Stabilisation of Ball and Beam Module Using Relatively Optimal Control

Nidya. M. V., Jeevamma Jacob, and Mija S. J.
National Institute of Technology, Calicut, India
Email: nidyamv@gmail.com, {jeeva,mija}@nitc.ac.in

***Abstract*—In this paper, a relatively optimal controller (ROC) is designed for stabilisation of ball and beam module. It is a nonlinear, underactuated bench mark system with two degrees of freedom. The controller has a dynamic structure and is designed by solving a convex optimisation problem. All the constraints associated with the system are incorporated for controller design. The performance analysis of closed-loop system under the effects of parametric uncertainties, external disturbances and perturbations in initial conditions are incorporated.**

***Index Terms*—nonlinear, underactuated, optimal control, stabilisation, parameter variation, disturbance**

I. Introduction

The 2 degrees of freedom (DOF) Ball and beam is an ideal platform for testing newly developed control strategies. Its nonlinear and underactuated nature can be considered as a challenge in control perspective. The fundamental concept of the ball and beam system can be applied to various problems, such as horizontal stabilization of an airplane during landing and in turbulent airflow, balancing goods carrier robots, etc.

In literature, several methodologies have been extensively used for the stabilisation and control of the ball and beam system. A family of semi-global stabilising output feedback controller is presented in [1]. Robust stability can be achieved with this controller. In [2], a control law based on approximate input-output linearisation is derived for the ball and beam system and it is compared with the control law derived using Jacobian approximation. Self-recurrent neural networks based adaptive controllers to stabilise the ball and beam is presented in [3]. The result with this controller is compared with the Linear Quadratic Regulator (LQR) method. A class of asymptotically stable proportional-derivative (PD) controllers is derived in [4], for the regulation of the ball and beam system. Experimental results are shown to illustrate the control system's stability and performance. In [5], a nonlinear controller is developed using state-dependent Riccati equation technique.

Though several works have been reported, very few papers considered the constraints in the system while performing the controller design. Receding horizon approach is a constrained optimisation method, but the necessity of solving an optimisation problem online makes the controller design complex. Relatively Optimal Controller (ROC) is another constrained optimal controller which overcomes the disadvantages of the receding horizon control. The first work on ROC was reported in 2003[6], in which the controller was introduced for discrete-time systems. An open loop optimisation problem was solved and the solution was utilised for designing a dynamic feedback controller. The initial condition of the dynamic compensator was assumed to be zero and zero terminal constraints was considered in this paper. In the next paper on ROC [7], the closed-loop poles were assigned in desired locations. The zero terminal constraint in [6] was neglected in [7]. A static piecewise-affine solution was given in [8], in which a state feedback controller was designed by suitably partitioning the state space into polyhedral sets. And a comparison of the static and dynamic compensator was also given. In [6], [7], and [8] the controllers were designed for discrete-time systems. ROC for continuous time system was presented in [8]. And output feedback ROC along with Youla- Kucera parameterization was presented in [10]. In all the papers on ROC, the system used to test the effectiveness of controller is a cart-pole system.

This work focuses on the derivation of the state space model of a ball and beam system from its transfer function model, and its stabilisation using a relatively optimal controller (ROC). The controller is a dynamic one, which gives optimum response for nominal initial condition and stabilises the system for any other initial conditions near to the nominal initial state. The unique feature of ROC among constrained optimal control methodologies is that it doesn't utilise online optimisation technique. The convex optimisation problem considering all system constraints can be easily solved using the MATLAB. Hence, the design and implementation of ROC is simple and less time consuming compared to other methods. The performance of the system for parameter variations, external disturbances and perturbations in initial conditions is analysed as a part of this work.

This paper is organised as follows: system description and mathematical model are discussed in section II, the control problem is discussed in section III, section IV explains the controller design, results and discussions are

Manuscript received August 6, 2018; revised February 8, 2019.

doi: 10.18178/ijmerr.8.2.265-272

described in section V and section VI gives the conclusions of the work presented in this paper.

II. System Description

Ball and beam is a benchmark system available in most of the control laboratories. It is used for testing newly synthesised control methods. Since it is nonlinear and underactuated, it is a challenge for control engineers to develop control strategies for the same.

It has a steel rod in parallel with a nickel chromium wire wound resistor, which forms the track on which the metal ball is free to roll. The ball acts similar to a wiper in a potentiometer, hence the voltage at the steel rod is used to find the ball position. When coupled to the SRV02 plant, [11] the DC motor drives the beam such that the motor angle controls the tilt angle of the beam. The ball then travels along the length of the beam. The beam is an end actuated one for this work, as the single actuator present at the rightmost end of the beam. The schematic diagram of the ball and beam module is given is Fig. 1.

