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Performance enhancement of PID controller for ball and beam system

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Abstract. The control of Ball and Beam system using enhanced PID controller is investigated in this paper. Even though the ball position on the beam is controlled by PID controller the performance measures like overshoot, settling time, ISE and IAE are poor. In order to improve the performance of this nonlinear unstable system, Enhanced PID controller (EPID) is proposed. The enhanced PID controller is implemented by cascading a feed-forward controller with an existing PID controller and this feed-forward controller is designed based on bode plot response of the system. The performance of the proposed EPID controller is compared with conventional Simple Internal Model Control (SIMC) based PID controller. The EPID controller eliminates overshoot and reduces the settling time, ISE and IAE. The set point tracking, robustness test and stability analysis are carried out in simulation using MATLAB to show the efficacy of the proposed controller.

Keywords: ball and beam, EPID controller, feed-forward controller

1 Introduction

Most industrial plants are nonlinear and come with a great deal of uncertainty. The nonlinear systems pose difficulties to control engineers to design an efficient controller. Various schemes have been developed to overcome the difficulties in the design of controller for nonlinear processes[5]. PID controllers are widely used in nonlinear system modelling and control for more than two decades[3]. As for conventional PI or PID methods within the framework of a unity feedback control structure, improved tuning rules has been provided in many papers [8, 9]. Tao Liu et al.[7] designed PID controller by H infinity optimal criterion by analytical and simulation approach where a low pass filter is added to roll of its high frequency and to reduce overshoot. Sigurd et al.[6] developed an analytical approach in which integral term has been modified to improve disturbance rejection for integrating process where fast response and stability are achieved. Visioli et al.[8] proposed tuning formulas for PID controllers applied to integral and unstable process using GA. The control parameters are determined based on process model in order to minimise integral performance criteria. Ho et al.[9] derived simple formulas to tune PID controller to meet Gain Margin and Phase Margin specifications and they suggested that the Gain Margin and Phase Margin can also made to give optimum response by specifying it based on ITAE criterion. Poulin et al.[2] developed systematic tuning method for unstable process based on frequency response.

The PID controller can be tuned by several tuning methods. However, the set point response is usually accompanied with excessive overshoot and large settling time for PID controller. The design of controller for the double integrating process has become very popular, since it is widely used in industrial processes such as aerospace control systems, Direct Current motors and high speed disk drives. For these systems, the well-known Ziegler- Nichols PID tuning rules, cannot be applied. Since, this rule lacks a time-domain performance parameter, it does not allow the user to achieve a particular control objective, and also produce responses which are too oscillatory[1].

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Even though the conventional PID controllers achieve the desired set point, the performance measures like overshoot, ISE and IAE are high. In order to improve the time domain specifications, EPID controller is proposed in this paper. To prove the effectiveness of the proposed control strategy, ball and beam system is taken as test bench. The ball and beam system is widely used because it is very simple to understand as a system and the control techniques that can be studied over many important classical and modern design methods. The ball and beam system is open loop unstable system.

This paper is organized as follows. Section 2 shows the mathematical model of ball and beam system. Section 3 shows the development of enhanced PID controller. The simulation results of conventional PID and proposed EPID controller for the position control of ball and beam system are presented in section 4. Section 5 concludes the paper.

2 Mathematical model of the ball and beam system

The ball and beam system is shown in Fig. 1. The ball is placed on the beam and moves freely over the length of the beam. Whenever the ball is away from the desired position, the controller modifies the angle (θ) of servo gear which in turn changes the beam angle (α) to regulate the ball position. A control algorithm is to be implemented in such a way that the desired position of the ball is stabilized on the beam. For this problem, it is assumed that the ball rolls without slipping and also the friction between beam and ball is negligible.

