{2}) \qquad (9)$$

$$x_m - x_1 = -(\dot{x}_m - \dot{x}_1)\frac{\Gamma}{2} \qquad (10)$$

Where Γ in equation refers to the time delay in the control input which is applied to the cart position and X_m denotes the modified output state condition. The following assumption is additionally considered along with generic assumptions as in [2] which were never investigated by researchers earlier for a rotary pendulum.
a) A small delay is considered in transmitting the input applied to the pendulum.
　　　　The derived plant equations are considered as follows under state space representation as follows:

$$\begin{bmatrix} \ddot{\theta}_0 \\ \ddot{\theta}_1 \\ \dot{\theta}_0 \\ \dot{\theta}_1 \\ \dot{\nabla} \end{bmatrix} = \begin{bmatrix} 0 & bd/E & -CG/E & 0 \\ 0 & qd/E & -bG/E & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -4/\tau 1 & -2/\tau 1 & 0 & -1/\tau 1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_0 \\ \dot{\theta}_1 \\ \theta_0 \\ \theta_1 \\ \nabla \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ A_1 \\ A_2 \\ 0 \end{bmatrix} u \qquad (11)$$

Where

$$a = J_{eq} + mr^2 \qquad (12)$$

$$b = mLr \qquad (13)$$

$$c = 4/3ML^2 \qquad (14)$$

$$d = mgL \qquad (15)$$

$$E = ac - b^2 \qquad (16)$$

$$G = \frac{\nabla_m \nabla_g K_t K_m K_g^2 - B_{eq} R_m}{R_m} \qquad (17)$$

$$A_1 = \frac{c\nabla_m \nabla_g K_t K_g}{R_m E} \qquad (18)$$

$$A_2 = \frac{b\nabla_m \nabla_g K_t K_g}{R_m E} \qquad (19)$$

3. Predominant Pole Determination Using Flower Pollination

Flower pollination algorithm is a nature-inspired algorithm, based on the pollination of plants. Yang [4] has clearly developed and outlined the advantages based on how pollen gets transferred which becomes the approach for the development of the algorithm. Nature has its vivid variety of plants which have evolved over centuries by a natural pollination process. The method the species of flowers use for evolving is interesting and thought provoking. The movement pattern of pollen from one flowering plant to another is a significant way which could be used for applying it as an algorithm for engineering problems. Biotic, crosspollination may occur at long distance, and the pollinators such as bees, bats, birds and flies can fly a long distance, thus they can considered as the global pollination. In addition, bees and birds may behave as Levy flight behaviour, with jump or fly distance steps obeying a Levy distribution [4]. The algorithm for the pollination is given below where the fitness considered is a cumulative function of all the constraints that are acting on the system.

Algorithm:
1. Initialize population
2. Find the best solution for the designated fitness function (Energy Function)

$$Z = (1 - E(1))^2 + 100 * (E(2) - E(1)^2)^2 + 100 * (E(3) - E(2)^2)^2$$

3. Provide switch probability
4. While N<Generations
      a. For all flowers
            i) Evaluate levy distribution
            ii) Evaluate global solution
5. If new solution is better update previous solution
6. Find current best solution
7. Designate the best positions as the pole locations

3. Results and Analysis

The analysis that was done as part of this study is categorized as case studies that varied mainly in terms of Computation time(Tc) and other important parameters such as
   a. Time delay
   b. Flower pollination parameters (Probability switch for levy distribution, population)
The poles are [-2.8 + 2.8i; -2.8 - 2.8i;-30; -40; -60]

Table 1. Flower Pollination Analysis

Case ID	Fitness Value	Best Solution	Iterations	Delay (Secs)	Tc(Secs)
1	10.28-2.39i	-0.87069+0.046i ;0.51183-0.056i ; 0.15285-0.010i	400	4	-
2	-247.89+15928.97i	1.8041-2.13i ; -1.8582+3.4i; -2+0i;	5000	1	8.04
3	-12.9213-15.23i	1.7009-1.06i ;-0.13107+0.38i; -0.2807+0.30i;	10000	1	6.62
4	1.19+0.22i	0.31499+0.00i ; 0.18518+0.01i ; 0.025453+0.01i	400	0.02	42.82
5	-38.80-15.59i	1.0412-0.035i; 1.1717+0.220i ; 1.5025-0.06i	400	1	13.47

Table 2. Performance Analysis of Flower Pollination

Category ID	Population	Levy Distribution	Iterations	Sensitivity
1	20	.8	20	S_T =High
2	50	0.4	100	S_{fp} =Low

