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Stability Control of Ball and Beam System Using Heuristic Computation Based PI-D and PI-PD Controller

[1] T. Ali, [2] M. Adeel, [3] S. A. Malik, [4] M. Amir

[1,2,3,4] Department of Electrical Engineering, International Islamic University Islamabad, Pakistan

[1] tayyab.ali@iiu.edu.pk

Abstract- The ball & beam system (BBS) exhibits an unstable open loop response, which requires a controller to act as a stable system. In this paper, Proportional Integral-Derivative (PI-D) and Proportional Integral-Proportional Derivative (PI-PD) controllers are suggested for the stability control of BBS. The tuning of these controllers is carried out using two popular heuristic computational techniques including Simulated Annealing (SA) and Cuckoo Search Algorithm (CSA). Furthermore, four different performance indices including Integral of squared error (ISE), Integral of absolute value of error (IAE), Integral of time multiplied by squared value of error (ITSE) and Integral of time multiplied by absolute value of error (ITAE) are used for the evaluation of transient performance of the suggested controllers. MATLAB/Simulink simulations are performed to show the closed-loop step-response achieved by the proposed controllers. The comparison of transient performance parameters including settling time (t_s), % overshoot (os), rise time (t_r) and steady state error ($e_{ss.}$) obtained by the proposed controllers is made with H-infinity based PID and Particle Swarm Optimization (PSO) based I-PD (PSO-I-PD) controllers. It is observed that BBS system with PI-PD controller tuned by CSA (CSA-PI-PD) yields oscillation free, stable, and fast response. CSA-PI-PD controller with ITAE index provided response of the BBS with zero % overshoot and settling time of 1.21s as compared to 20.7% overshoot and 4.3s settling time yielded by H-infinity based PID controller. Furthermore, CSA-PI-PD controller yielded transient response with 72% reduction in settling time and 88% reduction in rise time in comparison to PSO-I-PD controller.

Keywords-Ball and Beam system, PID controller, Evolutionary computation, Simulated Annealing (SA), Cuckoo Search Algorithm (CSA), Proportional Integral- Derivative (PI-D) and Proportional Integral-Proportional Derivative (PI-PD) controller

I. INTRODUCTION

The stability control is always being a crucial research problem in control systems. An unstable system is a useless system; therefore, most of the practical systems essentially require feedback control for stability and desired transient performance. Conversely, a fundamental problem arises in the study of such real, unstable systems is that they cannot be brought into the laboratory for analyses. Due to its simplistic design and dynamic characteristics, ball and beam system seems to be an ideal model for the solution of complex and non-linear control systems [1].

The ball & beam system is used as a benchmark for studying dynamics of various real systems including rocket toppling control system, control of exothermic & chemical process reactions and aerospace control etc [2]. Moreover, the system is widely used in control engineering teaching and laboratories for the demonstration of stability analysis and behavior of many complex and non-linear systems. The BBS consists of basic components such as ball, beam, motor, lever arm, gear, support block and position sensors. The BBS is non-linear and open-loop unstable system [3]. Due to unstable behavior of the system, feedback control is necessary to make this system stable. The main aim in ball & beam system is to adjust the ball position on the beam automatically by altering the beam angle [4-5].

Due to practical importance of the ball and beam system, many researchers have proposed variety of control methodologies for stability of the system. Simple Internal Model Control (SIMC) based PID controller has been implemented for the real time ball and beam system in [3]. Linear Quadratic Regulator (LQR) has been explored using Genetic Algorithm (GA). Moreover, a non-model based PID controller and model-based hybrid PID-LQR have also been implemented [4]. Dynamic responses of single input fuzzy logic controller (SIFLC) and PID controller have been investigated for the BBS [5]. Fuzzy controller has also been employed for the stability control of ball and beam system. Lyapnouv's stability theory has been used to derive a new stability criterion [6]. A feed forward neural network based controller has been invented to control the BBS using Genetic Algorithm (GA). It is suggested that proposed approach can be employed for the optimum control of other non-linear systems [7]. In [8], optimum PID controller has been designed with Genetic Algorithm (GA) and Differential Evolution (DE). Particle Swarm Optimization (PSO) based I-PD (PSO-I-PD) and H-infinity method based PID controllers have also been explored to control the ball and beam system. In [9], author has implemented the Improved Ant Colony Optimization (ACO) based fuzzy controller for the real-time ball & beam system. In [10], Co-efficient Diagram Method based PID (CDM-PID) controller has been successfully implemented to control the system. The results of CDM-PID controller have been compared with conventional Ziegler Nicholas (ZN) method for evaluation purpose. A fuzzy cascade controller has been designed for the ball and beam system in [11]. PI-PD controller is a modified version of classical PID controller. In [12], PI-PD has been optimized using extended non-minimal state space model predictive control (ENMSSMPC) approach for the optimum control of gasoline vapor pressure in a stabilized tower. PI-PD controller has also been implemented for the control of unstable and integrating processes by changing the poles of the systems to desired positions [13]. In [14], cascade PI-PD controller is designed for the automatic generation control (AGC) of hydro, gas and thermal power unit based power systems in presence of Plug in Electric Vehicles (PEV). The PI-PD controller has also been implemented for stable and unstable first order plus time delay (FOPDT) processes [15]. The Fuzzy-Proportional Integral Derivative (Fuzzy-PID) controller has been designed for the position control of ball and beam system [16].