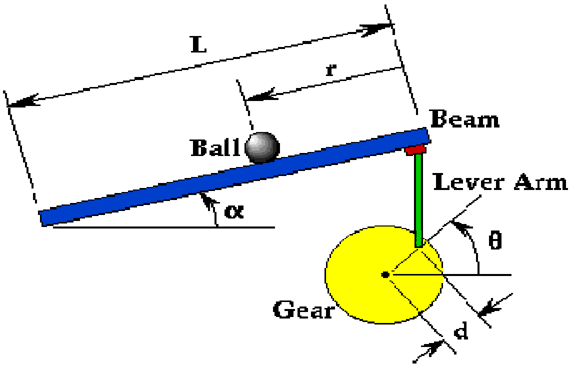

Fig. 1: Ball and Beam System

The simplified Lagrangian equation of motion for the ball (John Hauser 1992)[4] is given by the differential equation as

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

The equation which relates the beam angle to the angle of gear is given as

$$\alpha=\frac{d}{L}\theta. \tag{2}$$

The parameters and variables used in ball and beam system are summarized in Tab. 1.

On substituting the above values in eq. 1, the transfer function is obtained as,

$$\frac{r(s)}{\theta(s)}=\frac{0.7}{s^2}=\frac{K_m}{T_m s^2}. \tag{3}$$

Where K_m is the gain of the system and T_m is the time constant of the system. The above plant transfer function is a double integrator and it is unstable.

Table 1: Parameters of ball and Beam system

Variables	Description	Values
m	Mass of the ball (kg)	0.11
R	Radius of the ball (m)	0.015
d	Lever arm offset (m)	0.04 m
g	Gravitational acceleration (m/s^2)	9.8
L	Length of the beam (m)	1.0
J	Ball's moment of inertia (kgm^2)	2mR2/ 5 kgm^2
r	Ball position coordinate	-
α	Beam angle coordinate	-
θ	Servo gear angle	-

3 Enhanced PID controller

The feed-forward controller in cascade with the PID controller is called as enhanced PID controller and it is shown in Fig. 2.

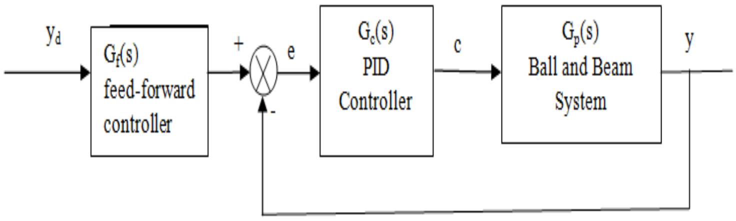

Fig. 2: Enhanced PID Controller

In the enhanced PID control structure shown in Fig. 2, $G_p(s)$ is the plant, $G_c(s)$ is the PID controller and $G_f(s)$ is the feed-forward controller. Y is the actual output of the system and y_d is the desired output. To overcome the disturbance in stability condition at high frequencies the feed-forward controller is used. For accurate position tracking, the feed-forward controller is required. Feed-forward control needs a feedback control system to compensate the error. In this paper, PID controller is used as feedback controller.

3.1 PID controller

Several tuning methods for PID controller are related to stable, unstable and integrating system whereas only few methods are available for double integrating process. Simple Internal Model Control (SIMC) is one of the tuning method for double integrating system to determine Kc, Ti and Td. The SIMC based PID parameters are given in Tab. 2.

Table 2: SIMC based PID controller parameters

Tuning Method	PID parameters	Equation	Values
SIMC Method	K_c	$\frac{0.0625}{K_m} \cdot \frac{1}{{\tau_m}^2}$	892.8
	T_i	$8\tau_m$	0.08
	T_d	$8\tau_m$	0.08

Where, K_m and τ_m are plant process parameters. In real time implementation, Sample time τ_m is chosen as 0.01sec.

3.2 Feed-forward controller

The feed-forward is used to reduce the high frequency error in the feed-forward path for improving the stability of the system. The feed-forward controller can be defined by a model $G_f(s) = \frac{a}{S+a}$. $G_f(s)$ is a first order low pass filter with cut off frequency “a” rad/sec. The cut off frequency is defined as the frequency at which the ratio of output to input has a magnitude of 0.707. This magnitude is converted to dB using the eq. 4, which is equal to -3 dB.

$$Magnitude = 20\log_{10}(\frac{output}{input}). \tag{4}$$

The cut off frequency “a” is computed as 1.1 rad/sec based on the bode response of the ball and beam system as shown in Fig. 3.