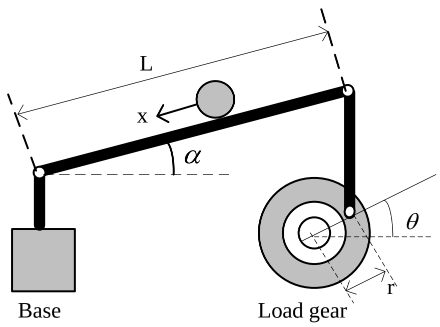

Figure 1. Schematic diagram of a ball and beam module

A. Transfer Function Model

To derive the mathematical model of the ball and beam module, the translational force due to gravity (F_t) and the rotational force due to torque produced by the rotational acceleration of the ball (F_r) are considered.

$$F_t = mg\sin\alpha \tag{1}$$

$$F_r = \frac{2}{5}m\ddot{x} \tag{2}$$

where m is the mass of the ball, x is the position of the ball and α is the beam pitch in radians.
Using (1) and (2), and by applying Newton's second law, the equation for acceleration of ball can be obtained as,

$$\ddot{x} = \frac{5}{7}g\sin\alpha \tag{3}$$

Assuming pitch of the beam α as small, the transfer function can be derived from (3) as shown in (4)

$$\frac{X(s)}{\alpha(s)} = \frac{5g}{7s^2} \tag{4}$$

The relation between servo load angle θ and the voltage applied to the motor V_m is given by the transfer function in equation (5). All the parameters are described in Table I.

$$\frac{\theta(s)}{V_m(s)} = \frac{\eta_g\eta_m K_t K_g}{J_{eq}R_m s^2 + \left(B_{eq}R_m + \eta_g\eta_m K_m K_t K_g^2\right)s} \tag{5}$$

Then

$$\frac{X(s)}{V_m(s)} = \frac{X(s)}{\alpha(s)}\frac{\alpha(s)}{\theta(s)}\frac{\theta(s)}{V_m(s)} \tag{6}$$

where, $\frac{\theta(s)}{\alpha(s)} = \frac{L}{r}$

B. State Space Model

Using (4) and (5) and taking $x = [x_1 \quad x_2 \quad x_3 \quad x_4]^T = [x \quad \dot{x} \quad \theta \quad \dot{\theta}]^T$, u = $[V_m]$, the dynamics of ball and beam can be represented in state space form as:

$$\dot{x} = Ax + Bu \tag{7}$$

Where

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{5gr}{7L} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\frac{\left(B_{eq}R_m + \eta_q\eta_m K_m K_t K_g{}^2\right)}{J_{eq}R_m} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{\eta_g\eta_m K_t K_g}{J_{eq}R_m} \end{bmatrix}$$

C. Constraints on the System

The constraints associated with the system are [11]

$V_m \le 4V$ $\quad$ $|u| \le 4$

$x \le 0.42m$ $\quad$ ie $\quad$ $|x_1| \le 0.42$ $\quad$ (8)

$-45° \le \theta \le 45$ $\quad$ $|x_3| \le 45$

The constraints have to be satisfied during the operation of the system.

TABLE I. Description and Values of Parameters of Servo and Ball and Beam

Symbol	Parameter description	Value	Unit
K_t	Motor torque constant	0.00767	Nm
K_m	Back EMF constant	0.00767	$V/(rd$
R_m	Armature Resistance	2.6	Ω
B_{eq}	Equivalent Viscous Damping	0.004	Nm $/(rd$
η_g	Gear box Efficiency	0.85	-
η_m	Motor efficiency	0.69	-
K_g	Gear box ratio	14:1	-

J_{eq}	Equivalent high gear inertia	0.002	$Kg\ m2$
g	Earth's gravitational constant	9.8	$m/s2$
R	Lever arm offset	1	$Inch$
L	Beam Length	16.75	$Inches$

III. Problem Formulation

The objective is to obtain the control input to stabilise the ball and beam, i.e. the disturbed system state has to reach the operating point as soon as possible with minimum expenditure of energy. The performance measure to suit this requirement is:

$$J = \frac{1}{2}\int_0^\infty \left(x^T Qx + u^T Ru\right)dt \tag{9}$$

where Q is positive semidefinite ($Q \geq 0$) and R is positive definite ($R > 0$). The constraints associated with the system are

$$\left.\begin{aligned} |u| &\leq u_m \\ |x_1| &\leq x_{1m} \\ |x_3| &\leq x_{3m} \end{aligned}\right\} \tag{10}$$

where u_m, x_{1m} and x_{3m} are the maximum allowable values of u, x_1 and x_3, respectively. The constraints listed in (10) must be satisfied during the operation of the system.