Case i) In this the total number of evalutions that were considered was 400 and the best solution that was obtained for the fitness is where the fitness minimum value is indicated in Table I. The poles that were placed using this method are also indicated and table II indicates the two categories in which the levy distribution and population were varied. It was seen that the sensitivity of the responses of the states for variation of population and levy distribution was less. However the significant impact of sensitivity was seen in S_T and was high when compared to the sensitivity for flower pollination (S_{fp}) cases as per category ID #2.
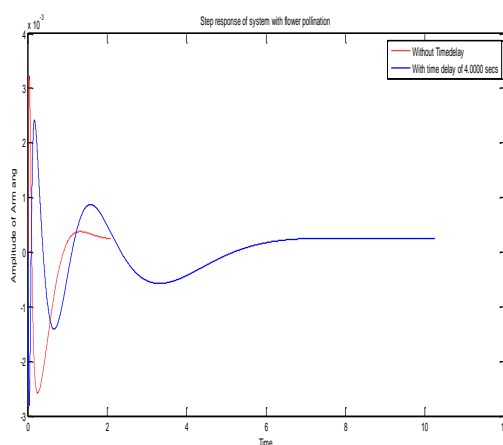

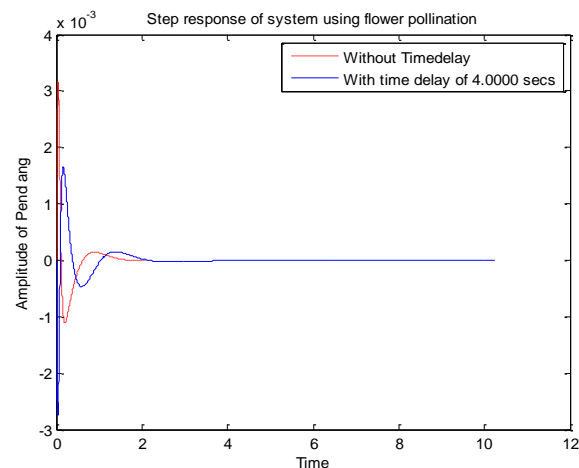Figure 2. Amplitude of Arm Angle for a Delay of 4 Seconds

Figure 3. Amplitude of Pendulum Angle for a Delay of 4 Seconds

Figure 2 indicates the variation of the arm angle for a delay of 4 seconds and it is clearly seen that the power loss is less and the overshoots with integrated time delay are also relatively less when compared to the case where the power loss is more. The variations is also seen for

less overshoot with integrated time delay for the pendulum angle in Figure 3 which indicates that there is less power loss and the energy usage or the control effort in the stabilization of the pendulum about the pendulum is less. The integrated model helps the system to have better control responses with less peak overshoots and relatively faster settling time. This would make the system response smoother with lesser oscillations. This clearly depicts the control efforts are less are the system response is smoother and more robust with the integrated time delay. Incorporating the delay as an independent state has made the overshoots reduce for the states indicating the velocity components for the rotary arm and the pendulum.

The response of the system when the time delay is reduced to 0.002 seconds shows very less variation in the step response of the system using flower pollination. This is imperative in this case as the delay of 0.02 seconds as such on one of the encoders of the system for a such a low value will not effect the system responses in terms of either the control effort required for stabilization, the peak overshoots required or the settling time. This clearly indicate the amount of power loss in this case is almost same to that of the case with no time delay. The responses clearly indicate that the control effort required is very much same and the time delay as such doesn't effect the system response. This indicates that the amount of powerloss involved with the system stabilization is more or less same and the control effort is same in terms of having similar peak overshoots and settling times. Figures 4 and 5 indicate the variations on the rotary arm and pendulum for the system response when a unit delay is considered. As the delay is again increased from a lower value of 0.02 seconds to one unit, the settling times, the peak overshoots become different. This indicates that with the integrated time delay model and by fine tuning the controller gains using settling time conditions we can see that the response has vivid oscillations which indicates in one sense the power losses associated with each of the state. This also indicates that the system dynamic response is affected by the time delay for the settling time and the overshoot, however the integrated model still makes the overshoot reduced because of the inclusion of the additional state into the system matrix.
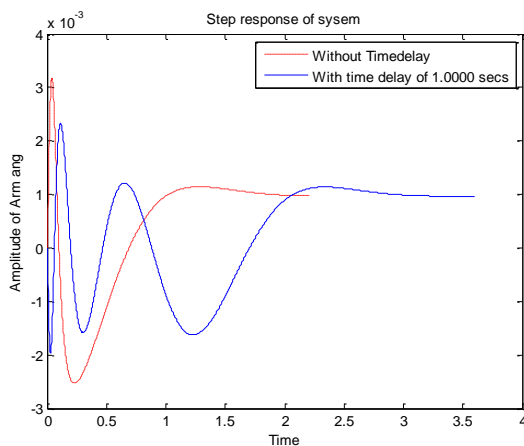

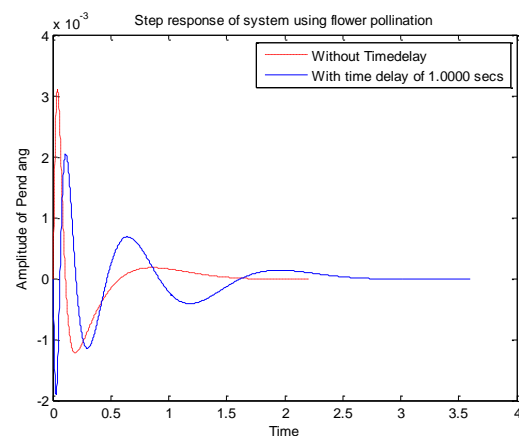Figure 4. Arm Angle for Time Delay of 1 Second

Figure 5. Pendulum Ang for Time Delay of 1 Second

Although the variation of the velocities indicated the presence of oscillations which is an indication of more power wastage in the stabilzation of the system, it is achieved at the cost of the overshoots which have been suppressed which becomes a guiding parameter for the system stabilization.