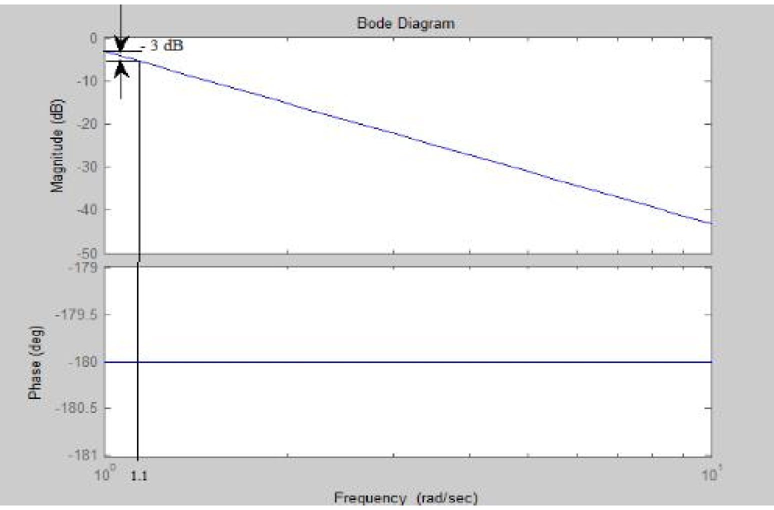

Fig. 3: Bode plot of Ball and Beam system

The PID controller tracks the desired ball position with high overshoot. In order to eliminate this overshoot, feed-forward controller is used. In real time, feed-forward controller cannot be used alone. However, it can be combined with PID controller for enhancing the performance of ball and beam system. Realization of the feed-forward controller is not possible in real time but it can be implemented in MATLAB, thereby establishing hardware-in-the-loop simulation.

4 Simulation results

In order to demonstrate the superiority of the enhanced PID controller simulations are carried out in MATLAB SIMULINK. The performance is evaluated by calculating overshoot, settling time, ISE and IAE for set point changes. To illustrate the performance enhancement, the proposed controller is compared with conventional PID controller. The closed loop response of PID controller and EPD controller are shown in Fig. 4. and the performance measures such as settling time, overshoot, IAE and ISE are obtained and tabulated in Tab. 3. The results show that EPID controller is better than PID controller.

4.1 Tracking cases

The operating range of ball and beam system is 0-40 cm. The set point tracking performance of PID controller and EPID controller with step input is evaluated at the operating point of 10 cm. The response is obtained as shown in figure for ± 5% and ± 10% set point changes at the operating point of 10 cm. The

