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PERFORMANCE OF PID CONTROLLER OF NONLINEAR SYSTEM USING SWARM INTELLIGENCE TECHNIQUES

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Abstract

In this paper swarm intelligence based PID controller tuning is proposed for a nonlinear ball and hoop system. Particle swarm optimization (PSO), Artificial bee colony (ABC), Bacterial foraging optimization (BFO) is some example of swarm intelligence techniques which are focused for PID controller tuning. These algorithms are also tested on perturbed ball and hoop model. Integral square error (ISE) based performance index is used for finding the best possible value of controller parameters. Matlab software is used for designing the ball and hoop model. It is found that these swarm intelligence techniques have easy implementation & lesser settling & rise time compare to conventional methods.

Keywords:

Swarm Intelligence, Ball & Hoop System, PID Controller, Integral Square Error

1. INTRODUCTION

The proportional Integral Derivative (PID) controllers are used in several industrial processes in the process industries. The PID controllers are so important due to its simplicity of design and robust performance for simple or complex nonlinear industrial processes [1] [2]. The three important parameters of PID controllers are proportional gain (K_p), integral constant (K_i) and derivative constant (K_d). The PID controller can be define using following differential equation,

$$G(s) = k_p + \frac{k_i}{s} + k_d \tag{1}$$

To achieve the desired response in the design of PID controllers these three constant should vary, it is called tuning of the controller. The tuning of the controller should be done so that output response has minimal settling time with small or zero overshoot. The two classical methods Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) have been used from many years for optimal tuning of PID controllers [3] [4]. Many times the conventional PID controllers tuning methods fail to get satisfactory response when the plants are nonlinear. Now a day, several heuristic algorithms have been developed for solving optimization problems [5]. Evolutionary algorithm (GA) and swarm intelligence based algorithms (PSO) are two important groups of population based algorithms.

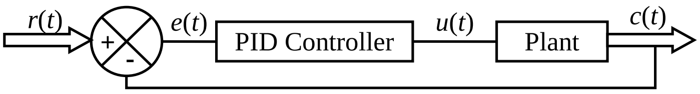

Fig.1. Closed Loop Control of Plant

A new swarm intelligence based algorithm is ABC algorithm developed by Karaboga in 2005 [6] [7]. The advantage of ABC is that it does not have slower convergence and tendency to stay on local optima. Several processes in industry have unstable behavior, such as various types of combustion systems, distillation columns, reactors etc. [8]. Without proper controlling of these types of systems it can be a risk to perform some real time experiments [9]. Modeling and simulation can be a safe method to find out the properties of such types of systems.

Performance index is a measure of quantification of system performance. The performance of a PID controller is suitably represented by the performance index. It is helpful for designing the optimum system effectively and to adjust the PID parameters in the system to get the required specification. Performances indices generally accepted by the control engineering discipline include the integral absolute error (IAE), integral square error (ISE), integral of time multiplied by square error (ITSE) and the integral of time multiplied by absolute error (ITAE). They are defined below,

$$IAE = \int_0^\infty |e(t)| dt$$

$$ISE = \int_0^\infty |e^2(t)| dt$$

$$ITAE = \int_0^\infty t|e(t)| dt$$

$$ITSE = \int_0^\infty t|e^2(t)| dt$$

These criterions places little emphasis on initial errors and heavily penalize errors occurring late in the transient response to a step input. Therefore, for the swarm intelligence, PID tuning, these performance indices represent error so all they should have minimum value. In transient response analysis maximum overshoot, rise time and settling time are significantly considered, for faster systems all they should have minimum possible value.

2. DYNAMICS OF BALL AND HOOP SYSTEM

In Ball and Hoop system steel ball is able to freely move on the inner surface of a circular hoop that is movable. The groove is present on the inside edge of the hoop due to which steel ball can roll freely inside the hoop. A motor is also used for rotation of the hoop. Initially ball moves in the direction of hoop rotation when it is rotated but after sometime at particular point, gravity balances the frictional forces and the ball falls back. By repeating this process ball will move in oscillatory motion.