IV. Controller Design

Relatively optimal control is a feedback control which is optimal for a nominal initial condition. The controller has a dynamic structure as shown in Figure 2. It can be used in applications, where the initial and final conditions of the system are fixed. The controller can stabilise the system even when the initial condition is non-nominal.

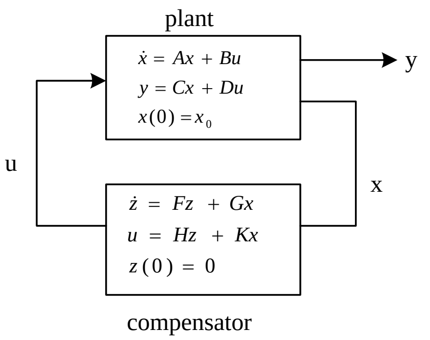

Figure 2. Controller structure

Then the closed-loop system comprising of system and controller is given by

$$\left.\begin{aligned} \dot{\tilde{x}} &= \left(\tilde{A} + \tilde{B}\tilde{K}\right)\tilde{x} \\ y &= \left(\tilde{C} + \tilde{D}\tilde{K}\right)\tilde{x} \\ \tilde{x}(0) &= \tilde{x}_0 \end{aligned}\right\} \tag{11}$$

where $\tilde{x} = \left[x(t) \quad z(t)\right]^T$, $\tilde{x}_0 = \left[x_0 \quad 0\right]^T$

$\tilde{A} = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix}$, $\tilde{B} = \begin{bmatrix} B & 0 \\ 0 & I \end{bmatrix}$, $\tilde{C} = \left[C \quad 0\right]$, $\tilde{D} = \left[D \quad 0\right]$, and $\tilde{K} = \begin{bmatrix} K & H \\ G & F \end{bmatrix}$

The controller matrix $\tilde{K}$ is designed such that the closed- loop system must have stable poles. Let β_i be the set of closed-loop poles, where $i = 1,2, \dots n + q$ and q is the order of the compensator. By introducing a $(n + q) \times (n + q)$ matrix P with eigenvalues β_i, the desired specifications on the closed-loop poles can be incorporated.

Consider a behaviour generated by the autonomous system in (11) as:

$$\dot{\gamma}(t) = P\gamma(t) \tag{12}$$

$$\gamma(0) = r \tag{13}$$

where (P, r) is a controllable pair.

The solution of system described in (12) can be written as

$$\gamma(t) = e^{Pt} r \tag{14}$$

Since, $\gamma(t)$ contains all the behaviours of the closed-loop system and $(P.r)$is controllable, the state and input variables of closed-loop system can be written as

$$x(t) = X\gamma(t);\ u(t) = U\gamma(t) \tag{15}$$

where X and U are real constant matrices of appropriate dimensions.

Using (12) and (15) in (7),

$$AX + BU = XP,\ X_0 = Xr \tag{16}$$

The performance index in (8) can be rewritten as shown below

$$J = r^T Wr \tag{17}$$

Where

$$W = \int_0^\infty e^{P^T t}\left(X^T QX + U^T RU\right)e^{Pt} dt \tag{18}$$

As W is in the form of solution of Lyapunov equation, it can be rewritten as an inequality as shown in (19), which is a convex constraint.

$$WP + P^T W + (X^T QX + U^T RU) \leq 0 \tag{19}$$

The constraints in (10) can also be written in terms of X and U as follows

$$\left.\begin{array}{c} \left|Ue^{Pt_k}r\right| \le u_m \\ \left|\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}Xe^{Pt_k}r\right| \le x_{1m} \\ \left|\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}Xe^{Pt_k}r\right| \le x_{2m} \\ k = 0,1,\ldots\ldots s \end{array}\right\} \quad (20)$$

Hence, a convex optimisation problem can be formulated as in (21).

$$\left.\begin{array}{c} \min_{X,U,W,Y} r^TWr \\ s.t. AX + BU = XP \\ x_0 = Xr \\ WP + P^TW + X^TQX + U^TRU \le 0 \\ \left|Ue^{Pt_k}r\right| \le u_m \\ \left|\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}Xe^{Pt}r\right| \le x_{1m} \\ \left|\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}Xe^{Pt}r\right| \le x_{3m} \\ k = 0,1,\ldots\ldots s \end{array}\right\} \quad (21)$$

The solution of this convex optimisation problem results in the optimum value of J along with a solution set (X, U, W).

