

Design and Implementation of Ball and Beam Control System

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ABSTRACT: The ball and beam control system usually defined as non-linear control system which basically derived and implemented to observe the controller performance. One important step in this design process is to develop a mathematical model of the system. The main purpose of this project is to balance ball on beam using proportional-integral-derivative (PID) controller design with MATLAB and related control algorithm to adjust the angle of beam with real time sensory feedback. A constant angle of beam causes the ball to slide in axial direction due to gravity. Based on closed loop real time control system and well-tuned parameter, it will necessarily adjust angle of the beam to minimise the error, namely the distance between the actual position and set-point position of the ball. The system includes a ball, a beam, a motor and ultrasonic sensor for position sensing of ball. The basic idea is to use the torque generated from motor to the control the position of the ball on the beam by actuating the beam in desired angle. The information from the ultrasonic sensor can be taken and compared with desired set values and the difference can be fed back to Arduino used as controller that is PID controller design in it. Servo Motor will be interfaced with Arduino Uno board which in turn actuate the beam in desired angle in order to attain the set-point requirement.

KEYWORDS: Proportional-Integral-Derivative (PID) controller, MATLAB, Arduino uno, Mathematical modelling, Transient parameters.

I. INTRODUCTION

The ball and beam control system is also called 'balancing a ball on a beam'. It can usually be found in most university control labs. It is generally linked to real control problems such as horizontally stabilizing an airplane during landing and in turbulent airflow. There are two aspects used in this system. One is the ball rolling up and down the beam, and the other is beam rotating through its central axis. The aim of the system is to control the position of the ball to a desired reference point, and reject disturbances such as a push from a finger. The control signal can be derived by feeding back the position information of the ball using ultrasonic sensor. The control voltage signal goes to the servo motor via arduino then the torque generated from the motor drives the beam to rotate to the desired angle. Thus, the ball can be located at the desired position. It is important to point out that the open loop of the system is unstable and nonlinear. The problem of 'instability' can be overcome by closing the open loop with a feedback controller. The modern state-space method can be employed to stabilize the system. The nonlinear property is not significant when the beam only deflects a small angle from the horizontal position, instead of this it is a location of ball away from desired set-point. In this case, it is possible to linearize the system. However, the non-linearity's become significant when the ball positioned at away from set-point and the angle of the beam from the horizontal is larger than 45 degrees, or smaller than -45 degrees. The position of the ball on the beam is controlled by servo motor which is provided at the one end of the beam.

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II.LITERATURE SURVEY

Previously, the ball and beam system has been built by many organisations. In the following, a brief literature review is presented.

Hirsch (1999) built his 'Ball on Beam System' in 1999. The system employed an ultrasonic sensor to measure the position of the ball. The angle of the beam was measured through the use of a potentiometer. The motor with a gearbox was driven with a high power op-amp circuit. The system is controlled by a PD controller [2].

Arroyo (2005) built the system named the 'Ball on Balancing Beam' in 2005, the system employed the resistive wire sensor to measure the position of the ball. The resistive position sensor acted as a wiper similar to a potentiometer resulting in the position of the ball. The signal from the sensor was processed in a DSP. A DC motor with reducing gear was used. The system was controlled by PD controller. This system was easy to build, and the simple PD controller was easy to design. The negative aspects of the 'Ball on Balancing Beam' system includes that the beam was made of acrylic, which may be too brittle for a sudden impact. Additionally, although the position of the ball was controlled by the PD controller, the tilt angle of the beam was not measured and controlled. Therefore, the system may be not very robust. [2]

Another one from the Department of Electrical Engineering at Lakehead University built a system named the 'Ball and Beam Balancer' (Ambalavanar, Moinuddin & Malyshev 2006), The system employed a DC motor with an integrated gearbox, a resistive wire position sensor, and a digital encoder. The system was controlled by LQR controller. These 'Ball and Beam Balancer' system had one input (voltage input of the motor), and two outputs (the position of the ball and the tilt angle of the beam). The system may be very robust because the state space method with the LQR controller is good at controlling MIMO (Multiple Input, Multiple Output) system. The beam of the 'Ball and Beam Balancer' system was heavy because it was made of aluminium, which has a high density compared to acrylic [2].