In designing a controller, optimum values of controller parameters (gains) plays the vital role. There exist many classical tuning methods like Ziegler Nicholas (ZN), modified Ziegler Nicholas (m-ZN) and Cohen Cool etc. However, in recent years, nature-inspired computational techniques have been widely used for the tuning of different controllers and these techniques have shown satisfactory results. A glance at the literature reveals that many different control methods have been used for the stability control of BBS; however, PI-D and PI-PD controllers have not been attempted for the BBS yet. The present work is emphasized on the stability control of ball and beam system (BBS) for which two different PI-D and PI-PD controllers are designed. Further, two heuristic computational techniques including SA and CSA methods are employed for the tuning of suggested PI-D and PI-PD controllers. The main contributions of this paper are:

(a) Design of PI-D and PI-PD controllers for the ball and beam system.

(b) Tuning of the proposed controllers using two evolutionary computational techniques including Simulated Annealing (SA) and Cuckoo Search Algorithm (CSA).

(c) Performance evaluation of proposed controllers using four different performance indices including ISE, IAE, ITAE and ITSE.

The rest of the paper is arranged as follows:
In Section II, transfer function of the BBS is derived, Section III provides description of controller design, Section IV provides brief overview of tuning methods (SA and CSA) used in this work. The overview of performance indices is provided in Section V. Finally, results and discussion section is presented in Section VI.

II. Mathematical Modeling of Ball and Beam System

In this section, brief description of the BBS is given followed by the derivation of transfer function between position of the ball (P(s)) and gear angle (**θ**(s)). Figure 1 shows the model of ball and beam system used in this work.

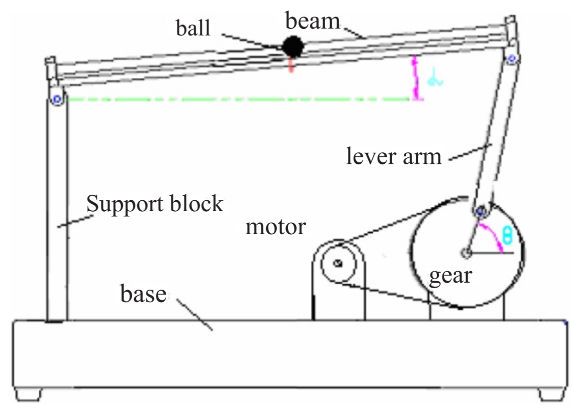

Fig. 1

In ball and beam system, the beam is mounted on the output shaft of an electrical motor. The beam will be twisted about its center axis when an electrical control signal will be applied to the motor amplifier. The main goal is to regulate the position of the ball on the beam automatically by varying the beam angle. The schematic diagram of ball and beam system is given in Figure 2.

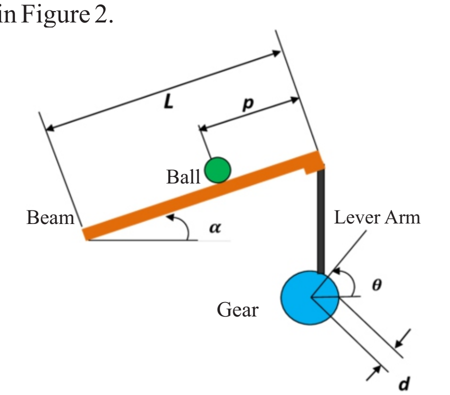

Fig. 2. Schematic diagram of ball & beam system

The ball can roll freely along the whole length of the beam. The beam is connected to the fixed support block at one side and to the movable lever arm at another one. The movement of lever arm is controlled by DC brush motor. The motor of BBS consists of built-in rotary optical incremental encoder that provides feedback information about current actual rotary position of the motor shaft. There is a slot along the beam where a linear potentiometer sensor that senses current linear actual position of the ball on the beam is present. Both measured positions are fed back to the control system to formulate a closed loop control.