Assume, there exists a Z such that

$$z(t) = Z\gamma(t) \quad (22)$$

Z is of appropriate dimension and it must satisfy

$$\begin{vmatrix} X \\ Z \end{vmatrix} \ne 0 \quad \text{and} \quad Zr = 0 \quad (23)$$

The equation for compensator matrix can be obtained by using (15) and (22) in the compensator dynamics

i.e. $$\begin{bmatrix} K & H \\ G & F \end{bmatrix}\begin{bmatrix} X \\ Z \end{bmatrix} = \begin{bmatrix} U \\ ZP \end{bmatrix} \quad (24)$$

Hence, $$\tilde{K} = \begin{bmatrix} U \\ ZP \end{bmatrix}\begin{bmatrix} X \\ Z \end{bmatrix}^{-1} \quad (25)$$

This dynamic compensator stabilises the system with minimum expenditure of energy, satisfying all the constraints associated with it. Simulation results and further analysis are covered in section V.

V. Results and Discussions

The state space model of the ball and beam system can be obtained by substituting the values of parameters given in Table 1.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0.2091 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -35.1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 61.54 \end{bmatrix}u$$

It is assumed that, initially, the ball is at 12 cm from the end and the beam is horizontal, with servo load angle zero. Hence, the initial condition is

$$x_0 = \begin{bmatrix} 0.12 & 0 & 0 & 0 \end{bmatrix}^T$$

The constraints associated with the system are listed in (8).

For designing the controller to stabilise the ball and beam system, a quadratic performance index is chosen as in (9). Where $Q = diag(1 \quad 1 \quad 2.5 \quad 2.5)$, $R = [1]$

The desired pole locations are taken as that of two Butter worth filters of order 4 and 5, with cut off frequencies 8 and 4, respectively.

The controllable pair (P, r) is chosen as:

$$P = \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \quad r = \begin{bmatrix} 8 & 0 & 4 & 0 & 4 & 0 & 2 & 0 & 2 \end{bmatrix}^T$$

Where

$$P_1 = \begin{bmatrix} -3.0608 & 7.3919 & 0 & -8 \\ -7.3919 & -3.0608 & 0 & -8 \\ 0 & 0 & -7.3916 & 3.0600 \\ 0 & 0 & -3.0600 & -7.3916 \end{bmatrix}$$

$$P_2 = \begin{bmatrix} -1.2364 & 3.8042 & 0 & 0 & 0 \\ -3.8042 & -1.2364 & 0 & 0 & 0 \\ 0 & 0 & -3.2358 & 2.3514 & 0 \\ 0 & 0 & -2.3514 & -3.2358 & 0 \\ 0 & 0 & 0 & 0 & -4 \end{bmatrix}$$

A convex optimisation problem is formulated as in (21) and its solution is utilised to calculate the compensator matrix. The poles of the compensator are $(-29.3653, -3.3386 \pm 9.3474j, -1.0119 \pm 4.4867j)$ implying that the compensator itself is stable. The closed-loop poles of the system are obtained close to the desired poles.

A. *System Response for Different Initial Conditions*

The simulation results obtained for ball and beam system with the designed ROC is shown in Figures 3-7. Two non-nominal initial conditions are considered for analysis along with nominal initial conditions.