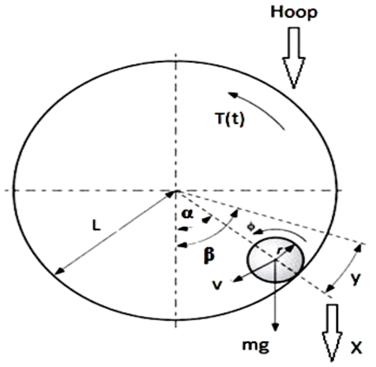

Fig.2. Ball and Hoop System

The Fig.2 shows the dynamics of Ball and hoop system, the system have several variables, hoop radius (L), ball mass (m), ball angle with vertical (α), hoop angle (β), ball radius (r), ball position on the hoop (y), input torque to the hoop (T). The Ball and Hoop model is a fourth order system [10] written as,

$$G(s) = \frac{C(s)}{R(s)} = \frac{1}{s^4 + 6s^3 + 11s^2 + 6s} \quad (2)$$

The Eq.(2) refers to original model of ball and hoop system. Another transfer function model has been also used here to validate the program codes which have been used to tune the PID parameters optimally. The fourth order transfer function of perturbed ball and hoop system is given as,

$$G_1(s) = \frac{1}{s^4 + 6.3s^3 + 12.1127s^2 + 6.9457s} \quad (3)$$

Since above mentioned system $G(s)$ and $G_1(s)$ is unstable, some optimization algorithms should be applied to stabilize them and to find optimal value of PID Parameters. A suitable fitness function is opted consist of a few components functions like system overshoot, settling time, rise time and peak time to minimize the error occurred in the plant.

3. SOFT COMPUTING TECHNIQUES

Several soft computing techniques used for tuning of PID controllers are particle swarm optimization (PSO), artificial bee colony optimization (ABC), bacterial foraging optimization (BFO) etc. Description of these algorithms is given in this section.

3.1 ARTIFICIAL BEE COLONY ALGORITHM

It is recently developed optimization algorithm which is related with honey bee [11] [12]. A gathering of honey bee is called swarm and able to complete any task with social behaviour. Three distinct types of bees are present in ABC algorithm these are called employed bees, onlooker bees and scout bees. Employed bees try to find food nearby the place where food is gathered and also share the information of food sources with onlooker bees. Onlooker bees try to select best food sources from those found by employed bees. The food sources have good quality have more chances to select by onlooker bees compare to lower quality food. Scout bees carrying out random search. The swarm is divided in two groups in ABC algorithm the first half group represent the employed bees, and the second half group represent the onlooker bees. The total solutions present in the swarm are equal to the quantity of employed bees or the onlooker bees.

Initial population of N solutions (Food sources) is generated by ABC and this population is randomly distributed. Here N denotes the swarm size. Consider $X_p = \{x_p, 1, x_p, 2……, x_p, Z)$ represent the p^{th} solution in the swarm, where Z represents the dimension size. A new solution W_p is generated by each employed bee X_p in neighborhood of present solution which is given by,

$$W_{p,q} = X_{p,q} + \mu_{p,q}\left(X_{p,q} - X_{q,r}\right) \quad (4)$$

where, X_r denotes a randomly selected candidate solution ($p \neq r$), here q represent a dimension index selected randomly from the given set (1,2,3,..,Z), and $\mu_{p,q}$ represent a random number within the limit [-1, 1].

After generating of new candidate solution W_p, a greedy selection method is used. If the fitness value of parent X_p is less than the fitness new value W_p than update X_p with W_p otherwise X_p is not changed. Nectar information is found out by onlooker bee and it also chooses the food source according to its nectar amount. The roulette wheel selection mechanism is used for this probabilistic selection that is given by,

$$T_p = \frac{fit_p}{\sum_{q=1}^{q=N} fit_p} \quad (5)$$

where, fit_q is the fitness value of the p^{th} solution present in the swarm.

3.2 PARTICLE SWARM OPTIMIZATION (PSO)

The particle swarm optimization was originally developed by Kennedy and Eberhart [10]. In this method multidimensional search space is opted and in each particle social behaviour is simulated. In each iteration's, particles find their positions according to a set goal, and local nearby particles share memory information to adjust velocities and positions of individuals. Each Particle in the swarm is represented by the current position of the particle and the current velocity of the particle [14]. In particle swarm optimization each particle has an updating position vector and updating velocity vector by moving through the problem space.

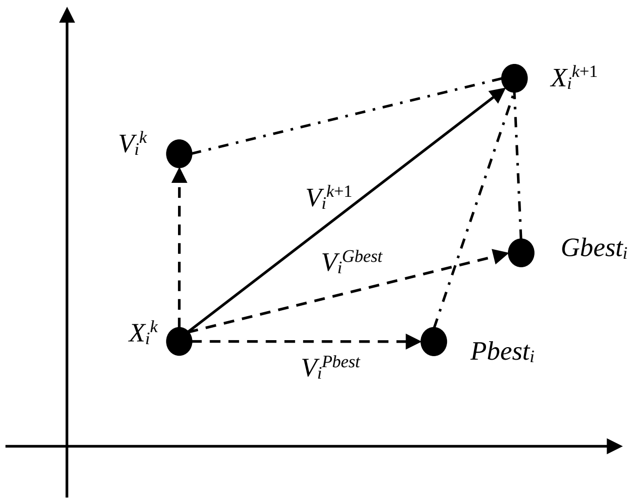

Fig.3. Finding the Searching Point by PSO

3.2.1 PSO Algorithm:

In the swarm the j^{th} particle is represented as, $X_j = (x_j^1, x_j^2, ..., x_j^n)$ in the n dimensional space.