The linear acceleration of the ball along the mounted beam can be expressed as Lagrangian equation of motion [3].

$$\left(\frac{J}{R^2} + m\right)\ddot{p} + mg\sin\alpha - mp\dot{\alpha}^2 \quad (1)$$

where

g represents the gravitational acceleration
R is the radius of the ball
J is the ball's moment of inertia
m is the mass of the ball
p is the position of the ball
α is the beam angle

Since (1) is a non-linear equation, linearization of (1) about beam angle (α) equal to zero gives,

$$\left(\frac{J}{R^2} + m\right)\ddot{p} = -mg\alpha \quad (2)$$

The beam angle (α) can be expressed as (3),

$$\alpha = \left(\frac{d}{L}\right)\theta \quad (3)$$

where

L is the length of the beam
d is the distance between the center of the gear and joint of the lever arm

Substituting (3) into (2), we get

$$\left(\frac{J}{R^2} + m\right)\ddot{p} = -mg\left(\frac{d}{L}\right)\theta \quad (4)$$

Taking Laplace transform of (4) yields as

$$\left[\frac{J}{R^2} + m\right]P(s) = -\frac{mgd}{L}\theta(s) \quad (5)$$

Rearranging the equation (5) gives the desired transfer function of the ball & beam system represented as $G_{BB}(s)$.

$$G_{BB}(s) = \frac{P(s)}{\theta(s)} = -\frac{mgd}{L\left(\frac{J}{R^2}+m\right)}\frac{1}{s^2} \quad (6)$$

Using the parameters values from Table 1, $G_{BB}(s)$ can be written as,

$$G_{BB}(s) = \frac{P(s)}{\theta(s)} = \frac{0.28}{s^2} \quad (7)$$

TABLE 1: PARAMETERS OF BALL & BEAM SYSTEM

Symbol of parameter	Values
m	0.11 kg
g	9.8 m/s^2
d	0.04 m
L	1 m
J	2mR^2/5 kgm^2
R	0.015 m

III. CONTROLLER DESIGN FOR BALL & BEAM SYSTEM

In this paper, two different controllers including Proportional Integral- Derivative (PI-D) and Proportional Integral- Proportional Derivative (PI-PD) controller have been employed for the stability analysis of ball & beam system. These two controllers have two degree of freedom which provides both feedback and close-loop characteristics. These characteristics can be controlled independently in order to get better transient response of the desired system [17-18].

3.1. PI-D Controller

In this control scheme PI controller in connected in feed-forward path whereas D controller is connected in feedback path as shown in Figure 3. The resulting controlling scheme is applied to ball and beam system for the investigation of desired input response. Y(s) and R(s) are the frequency domain representation of the ball position (output) and angle of the beam (input) of system respectively. K_P, K_i and K_D represent the proportional, integral and derivative gain respectively.

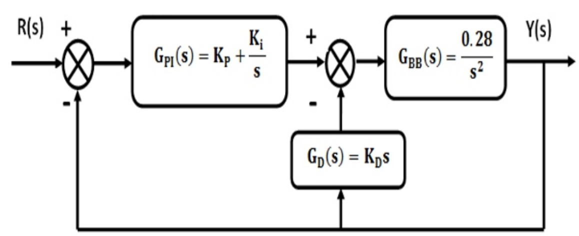

Fig. 3: Block diagram of PI-D controller applied to ball & beam system

Close-loop transfer function of the PI-D controller ($G_1(s)$) can be written as

$$G_1(s) = \frac{Y(s)}{R(s)} = \frac{0.28K_Ps+0.28K_i}{s^3+0.28K_Ds^2+0.28K_ps+0.28K_i} \quad (8)$$

3.2 PI-PD Controller

PI-PD controller is a configuration in which PI controller is connected in feed-forward path and PD controller is connected in feedback path as given in Figure 4. Again, Y(s) and R(s) are the frequency domain representation of the ball position (output) and angle of the beam (input) of system respectively whereas K_P, K_i and K_D represent the proportional, integral and derivative gain respectively.