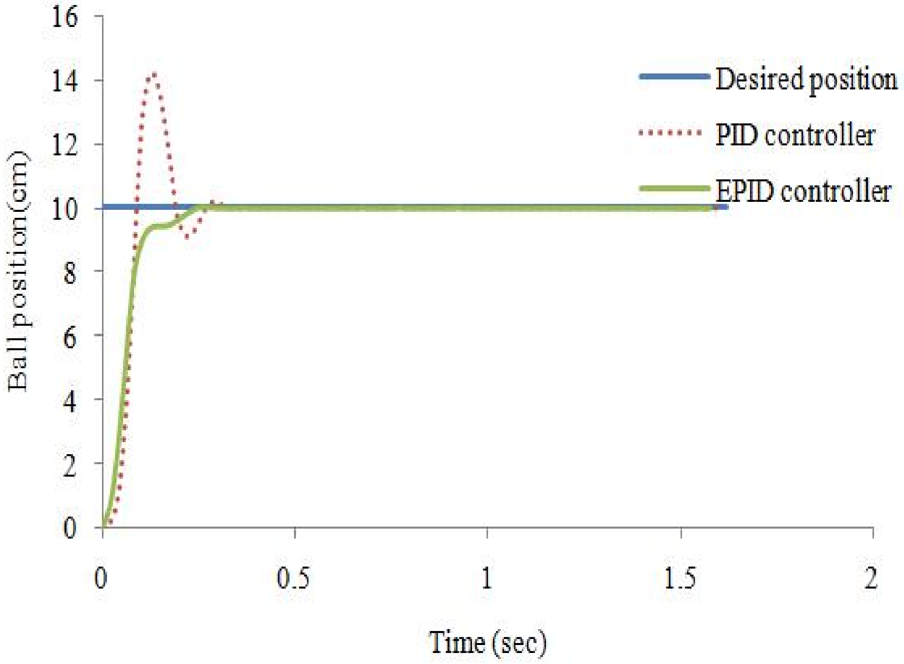

Fig. 4: Closed loop response of PID and EPID Controller

Table 3: Result of process with PID controller and EPID controller

Controller	Settling time	Overshoot	ISE	IAE
EPID	0.2 sec	0%	487.48	70.03
PID	0.3 sec	40%	688.26	101.82

response is shown in Fig. 5. From the response curve, it is clear that the response made by EPID controller is forced to follow the set point and gives better response when compared to conventional PID controller. EPID controller performances are found to have no overshoot and small settling time. The performance of the controllers is analyzed by measuring the different error indices like ISE and IAE. The performance measures are tabulated in Tab. 4.

Table 4: Servo performance at the operating point of 10 cm

Performance Measures	+5%		+10%		-5%		-10%	
	PID	EPID	PID	EPID	PID	EPID	PID	EPID
Overshoot (%)	2.25	Nil	10.92	Nil	8.7	Nil	26.66	Nil
Settling Time (sec)	1.2	1.15	1.21	1.18	1.23	1.15	1.21	1.19
ISE	176.24	176.97	707.43	703.26	176.5	174.54	706.49	697.87
IAE	92.69	91.61	187.17	185.15	92.22	91.53	183.03	184.67

The robustness of the EPID controller is performed at the operating of 20 cm. The responses obtained using PID and EPID controllers for ± 5% and ± 10% change at the operating point of 20 cm is shown in Fig. 6. The output derived from the response is tabulated in Tab. 5.

Square wave tracking is done to test the controller to follow the continuous changes in set point. The simulation is carried out and the response is shown in Fig. 7. The EPID controller follows the square wave trajectory with minimum offset compared to the PID controller.

The stability of the system is analyzed using Nyquist criteria. The unit circle is drawn in the Nyquist plot. From the Fig. 8., the system is stable.