The updated velocity and the distance is given as,

$$V_{j,k}^{(t+1)} = W \cdot V_{j,k}^{(t)} + C_1 \times rand(\ ) \times \left(Pbest_{j,k} - X_{j,k}^{(t)}\right) + C_2 \times rand(\ ) \times \left(gbest_k - X_{j,k}^{(t)}\right) \quad (6)$$

$$X_{j.k}^{(t+1)} = X_{j,k}^{(t)} + V_{j,k}^{(t+1)} \quad (7)$$

for $j = 1,2,3,...,N$, $k = 1, 2, 3,..., n$.

where,

Pbest - Best previous position of the j^{th} particle,

g*best* - Best particle among the entire swarming population

N - Total number of particles in the group.

n - Dimension index

t - Pointer of iteration

$V_{j,k}^{(t)}$ - Velocity of particle at iteration *j*

rand( ) - Random number between 0 and 1

$X_{j,k}^{(t)}$ - Current position of the particle '*j*' at iteration

W - Inertia weight

C_1, C_2 - Acceleration Coefficients

3.3 BACTERIAL FORAGING OPTIMIZATION ALGORITHM (BFOA)

Bacteria Foraging Optimization (BFOA) is initially proposed by Passino [16]. It is inspired by the bacteria Escherichia coli. This algorithm is global optimization algorithm and used for solving several typical control problems. Presently, this algorithm is widely used by researchers because of its efficiency in solving real-world optimization problems of several fields. A set of random solutions are produced at the starting of BFOA and then foraging behaviour of E.coli is performed by four principal mechanisms: chemotaxis, swarming, reproduction and elimination.

A healthy function is used by taking the bacteria having good foraging effect and each bacteria having lower fitness value is removed. At each iteration the bacterial group moves to new foraging and try to improve the probability to find the optimum solution[19] [20].

3.3.1 Four Foraging Behaviour of BFOA:

- *Chemotaxis*: It is related with the stress response of bacteria in the environment. In this method bacterium has two positions tumbling and swimming. Tumbling indicate the movement in changing direction and swimming indicate the movement in the same direction.
- *Swarming*: It is related with the group behaviour in several bacteria like E.Coli. In this process the bacterium get the collective behaviour through attraction & repulsion forces.
- *Reproduction*: In this process least healthy bacteria die while bacteria having good health are split into two bacteria and they are placed in the same location as their parents.
- *Elimination–Dispersal*: It is related with sudden changes in local environment in the place where bacterium population lives. There can be several reasons for it like rise in temperature. Due to this some bacterium are replaced by new bacterium according to some preset probability. In this way bacterium is dispersed in new location and finds more abundant area.

4. SIMULATION AND RESULTS

The simulation and analysis of the proposed ball & hoop system and perturbed ball and hoop system is done by Matlab software. The fitness function opted here is given by,

$$F = \frac{1}{e \times \beta + overshoot \times \alpha} \quad (8)$$

where,

F - Fitness function

overshoot - peak overshoot

e - steady state error

α, β - Scaling factors (here α & β are opted 1.2)

4.1 ORIGINAL BALL & HOOP SYSTEM

Transfer function of original Ball & Hoop system is given by Eq.(2).

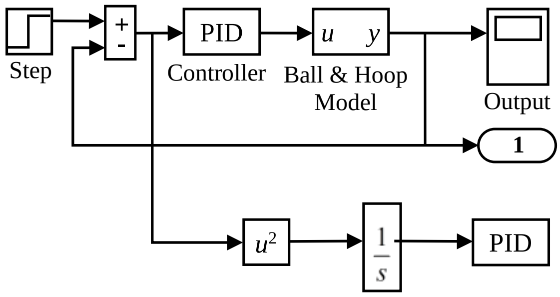

Fig.4. ISE Controller Simulation

ISE (Integral Square Error) index is given by,

$$ISE = \int_0^\infty \left|e^2(t)\right| dt \quad (9)$$

Particle swarm optimization algorithm selection parameters are given in Table.1 for both ball & hoop system and perturbed ball and hoop system.