They are

$$x_0 = \begin{bmatrix} 0.12 & 0 & 0 & 0 \end{bmatrix}^T$$

$$x_{01} = \begin{bmatrix} 0.09 & 0 & 0.0873 & 0 \end{bmatrix}^T$$

$$x_{02} = \begin{bmatrix} 0.13 & 0 & 0.0873 & 0 \end{bmatrix}^T$$

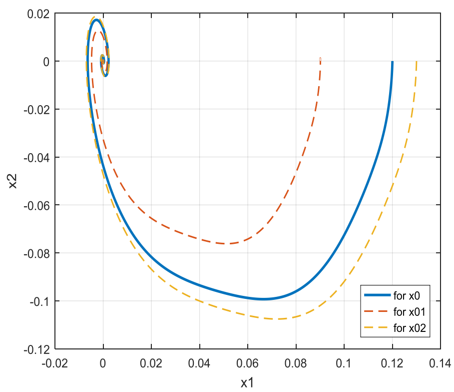

Figure 3. State trajectory (X1-X2) for different initial conditions

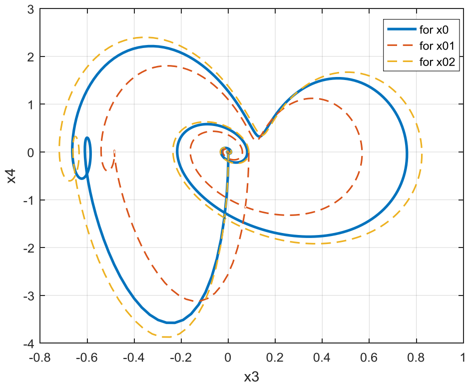

Figure 4. State trajectory (X3-X4) for different initial conditions

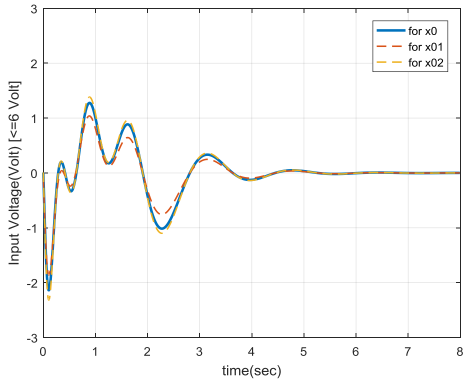

Figure 5. Input trajectory for different initial conditions

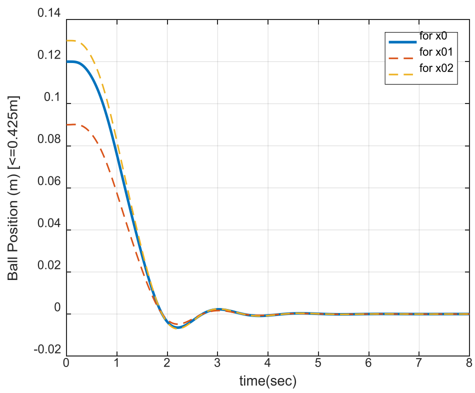

Figure 6. Ball position trajectory for different initial conditions

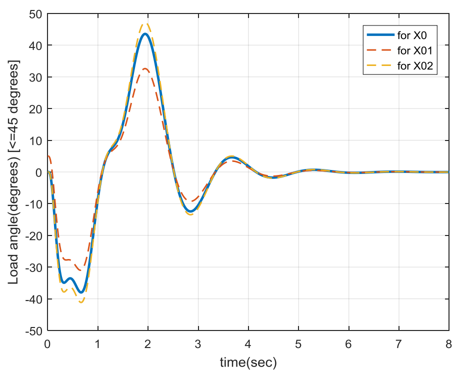

Figure 7. Servo angle trajectory for different initial conditions

From the plots given in Figure 3-7, it is clear that the system is optimally stabilised in less than 6 seconds by satisfying all the constraints. The controller has taken the ball from the nominal initial position of 12cm to the origin (midpoint). Though the controller is designed for nominal initial condition, it guarantees stability for non-nominal initial conditions also, which are close to the nominal one.

B. *System Response for Parameter Variations*

No mathematical model is perfect, because it is derived by taking some assumptions or approximations. Hence, it is required to analyse the controller performance for parameter variations. The system model can be rewritten as in (26), by incorporating the effect of parameter deviations.

$$\dot{x} = (A + dA)x + (B + dB)u \tag{26}$$

where dA and dB are % changes in parameter matrices A and B.

The responses obtained with the different percentage changes in matrix A of the system are shown in Figures 8-12. Figure 8 and Figure 9 show the phase portrait for two planes. Figures 10-12 show the variations of input voltage, the position of the ball, and servo angle with respect to time.