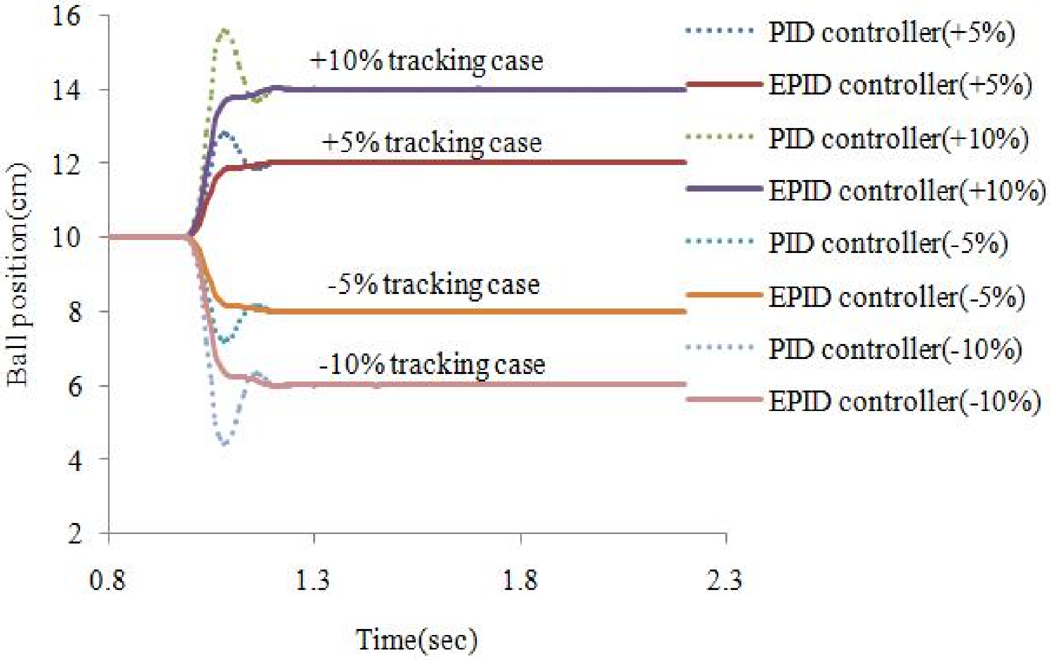

Fig. 5: Servo response at the operating point of 10 cm

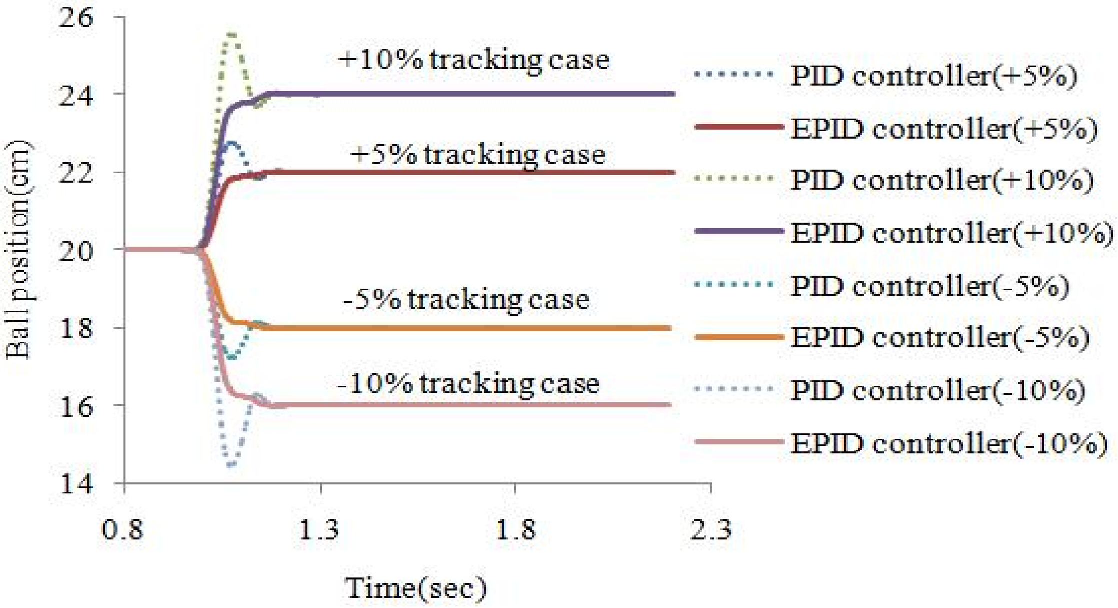

Fig. 6: Servo response at the operating point of 20 cm

Table 5: Servo performance at the operating point of 20 cm

Performance Measures	+5%		+10%		-5%		-10%	
	PID	EPID	PID	EPID	PID	EPID	PID	EPID
Overshoot (%)	3.9	Nil	6.25	Nil	4.8	Nil	7.8	Nil
Settling Time (sec)	1.2	1.17	1.22	1.17	1.19	1.14	1.21	1.16
ISE	181.65	181.97	727.62	725.69	181.7	180.73	723.85	723.85
IAE	96	94.45	191.88	188.9	95.76	94.37	191.64	188.81

