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Optimal PID Controller Parameters Tuning of Ball and Beam System

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***Abstract*: -- Ball and Beam System (BABS) is a nonlinear and also an unstable system specially designed for understanding various control problems. The Proportional Integral and Derivative (PID) controller is mostly used to stabilize the ball on the beam. Initially, the PID controller is designed using Skogestad Internal Model Control (SIMC) tuning method for stabilizing the ball at specified position on the beam. The behavior of the BABS is based on the parameters of PID controller. The parameters of PID controller are optimized using Particle Swarm Optimization (PSO) for improving the performance of the ball and beam system. The settling time is used as a performance criterion for optimization. The simulation results show that the PSO based PID controller gives better performance when compared to the SIMC based PID controller of BABS.**

***Keywords* — Ball and beam system (BABS), PID controller, SIMC and PSO.**

I. INTRODUCTION

In process industries, some of the systems are unstable by nature and require feedback control for better performance. Due to lack of safety of real unstable systems that cannot be used for analysis, the BABS is developed to analyze the various control techniques [1]. The reason for a wide use of ball and beam system is that simple to understand as a system and for a fixed input, the ball does not stay in one place hence it is an open loop unstable system. Modeling is an important part which decides the performance of the BABS. Here the control task is to adjust the position of the ball on the beam automatically by changing the angle of the beam [2] [3]. Therefore, a feedback control must be used to keep a ball at specified position. The PID controller is most widely used feedback controller in industries because of its simplicity and good performance [4]. The PID controller has three parameters such as proportional gain, integral time and derivative time. In order to get the desired performance of the ball and beam system, the PID controller parameters are to be tuned properly. Classical and modern tuning methods are used to maintain the ball's position on the beam [5] [6]. But here the BABS is a double integrating system so that the conventional tuning method (Ziegler-Nichols Tuning) is not feasible due to sustained oscillations [7]. Model based tuning method is used to obtain the parameters of PID controller of ball and beam system. SIMC based PID controller is designed and the response of the BABS needs improvement [8] [9]. In order to improve the behavior of the BABS, the PID controller parameters are to be optimized. There are many optimization techniques were developed for designing the optimal PID controller. In this paper, Particle Swarm Optimization (PSO) is used to optimize the parameters of PID controller of BABS. The performance of BABS is analyzed using simulation results based on SIMC-PID and PSO-PID controller tuning.

II. BALL AND BEAM SYSTEM (BABS)

The control model of BABS is shown in figure1. The ball is placed on the beam which rolls freely over the beam. One end of the beam is fixed and another end is connected with DC servo motor. The encoder gives an actual position of motor shaft and linear potentiometer gives the current position of the ball on the beam. Both measurements are given as feedback to the controller through an intelligent drive. Feedback control must be used to maintain the ball on the beam in specified position. By comparing the actual position with the specified position, the error is calculated. The PID controller calculates the control signal based on the quantified error and the controller parameters. The control signal from Personal Computer controls the position of the ball through an intelligent drive.

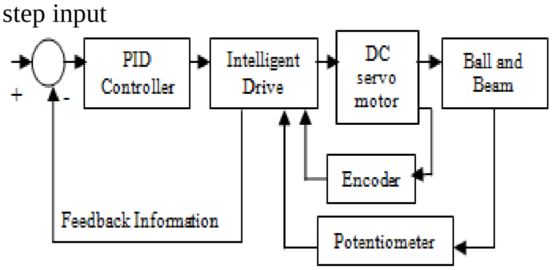

Figure 1 Control model of BABS

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III. DYNAMICS OF BABS

The gravitational, inertial, centrifugal forces contribute to the dynamics of the BABS. Here it is premised that the ball rolls without slipping and also the friction between ball and beam is negligible. The specifications to develop a mathematical model are tabulated in Table I.
The simplified Lagrangian equation of motion for ball is given by the differential equation as [10],

$$\left(\frac{J}{R^2}+m\right)\ddot{r}+mg\sin\alpha-mr(\dot{\alpha})^2=0 \quad (1)$$

Table1. Specifications of BABS

Symbol	Description	Values
M	Mass of the ball	0.11 Kg
R	Radius of the ball	0.015 m
D	Lever arm offset	0.04 m
G	Gravitational constant	-9.8 m/s²
L	Length of the beam	40 cm
J	Ball's moment of inertia	2mR²/5 Kgm²
r	Ball position coordinate	-
A	Beam angle coordinate	-
θ	Servo gear angle coordinate	-