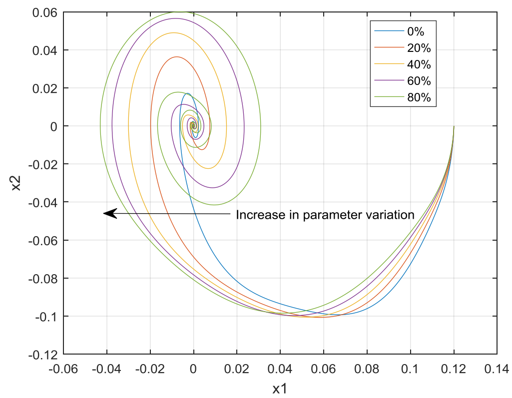

Figure 8. State trajectory (X1-X2) for variations in state matrix

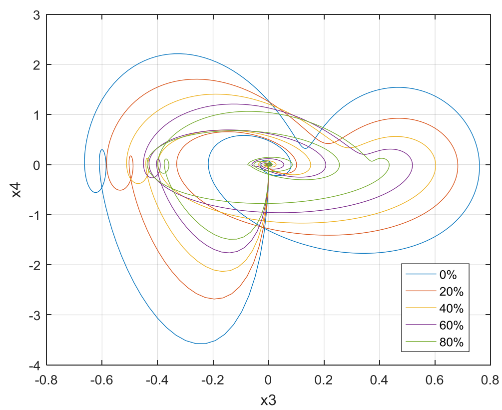

Figure 9. State trajectory (X3-X4) for variations in state matrix

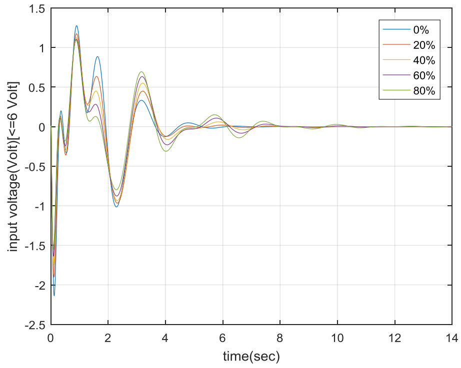

Figure 10. Input voltage trajectory for variations in state matrix

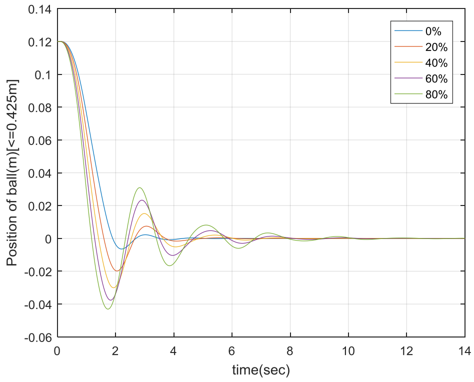

Figure 11. Ball position trajectory for variations in state matrix

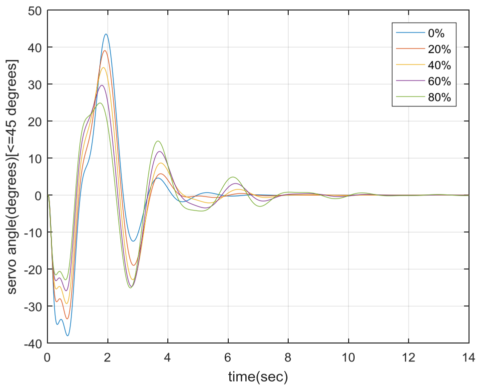

Figure 12. Servo angle trajectory for variations in state matrix

From the plots, it is observed that the settling time is increased with the increase in parameter variation. Up to 16 % of variation in matrix A of system model in (7), the system performance is not affected. Settling time remains same as in the case with 0 % parameter variation. Up to 80 %, constraint satisfaction and stabilisation are achieved but it is not optimal.

System responses for input parameter variations (dB) in percentage are shown in Figure 13-18. Figure 13 and Figure 14 show the phase portrait for two planes. Figures 14-18 show the variations of input voltage, position of ball, and servo angle with respect to time.

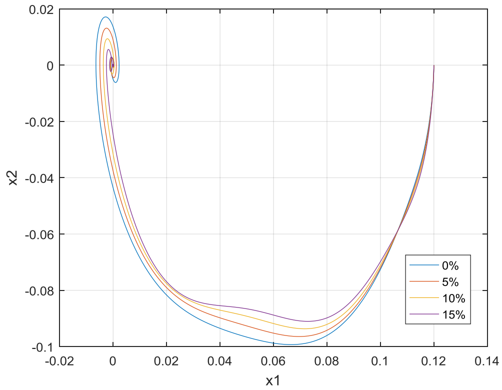

Figure 13: State space (X1-X2) for variations in input matrix

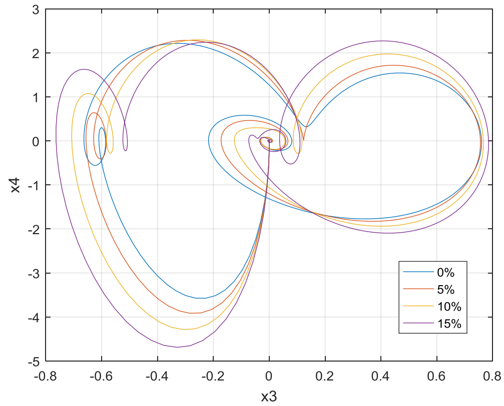

Figure 14.State space (X3-X4) for variations in input matrix

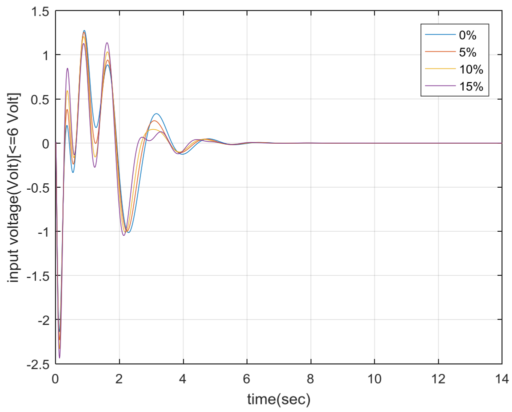

Figure 15. Input trajectory for variations in input matrix

From figures given above, it is clear that up to 15 % change in input parameter matrix, the system performs satisfactorily. All system constraints are satisfied during the operation. The module gets stabilised within 6 seconds. For parameter variation above 15 %, system constraint on servo angle is violated and decaying oscillations appear in the response. Hence settling time increases.