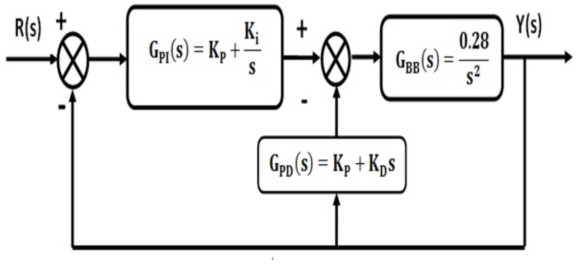

Fig. 4: Block diagram of ball & beam system with PI-PD controller

Close-loop transfer function ($G_2(s)$) for the proposed PI-PD controller and plant is written as:

$$G_2(s) = \frac{Y(s)}{R(s)} = \frac{0.28K_P s + 0.28K_i}{s^3 + 0.28K_D s^2 + 0.56K_p s + 0.28K_i} \quad (9)$$

IV. Tuning of Controllers Using Heuristic Computation

Heuristic computation techniques are artificial intelligence based algorithms, which are based upon Darwinian Theory. These techniques are very useful for optimization problems. In past, many tuning algorithms have been utilized to determine optimum values of the controller parameters. In recent decade, heuristic computational techniques have been widely used for the tuning of controllers such as Simulated Annealing (SA), Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swam Optimization (PSO). In this work, Cuckoo Search Algorithm (CSA) and Simulated Annealing (SA) have been explored. The closed loop system with controller is solved to obtain the desired error signal and then error criterion is applied to obtain resultant fitness function. The optimum values of controller parameters are found by solving the resultant fitness functions. The optimum values thus obtained are used for evaluating the controller performance. The tuning methodology employed in this work is shown in Figure 5. In Figure 5, E(s) represent the error signal that is the difference between actual and desired signal. The system keeps on finding the controller parameters until error signal decay down to zero.

4.1 Simulated Annealing (SA)

Simulated Annealing (SA) is a nature inspired optimization technique that was invented by Kirkpatrick et al. in 1983 [19]. Kirkpatrick explore the idea of Metropolis (1953). Physical annealing processes of a solid material and Simulated Annealing

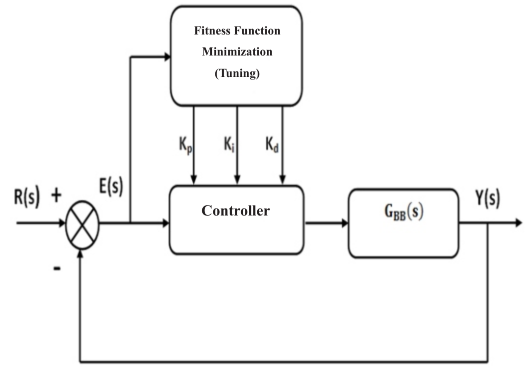

Fig. 5: Block diagram of the stability control of ball & beam system with heuristic computation tuning

for an optimization problem are analogous to each other. The minimum energy of the solid material is equal to the minimum value of cost (objective) function. Being a global optimization technique, SA can easily distinguish between different local minima. This is a very beneficial property for the researchers to optimize their problems with global minimum. SA has been effectively used to resolve different problems in recent years as demonstrated in [20-25]. The flow chart of SA algorithm is given in Figure 6.