III.SYSTEM CONFIGURATION

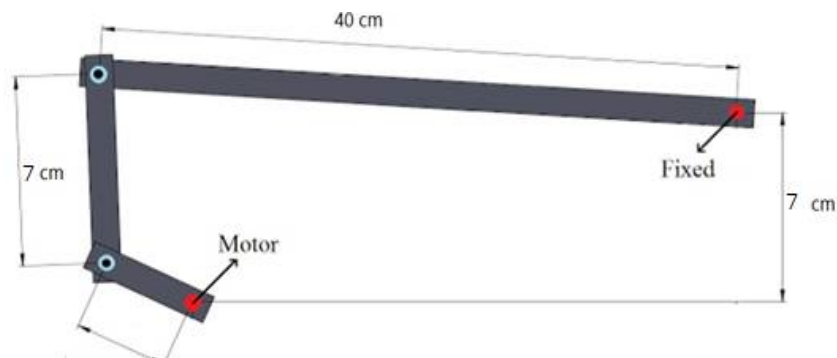
To implement the ball and beam system, it is necessary to discuss what configuration theory are involved in this project. According to literature survey, it is essential to understand all the possible configurations in order to devise the final. There are two types of configuration. One is based on the shaft supporting the beam in the middle and rotates against its central axis. Most of the ball and beam systems use this type of configuration. The advantage of this configuration is that it is easy to build, and the mathematical model is relatively simple. Another configuration is shown in fig. The beam is supported on the both sides by two lever arms. One of lever arms is pinned, and the other is coupled to output gear of motor. The disadvantage of this configuration is that more consideration of the mechanical parts is required, and this may add some difficulties in deriving a mathematical model. But, we implemented the second one configuration with help of 'Control Tutorial for Matlab and Simulink', that is it has been easier to modelled this system mathematically, we have design the system with this type of configuration with accurate measurements and mechanical consideration which as shown in below Fig(a)Final Configuration. But also the main parts of the system with configuring manner are the base, support, beam, ball and sensors. We have designed base and support of system from wooden material like plywood because of it provides not only portable facility but also easy to attachable, flexible facility to connecting beam respectively.

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Fig(a) Final Configuration

We have used medium ranged heavy material like light stainless steel for beam build up because it satisfies motor operate with its equalise torque specification, with size of 40 cm. The main design objective of the final model was to create a structure that is not only sturdy and well balanced, but is also light-weight and portable to carry. Thus, it was determined that the best option was to select light metal because of it not only helps to portable manner but also it helps to motor operate with its equalise torque specification. Also it designed in simple construction and low cost.

IV.COMPONENTS OF THE SYSTEM

Ultrasonic Sensor: There are several position sensors which are suitable for this project. They are conductive plastic or resistive wire (nickel-chromium), ultrasonic range sensor. Here in our project we have used ultrasonic range sensor which measures distance between ball and itself that is the position of ball and fed this signal to the controller. Hence we have used the Ultrasonic ranging module HC - SR04 provides 2cm - 400cm non-contact measurement function, the ranging accuracy can reach to 3mm. The modules include ultrasonic transmitters, receiver and control circuit. The basic principle of work of this sensor is on time difference basis that is by generating an ultrasonic wave or pulse and measuring a time it takes for echo to return.

MG995 Servo Motor: Basically, motor is a device that changes electrical energy into mechanical energy. It plays the most important part of the ball and beam control system as actuator for beam to tilt the beam in desired angle to attain the balls position at required set-point. A cheap, linear motor with good Controllability is necessary for this application. A servo motor with an integrated gearbox used for this system. In our project we have used MG995 servo motor which is the most famous servo made by TowerPro.MG995 is a digital metal gear high torque servo for airplane, helicopter.

Arduino Uno Board: Arduino is an open-source prototyping platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. Also, you can tell your board what to do by sending a set of instructions to the microcontroller on the board. Basically Arduino board used as controller as well as serial communicator between computer and hardware system. Hence we have used the Arduino board as controller. Also already designed PID controller with help of MATLAB automatically worked with its PID wallet which presented in Arduino library. Also updated version of Arduino 1.6.8 shows real time simulation which we have used for simulation of our ball and beam control system.