Table 3. Parameters

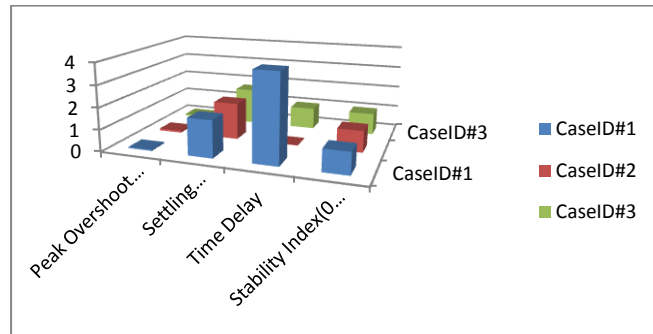| Parameter	Value
Population Size	20
Probability Switch	0.8

Figure 6 Parameter Variation for Different Cases

Table 4. System Response Specifications

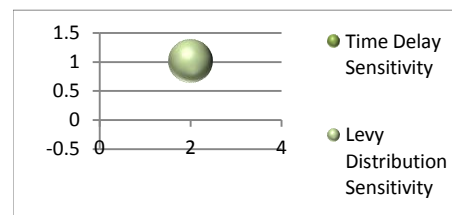| Case ID	Peak Overshoot Time(Pend Velocity)	Settling Time (Pend Vel)	Time Delay	Stability Index(0 or 1)
	0.06	1.7	4	1
2	0.09	1.7	0.02	1
3	0.09	1.7	1	1

Figure 7. Bubble Chart Analysis

It can be clearly seen from Figures 2 to 5 that the stability achieved in comparison for various time delays was more or less the same but the variation is seen in terms of the control effort required, the power wastage that happens with varied oscillations and less settling time and decreased peak overshoots. Table 4 indicates the settling time and peak overshoot comparisons for the three cases where in case I the time delay was 4 seconds, in case II the time delay was 0.002 seconds and case III the time delay was 1 second. It was observed that the effect of time delay was not predominant. In all the cases it was assume that the probability switch was 0.8 and population was 20. A comparison of various parameters is given in Figure 6. Figure 7 clearly indicates the impact of time delay on sensitivity of the system is high when compared to the parameter variation of pollen levy distribution changes which is not significant based on Table 4 and 3. As seen in Table 4, in all the cases the stability index was high which clearly indicates that the system was stable and was efficiently controlled. Figure 7 is a bubble chart and the relative importance of time delay becomes predominant over the significance of the variation of the flower pollination. Thus, the bubble for the sensitivity as per Table 2 is low and thus the bubble is not noticed for levy distribution sensitivity.

4. Conclusion

From the analysis it can be concluded that flower pollination method is an effective method for the control of stabilization of inverted pendulum wherein the design of the closed loop system poles was achieved by optimization. It can be further applied to complex dynamic systems such as robotic manipulators, space crafts, advanced under actuated ships which require energy efficient methods and this method is directly a method wherein stability index will be high. The sensitivity studies carried out indicate the impact due to the inclusion of time delay into the system parameters significantly affect the system when compared to that of parameter variation of the pollination process. Though pole positions are determined by the flower pollination, the predominance of time delay and design of poles with a given set of flower pollination gives the necessary condition within the limits of time delay and the parameter variation of levy distribution is significantly less. The sensitivity analysis done can be applied to high end complex dynamic robotic systems wherein the sensitivity of cruicial parameters can be

analyzed and thus can be utilized for the understanding and control of these systems. The efficient energy usage depicted through the flower pollination could be applied for a class of robotic systems.

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Appendix A: System Parameters of Rotary Pendulum

Parameter	Description	Value
M_p	Mass of Pendulum	0.127 kg
M_r	Mass of rotary arm	0.2570 Kg
R_m	Motor armature resistance	2.6 Ohm
B_p	Equivalent Viscous Damping Coefficient	0.0024 N.m.s/rad
J_{eq}	Equivalent moment of inertia w.r.to load	0.0021 Kg.m^2
J_m	Motor armature moment of inertia	4.6063e-07 Kg.m^2
J_r	Rotary arm moment of Inertia	9.9829e-04 Kg.m^2
L_p	Pendulum full length	0.3365m
K_m	Motor back-emf constant	0.0077 V.s/rd
K_t	Motor torque constant	0.0077 N.m/A
l_p	Distance from Pivot to Centre Of Gravity	0.1556 mt
l_r	Rotary arm distance from pivot to center of mass	0.0619 mt
VMAX_AMP	Amplifier Maximum Output Voltage	24V
IMAX_AMP	Amplifier Maximum Output Current	4A