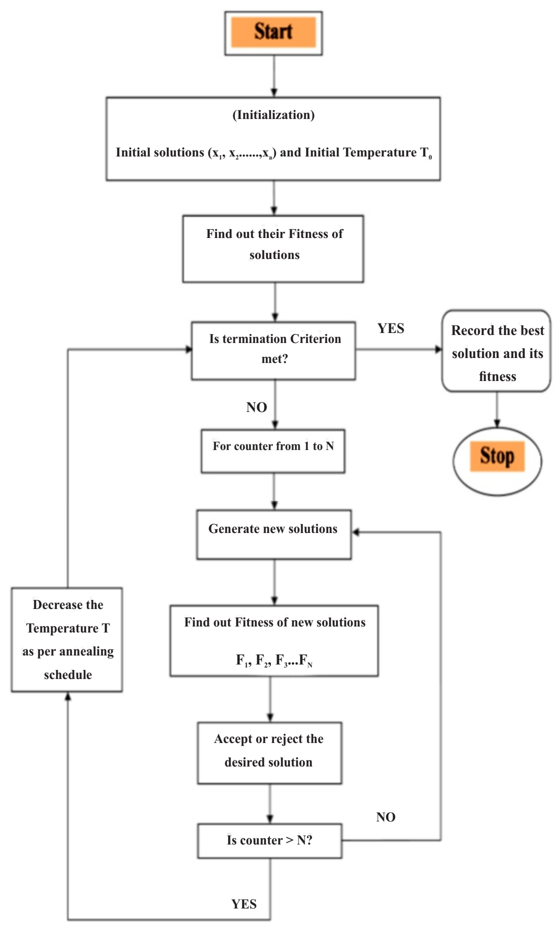

Fig. 6: Flow chart of Simulated Annealing (SA) Algorithm

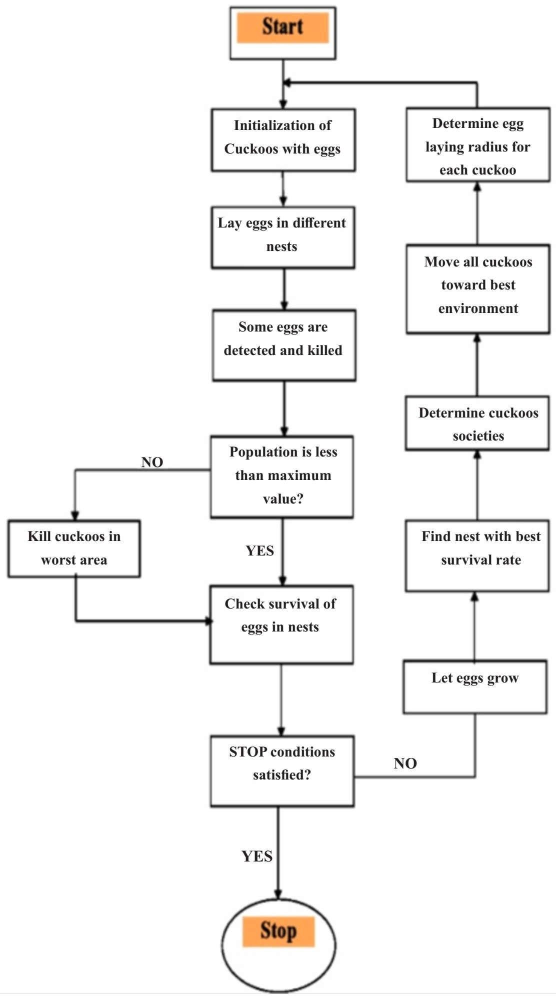

Fig. 7: Flow chart of Cuckoo Search Algorithm (CSA)

V. Performance Indices

To achieve an optimum response, we need to minimize different time domain based performance indices (error criteria). The minimization of error signal is achieved by using different tuning techniques as discussed earlier. A performance index measures the system's performance, which is associated with different parameters like overshoot (os), settling time (t_s), rise time (t_r), and steady state error ($e_{ss.}$) etc. The performance indices, which have been used in this research work are Integral of absolute value of error (IAE), Integral of time multiplied by absolute value of error (ITAE), and Integral of squared error (ISE) and Integral of time multiplied by squared value of error (ITSE). These performance indices are calculated over some defined time interval T. The time (T) is chosen in such a way that it will cover much of the transient response of the system. If a system has a response similar to 2[nd] order system, then best choice of T will be settling time (t_s). These indices can be calculated by using following formulae.

$$\mathrm{ITAE} = \int_0^T t|e(t)|dt \tag{10}$$

$$\mathrm{ITSE} = \int_0^T te^2(t)dt \tag{11}$$

$$\mathrm{ISE} = \int_0^T e^2(t)dt \tag{12}$$

$$\mathrm{IAE} = \int_0^T |e(t)|dt \tag{13}$$

All of these performance indices have been used as an objective function respectively and we have observed the system response for each performance index separately. Simulated Annealing (SA) is implemented through MATLAB Optimization Toolbox whereas Cuckoo Search Algorithm (CSA) was implemented by using MATLAB code.