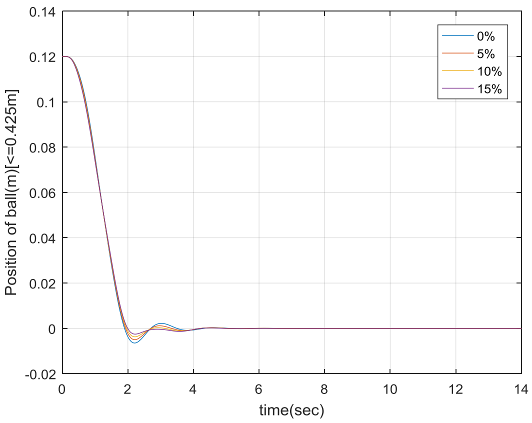

Figure 16. Position trajectory for variations in input matrix

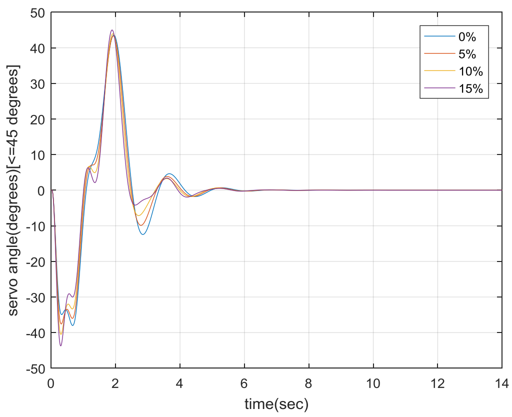

Figure 17. Servo angle trajectory for variations in input matrix

From the figures given above, it is clear that up to 15% change in input parameter matrix, the system performs satisfactorily. All system constraints are satisfied during the operation. The module gets stabilised within 6 seconds. For parameter variations above 15 %, the system constraint on servo angle is violated, and decaying oscillations appear in the response. Hence the settling time increases.

C. *System Response for Disturbance*

The performance of the ball and beam system is affected by external disturbances, like wind, sudden movements, etc. It has a great influence on the system responses. Considering the worst case where disturbances exist in both channels, the system dynamics can be rewritten as,

$$\dot{x} = Ax + Bu + Dn \tag{27}$$

where $Dn = [d_1(t) \quad 0 \quad d_2(t) \quad 0]^T$ represents the effects of disturbance present in the system. $d_1(t)$ and $d_2(t)$ are random noises as shown in Figure 18, which exist for 5 seconds in two axes.