Table.1. PSO Selection Parameters

Population size	200
Number of iterations	200
Inertia weight, *W*	0.6
Velocity constant C_1	1.5
Velocity constant C_2	1.5

Table.2. Performance of Ball & Hoop System Using Swarm Intelligence Techniques

Method of Tuning	Overshoot (%)	Settling Time (s)	Rise Time (s)	Peak Time (s)
PSO	51.6982	7.8549	0.7642	4.7341
BFO	47.6519	15.7531	1.4132	4.3128
ABC	52.2845	20.6358	1.8210	5.4241

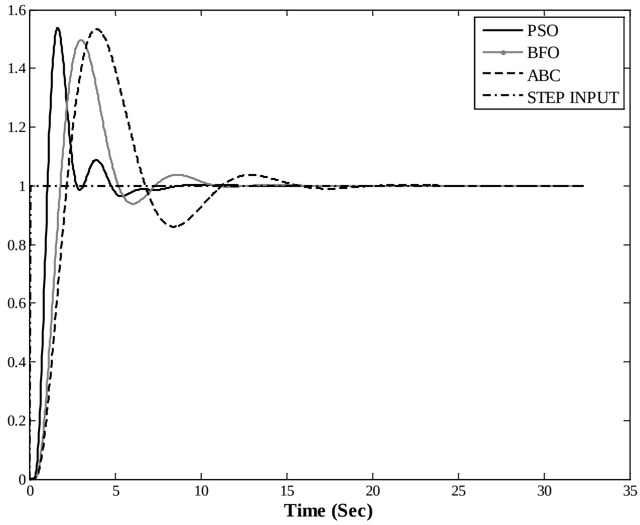

Fig.5. Comparative Step Response of PID Controller for Original Ball & Hoop System

4.2 PERTURBED BALL & HOOP SYSTEM

Transfer function of perturbed Ball & Hoop system is given by Eq.(3).

Perturbed ball & hoop system is also simulated using integral square error (ISE) controller and Matlab software.

Table.3. Performance of Perturbed Ball & Hoop System Using Swarm Intelligence Techniques

Method of Tuning	Overshoot (%)	Settling Time (s)	Rise Time (s)	Peak Time (s)
PSO	43.8965	16.1232	1.8122	4.6632
BFO	21.3845	19.6443	2.1102	6.5132
ABC	48.2031	14.2821	0.7953	1.8976

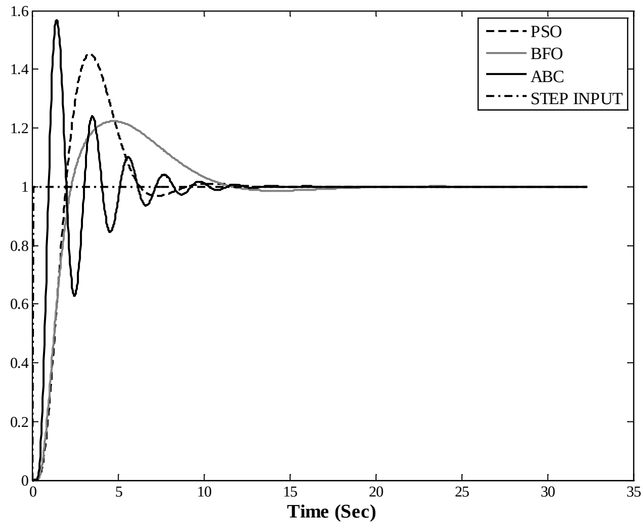

Fig.6. Comparative Step Response of PID Controller for Perturbed Ball & Hoop system

5. CONCLUSION

In this Paper, several swarm intelligence algorithms are proposed. Step responses of PID controller tuned by various bio-inspired techniques are compared. However, the classical methods are also good for simpler linear systems but these conventional methods are not suitable for non-linearized and non-minimum phase behaviour showing systems. This paper has projected the application of particle swarm optimization (PSO), bacteria foraging optimization (BFO), artificial bee colony (ABC) optimization for the controller design of a Ball and Hoop System. The main objective is to minimize the settling time, rise time, steady state error and the maximum overshoot. Here the best results have been obtained for Ball and Hoop plant by robust tuning of PID controller and the errors have been minimized for the stabilization of system. For ISE index, the optimal parameters for the system are attained by using PSO tuned PID controller but the overshoot is high. In the same way, BFA optimization has produced the least overshoot for ISE index. Artificial Bee Colony (ABC) optimization has attained the least rise time for ISE for perturbed ball & hoop model.

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