VI. Simulation Results and Discussion

In this section, PI-D and PI-PD controller with Simulated Annealing (SA) and Cuckoo Search Algorithm (CSA) tuning techniques have been implemented for the stability analysis of ball & beam system. For simulations, MATLAB/Simulink software has been utilized. In all simulations, unit step input is taken as reference position. First, the open loop response of ball and beam system is investigated. Figure 8 represents the open-loop response of the system. It can be seen that the response is growing with time i.e. an unstable response, which reveal that the open loop response of the system is unstable in nature and it requires the application of a suitable controlling scheme, which can lead the system's dynamics to acquire a stable response.

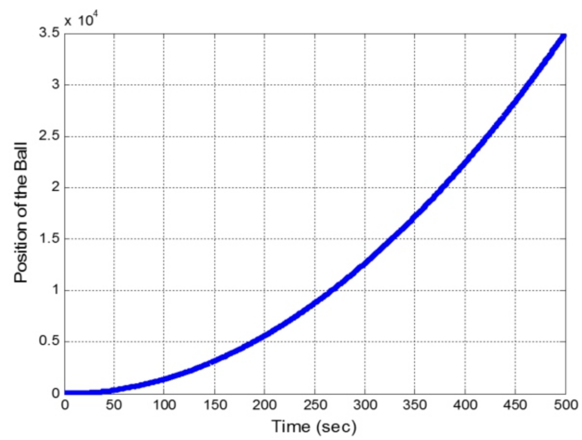

Fig. 8: Open Loop step Response of ball & beam system

Now the feedback control is applied using PI-D and PI-PD controllers tuned by SA and CSA. For performance comparison, four different transient response parameters including rise time, overshoot, settling time and steady state error have been used for the performance evaluation of controllers. In Table 2, controller parameters of PI-D controller with SA and CSA are provided.

TABLE 2: TUNING OF PI-D CONTROLLER USING SA AND CSA

Performance Index	Tuning parameters with SA			Tuning parameters with CSA		
	K_P	K_i	K_D	K_P	K_i	K_D
ISE	34.98	59.79	11.33	30.97	56.71	18.80
ITSE	29.95	59.40	14.86	34.88	60	16.83
IAE	30.40	60	17.26	27.60	47.77	11.88
ITAE	28.08	58.37	18.77	31.82	60	21.42

Figure 9 shows the closed loop response of ball and beam system with PI-D controller tuned by Simulated Annealing (SA-PI-D). It can be seen that SA-PI-D controller with ISE index gives the smaller value of rise time (0.35s) but with greater % overshoot of about 23.6% as compared to other performance indices including IAE, ITAE, and ITSE. On the other hand, SA-PI-D controller with ITSE index gives relatively smaller % overshoot (7.3%) but it gives a slightly larger settling time of about 7.27s as compared to other performance indices. As for as settling time is concerned, it is observed that ITAE index gives the lower value of settling time of 3.31s as compared to other performance indices. Further, it can be seen that SA-PI-D controller with all performance indices yields small steady state errors.

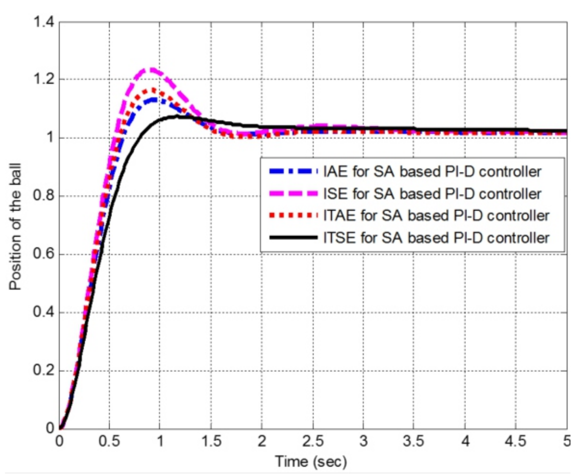

Fig. 9: Step response of BBS with SA-PI-D controller

Figure 10 represents the output response of PI-D controller tuned by Cuckoo Search Algorithm (CSA-PI-D). It can be observed that CSA-PI-D controller with ITAE index gives the smaller value of settling time (3.86s) but it gives a slightly greater % overshoot of about 31.6% as compared to other performance indices. On the other hand, CSA-PI-D controller with ITAE index also gives relatively smaller value of rise time (0.39s) but it gives a smaller steady state error too. Further, it can be seen that CSA based PI-D controller with ITSE index gives the lower value of % overshoot (2.9%) as compared to other performance indices. Moreover, CSA-PI-D controller with all performance indices undergoes a small steady state error.