On linearising the (1) about the beam angle, $\sin\alpha=\alpha$ for small α the equation is obtained as,

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

Equation for relating the beam angle to the angle of gear is,

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

Substituting (3) in (2) and applying Laplace transform, the transfer function is obtained as,

$$\frac{r(s)}{\theta(s)}=-\frac{mgd}{L\left(\frac{J}{R^2}+m\right)s^2} \quad (4)$$

With the parameters of BABS in Table 1, the transfer function is obtained as,

$$\frac{r(s)}{\theta(s)}=\frac{0.7}{s^2} \quad (5)$$

Equation (5) shows that the plant transfer function is a double integrating process. As such it is an unstable system and it provides a challenging control problem. In real time demonstration, the sample time is taken as 0.1 sec and this is considered as the time delay (θ). Including delay the transfer function is obtained as,

$$G_p=\frac{r(s)}{\theta(s)}=\frac{0.7e^{-0.1s}}{s^2} \quad (6)$$

Equation (6) shows the final transfer function of Ball and Beam System.

IV. PID CONTROLLER

PID controller is designed for BABS to stabilize the ball at a specified position by varying the beam angle. Using proportional, integral and derivative controller each in a parallel combination, PID controller is constructed. The parameters of PID controller are obtained using SIMC tuning rule which is a model based tuning technique [7] [8].
For a double integrating process

$$G_p=\frac{K_m e^{-\theta s}}{s^2} \quad (7)$$

SIMC-PID parameters of cascade form are,

$$K_c=\frac{0.0625}{K_m}\cdot\frac{1}{\theta^2} \quad (8)$$

$$T_i=8\theta \quad (9)$$

$$T_d=8\theta \quad (10)$$

Where K_c, T_i, T_d and θ are the proportional, integral, derivative parameters and delay time respectively.
To derive the corresponding settings for parallel form PID controller [11],

$$C(s)=\left(K_p+\frac{1}{T_i's}+T_d's\right) \quad (11)$$

Where,

$$K_p=K_c\left(1+\frac{T_d}{T_i}\right)$$

$$T_i'=T_i\left(1+\frac{T_d}{T_i}\right)$$

$$T_d'=\frac{T_d}{\left(1+\frac{T_d}{T_i}\right)}$$

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By substituting the process gain $(K_m = 0.7)$ and delay time $(\theta = 0.1)$ values, SIMC-PID controller parameters are shown in Table II.

Table II. Parameters of SIMC-PID controller

Kp	Ti (sec)	Td (sec)
17.8	1.6	0.4

V. PARTICLE SWARM OPTIMIZATION BASED PID CONTROLLER

Particle Swarm Optimization is one of the optimization techniques which is based on the movement and intelligence of swarms. It was developed from the research on swarm like birds flocking [12]. The entire population of bird is called as a swarm and each member in a population is called as a particle. Each particle contains three members such as proportional gain, integral time and derivative time. Particles in a swarm moving around the search space towards the best solution. Each particle keeps track of its best solution personal best (pbest) and the best value of any particle global best (gbest). Each particle modifies its position corresponding to its current position, current velocity, a distance between its current position and pbest and the distance between its current position and gbest [13] [14]. The parameter settings for PSO are shown in table III.

Table III. Parameter settings for PSO

Parameter	Values
Number of particles	10
Number of iterations	10
c1	2
c2	2
Inertia of weight factor	1
Boundary values of Kp	10-20
Boundary values of Ti	0-3
Boundary values of Td	0-1

The searching procedures for proposed PSO - PID controller are shown below,

1. Specify the lower and upper boundary values of the three controller parameters and set randomly the particles of the population. Using the following equations position and velocity are initialized.