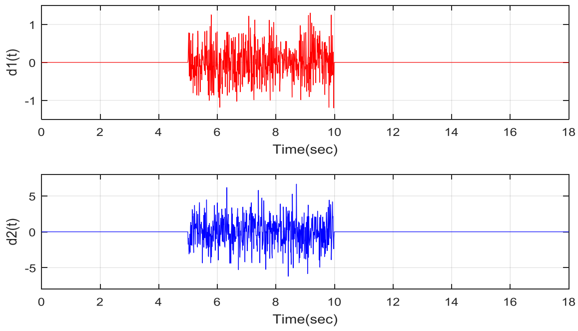

Figure 18. Disturbance in the system

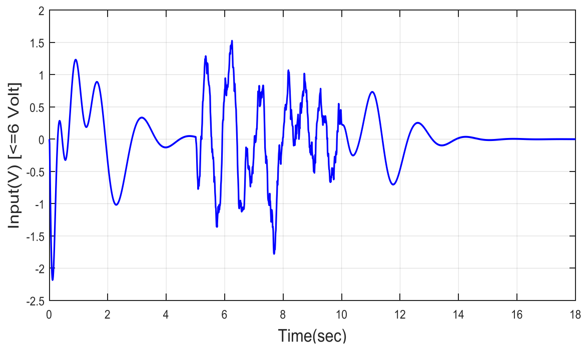

Figure 19. Input trajectory with disturbance

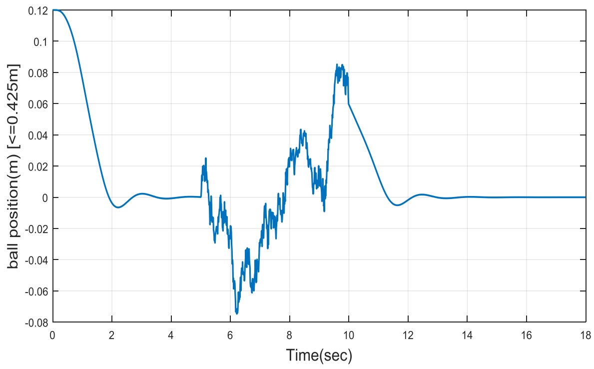

Figure 20. Position trajectory with disturbance

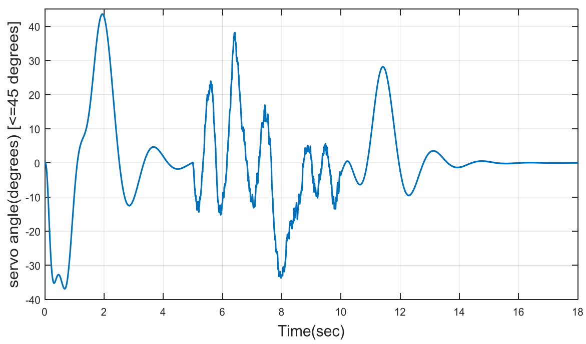

Figure 21. Servo angle trajectory for input parameter variations

The input required in the presence of disturbances and its effects on the system response are shown in Figures 19-21.It is clear from the figures that, though the settling time increases, the controller is able to bring the system back to stability. All system constraints are obeyed during the operation.

D. Pole Locations of the System

The pole locations of open loop and closed-loop system are given in Figure 22. The poles of open loop system are $(0,0,0,-35.1)$. The open loop system is unstable due to the existence of multiple poles at the origin. The ROC is designed by considering the desired locations of closed-loop poles. From figure 22, it is found that the closed-loop system's poles are merged with that of the poles of two Butterworth filters, which are the desired locations. Stability is assured as all closed-loop system poles are on the left half side of s-plane.

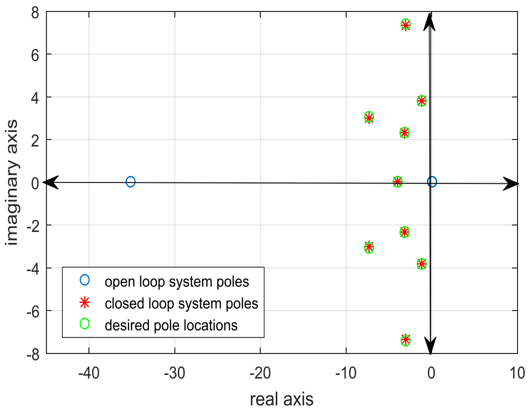

Figure 22. Pole locations of the open loop and closed-loop systems

VI. Conclusion

In this paper, an existing ROC is proposed for the ball and beam module. The stabilisation of the system is performed with minimum expenditure of energy while satisfying all the system constraints. Since the closed-loop poles are fixed at the design stage of controller; stability is ensured even in the presence of parametric uncertainties, external disturbances as well as perturbations in the initial condition. The simulation results illustrate that, without violation of constraints, the closed-loop system can accommodate a worst case of state and input parameter variations of 80 % and 15 %, respectively. Furthermore, no instability or constraint violation is observed even under the effect of random disturbances of small magnitude and duration. From the analysis, it is also found that ROC guarantees stability for non-nominal and optimal stability for nominal initial conditions. Hence, it is suitable for continuous time systems having dynamics similar to the ball and beam module.

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Nidya M. V. was born on 27th January 1990 in Kozhikode, Kerala, India. Currently she is pursuing her Ph. D in control systems at National Institute of Technology, Calicut, India. She has completed her graduation in Electrical and Electronics Engineering in 2011, from School of Engineering, Cochin University of Science and Technology (CUSAT), Cochin, India. She completed her post-graduation in Instrumentation and Control Systems from National Institute of Technology, Calicut, India in 2014.She is a member of IEEE Control System Society since September 2016.

Jeevamma Jacob was born in 1961, in Ernakulam, Kerala, India. She received her BSc. Engineering degree from M. A. College of Engineering, , Kerala University, India and M. Tech degree from National Institute of Technology, Calicut, India. She received her Ph. D degree from Indian Institute of Technology, Bombay, India in 1994.She is working as a Professor in National Institute of Technology Calicut, India. She is a member of IEEE Control System Society and life member of ISTE and System Society of India (SSI).

Mija S. J. was born in Trivandrum, India in 1979. She received the B. Tech degree in Electrical and Electronics Engineering and M. Tech degree in Guidance and Navigational Control from University of Kerala, India in 2000 and 2002 respectively. She received the Ph. D degree in 2014 from National Institute of Technology, Calicut where she is working as an Assistant Professor, since November 2007. She is a member of IEEE, IEEE WIE and IEEE Control System Society and life member of System Society of India (SSI).