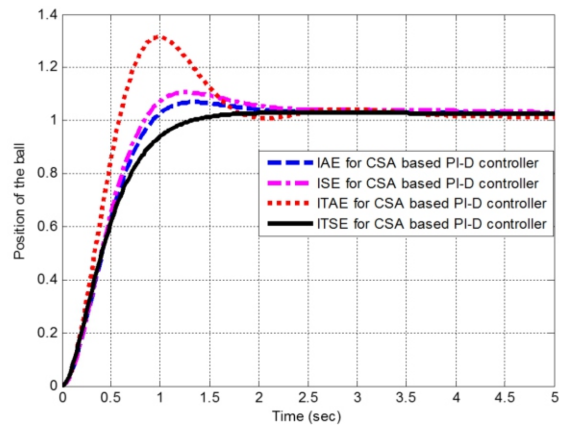

Fig. 10: Step response of BBS with CSA-PI-D controller

Table 3 shows the comparison of transient response parameters of SA-PI-D and CSA-PI-D controllers. It is analyzed from the results of Table 3 that SA-PI-D controller yields relatively better transient response than CSA-PI-D controller in terms of rise and settling time. Conversely, the comparison reveals that CSA-PI-D controller is better than SA-PI-D controller in terms of overshoot only.

TABLE 3: PERFORMANCE COMPARISON OF SA-PI-D WITH CSA-PI-D CONTROLLER

Controller \ Performance Parameter		Rise time (sec)	Settling time (sec)	% Overshoot	s-s Error
SA-PI-D controller	**ISE**	0.35	4.71	23.6	7.5e-14
	ITSE	0.52	7.27	7.3	1.2e-07
	IAE	0.43	3.62	13.1	1.8e-06
	ITAE	0.40	3.31	16.4	9.2e-07
CSA-PI-D controller	**ISE**	0.56	7.89	10.6	2.2e-08
	ITSE	0.75	8.30	2.9	3.9e-05
	IAE	0.61	7.91	6.91	3.8e-06
	ITAE	0.39	3.86	31.6	1.1e-16

Next, the performance of PI-PD controller has been investigated. The tuning parameters of PI-PD controller with SA and CSA are given in Table 4.

TABLE 4: TUNING OF PI-PD CONTROLLER USING SA AND CSA

Performance Index	Tuning parameters with SA			Tuning parameters with CSA		
	K_P	K_i	K_D	K_P	K_i	K_D
ISE	59.9	15.5	14.82	42.32	5.94	16.77
ITSE	57.4	6.81	21	56.96	3.74	27.6
IAE	59.9	5.63	17.04	42.95	3.84	18.06
ITAE	59.74	6	15.64	48.75	21.59	13.04

Figure 11 shows the output response of PI-PD controller tuned by Simulated Annealing (SA-PI-PD). It can be observed that SA based PI-PD controller with ISE index gives the smaller value of % overshoot (1.35%) and rise time (0.49s) but it gives a slightly larger value of settling time (3.50s) as compared to other performance indices. Meanwhile, SA-PI-PD controller with ITAE index gives relatively lower value of settling time (1.76s) but it undergoes a small steady state error. All other performance indices except ITAE have given zero steady state error that resulted in ideal steady state response of the system.

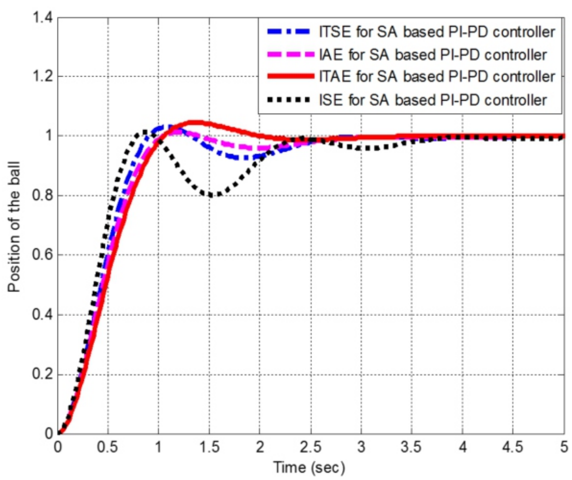

Fig. 11: Step response of BBS with of SA-PI-PD controller

Figure 12 shows the output response of PI-PD controller tuned by Cuckoo Search Algorithm (CSA-PI-PD). From the Figure 12, it is observed that all performance indices have given zero steady state error; this is a major achievement with CSA-PI-PD controller. Further, it can be analyzed that CSA-PI-PD controller with ITAE index have reduced the settling time (1.21s) with zero % overshoot whereas CSA-PI-PD controller with IAE index gives relatively lower value of rise time (0.57s) but it undergoes a small % overshoot of about 2.6%. Further, it can be seen that both ISE and ITSE indices have given zero %