position(j,i)=rand*(ubound(j)-lbound(j))+lbound(j) (12)

velocity=0.1*rand(dim,n) (13)

where,

rand - random number between 0 and 1

dim - dimension of the search space(K_p, T_i and T_d totally 3)

n - number of particles

2. For each particle calculate the value of fitness function (ts).
3. Compare the fitness of each particle with its pbest. If the current solution has best fitness then replaces pbest with the current fitness.
4. Compare the fitness of all particles with global best (gbest). If any of the particle is better than gbest, and then replace gbest.
5. Update the velocity and position of all particles. The velocity of j^{th} particle and the position of j^{th} particle is updated using following formulas,

$$v^{(t+1)}_{j,g} = w.v^{(t)}_{j,g} + c_1 * R_1() * (pbest_{j,g} - x^{(t)}_{j,g}) + c_2 * R_2() * (gbest_g - x^{(t)}_{j,g}) \quad (14)$$

$$x^{(t+1)}_{j,g} = x^{(t)}_{j,g} + v^{(t+1)}_{j,g} \quad (15)$$

j=1,2,.......m

g=1,2,.......n

where,

m - number of particles in a population

n - number of members in a particle

v - velocity of the particle

p - position of the particle

c_1 - weight of local information

c_2 - weight of global information

pbest - best position of the particle

gbest - best position of the swarm

6. Repeat the steps 2 to 6 until the desired fitness is reached.
7. The particles that generate the latest gbest are the optimal PID controller parameters.

The fitness function used for the optimization is the settling time. The optimized values of PID controller parameters are obtained with a minimization of settling time after the 10th iteration. Among various trials the best obtained values are shown in table III.

Table IV. Parameters of PSO-PID controller

Kp	Ti (sec)	Td (sec)
13.1381	2.7315	0.5239

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VI. RESULTS AND DISCUSSIONS

The BABS is simulated using MATLAB. The open loop unit step response of the BABS is shown in figure 2. From the open loop simulation result of the system, it is observed that the ball does not stay in specified position and it must need a feedback controller.

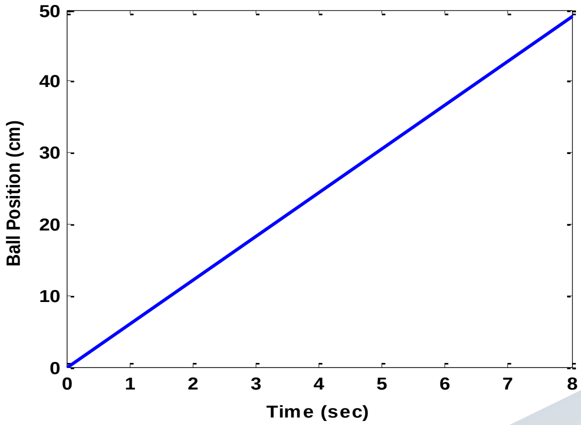

Figure 1 Open loop unit step response of ball and beam system

Simulation result of PSO based PID controller of BABS compared with SIMC based PID controller is shown in figure 3.

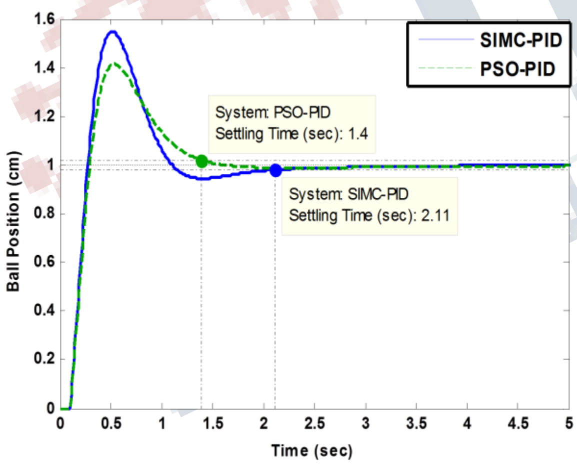

Figure 2. Simulation result of BABS

Performance comparison of the BABS

Controller	SIMC-PID	PSO-PID
Rise time (sec)	0.138	0.151
Peak overshoot	54.8	41.4
Settling time	2.11	1.4
Offset	0	0

The performance comparison between SIMC-PID and PSO-PID controller response of the BABS is shown in table V. PSO based PID controller response of ball and beam system gives 24.45 % reduced peak overshoot and 33.64 % reduced settling time compared to SIMC based PID controller of BABS.

VII. CONCLUSION

The performance of BABS is analyzed with Particle Swarm Optimization based PID controller. The PSO-PID controller outperforms SIMC-PID controller with respect to the time domain specifications. In future the PSO optimized PID controller can be adopted for second order real time applications in process industries.

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