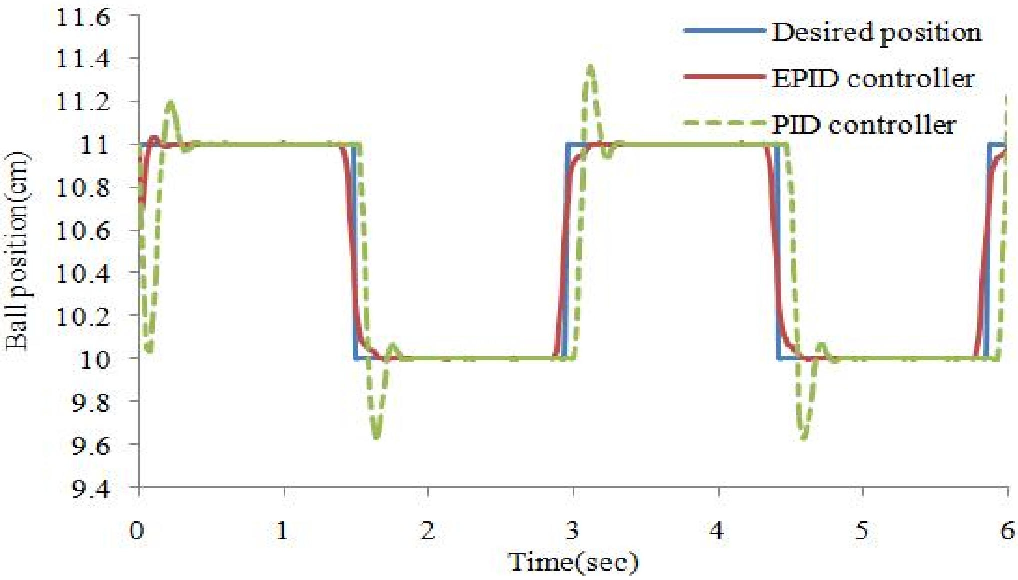

Fig. 7: Square wave Tracking of System with Controller

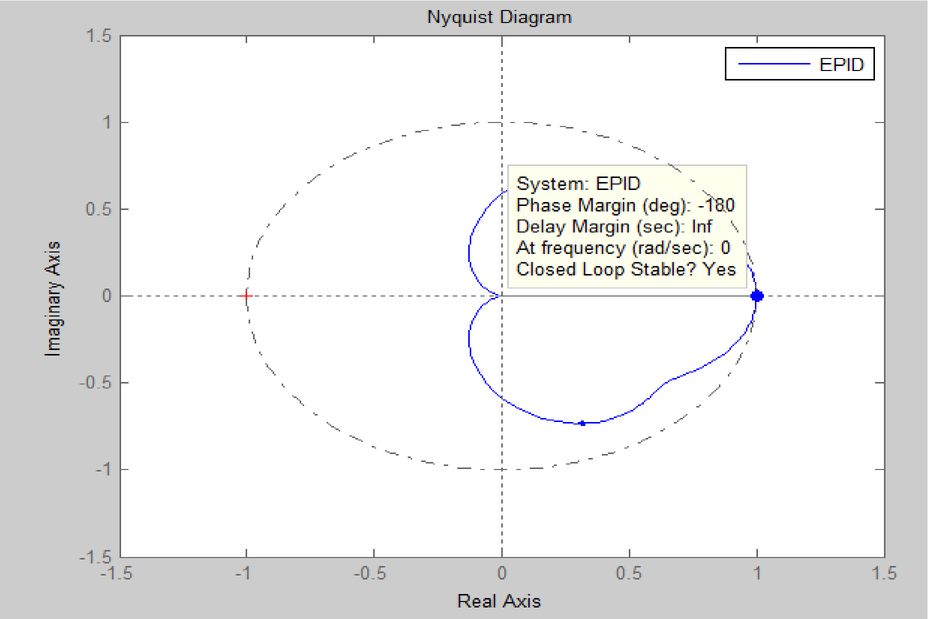

Fig. 8: Nyquist plot of the system with controller

5 Conclusion

In this paper, Enhanced PID controller is designed for ball and beam system. The set point tracking and square wave tracking has been done to test the performance of the controller. The results show that both servo and robust performance of the PID controller is enhanced by adding a feed-forward controller with proper design. The EPID controller eliminates the overshoot and decreases the error indices such as ISE and IAE comparing to the conventional PID controller. The stability of the system is tested using Nyquist plot. The proposed EPID controller is found to be superior to the PID controller.

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