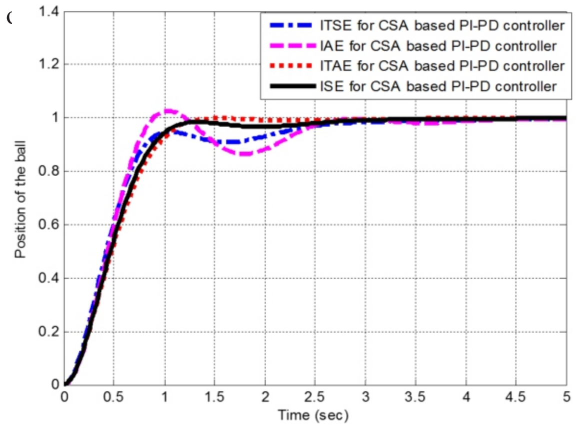

Fig. 12: Step response of BBS with of CSA-PI-PD controller

Table 5 shows the comparison of transient response parameters of SA-PI-PD and CSA-PI-PD controllers. It is observed from the results of Table 5 that both controllers yielded relatively satisfactory transient response performances. Moreover, it can be stated that % overshoot has been completely minimized to zero with CSA-PI-PD controller along with zero steady state error. Further, rise and settling time have also been reduced successfully with both SA-PI-PD and CSA-PI-PD controllers.

TABLE 5: PERFORMANCE COMPARISON OF SA-PI-PD WITH CSA-PI-PD CONTROLLER

Controller	Performance Parameter	Rise time (sec)	Settling time (sec)	% Overshoot	s-s Error
SA-PI-PD controller	**ISE**	0.49	3.50	1.35	0
	ITSE	0.58	2.50	3.14	0
	IAE	0.64	2.50	1.40	0
	ITAE	0.68	1.76	4.57	1.2e-15
CSA-PI-PD controller	**ISE**	0.72	2.51	0	0
	ITSE	0.66	2.74	0	0
	IAE	0.57	2.56	2.6	0
	ITAE	0.77	1.21	0	0

From the results of Table 3 and Table 5, it is suggested that CSA-PI-PD controller exhibits relatively better transient response performance than SA-PI-PD controller. These results clearly reveal the effectiveness of heuristic computation based PI-PD controller in terms of both transient and steady state characteristics.

VII. CONCLUSIONS

The stability control of ball & beam system is investigated using PI-D and PI-PD controllers. Heuristic computation techniques including Cuckoo Search Algorithm (CSA) and Simulated Annealing (SA) have been explored for the tuning of propsed controllers. Furthermore, four differnt performance indices such as ISE, IAE, ITAE and ITSE have been used for the assessment of transient response performance of ball and beam system with controllers . All simulations and algorithms have beem carried out in MATLAB/Simulink. The closed-loop responses of PI-D and PI-PD controllers with each tuning technique (SA & CSA) have been obtained by simulations. A comprehensive comparison between the results of proposed controllers is made for the evauation purpose. It is analyzed that both PI-D and PI-PD controllers have given satisfactoy results with each proposed tuning technique. PI-D controller exhibits more settling time (t_s), overshoot (os) and steady-state error (e_{ss}) than PI-PD controller. Further, it can also be seen that PI-PD controller with all perfromance indices except IAE has completely eliminated the % overshoot. That's why, it is suggested that CSA-PI-PD controller is relatively much better than H-infinity based PID and PSO based I-PD controllers. On the basis of simulation results, it can be concluded that PI-PD controller tuned by SA and CSA methods is a viable and handy controller for the ball and beam system. In future, CSA-PI-PD controller can be applied to some other processes/plants. Further, other heuristic computational techniques such as Teaching Learning Based Optimization (TLBO), African Buffalo optimization (ABO) and Artificial BEE Colony (ABC) can be utilized for the tuning of controllers.

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