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V.MATHEMATICAL MODELLING OF SYSTEM

Theoretical Analysis: A ball is placed on a beam, see figure below Fig (b) Theoretical Configuration, where it is allowed to roll with 1 degree of freedom along the length of the beam. A lever arm is attached to the beam at one end and a servo gear at the other. As the servo gear turns by an angle θ , the lever changes the angle of the beam by α . When the angle is changed from the horizontal position, gravity causes the ball to roll along the beam. A controller will be designed for this system so that the ball's position can be manipulated [5].

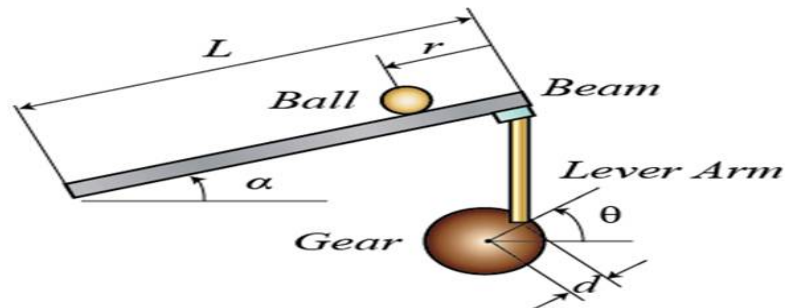


Fig (b) Theoretical Configuration

This is theoretical analysis for ball and beam control system shown in fig (a) Theoretical configuration considering with all variables and constants affecting to this control system which describes system behaviour in the form of transfer function with help of The Lagrangian equation of motion.

The constants and variables for the above system are defined as follows as:

- | | |
|---|---|
| (m) Mass of ball (in kg) | (L) Length of beam (in m) |
| (R) Radius of ball (in m) | (J) Balls moment of inertia (in kg.m ²) |
| (d) Lever arm offset (in m) | (r) Ball position coordinate |
| (g) Gravitational acceleration (in m/s ²) | (Alpha α) Beam angle coordinate |
| (theta θ) Servo gear angle | |

The second derivative of the input angle α actually affects the second derivative of r . However, we will ignore this contribution. The Lagrangian equation of motion for the ball is then given by the following [5]

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

The beam angle (α) can be expressed in terms of the angle of the gear (θ). [5]

$$\alpha = \frac{d}{L} \theta$$

Hence with help of 'Control Tutorial for Matlab and Simulink' we have modelled our system in mathematical way in MATLAB software.

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Building The Model In Simulink:

In this rather than express all the forces and geometric constraints we will model the nonlinear Lagrangian equation of motion directly. This equation gives \ddot{r} as a function of the state and input variables, $r, \dot{r}, \alpha,$ and $\dot{\alpha}$. We will make use of the Function block to express this function. First, we must express the derivatives of the output r . So, first of all open a new model window in Simulink. Insert an Integrator block. Insert a second Integrator to the right of the first, and connect the two with a line. Label the line connecting the two " $d/dt(r)$ ". Draw a line from the second Integrator and label it " r ". Insert an Out1 block and connect it to the " r " signal line. This will form the output of the system. Change the label of the Out1 block to " r ". Now, we will insert the function which takes the vector $[r \ \dot{r} \ \alpha \ \dot{\alpha}]$ and returns \ddot{r} . Insert a Function block and connect its output to the input of the first Integrator. Edit the Function block, and change its function to the following [5]:

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

This function block takes an input vector, u , where each component is referred to as $u [1], u [2]$ etc. In our case $u [1] = r,$ $u [2] = \dot{r}, u [3] = \alpha$ and $u [4] = \dot{\alpha}$. Then change the label of the Function block to "Ball-Beam Lagrangian Model". Then, we will begin to construct the function input vector u by feeding back the state signals from the integrators and forming a vector from them with a Mux block. Insert a Mux block and connect its output to the input of the Ball-Beam block. Edit the Mux block and change its number of inputs to 4. The Mux block should now have four inputs. Tap a line off the $d/dt(r)$ signal and connect it to the second input of the Mux block. Tap a line of the r signal and connect it to the first input of the Mux block. Then we will construct the signals α and $\dot{\alpha}$ from the input \emptyset . Insert an In block on the left side of your model window. Change its label to "theta". Insert a Gain block and connect it to the theta block. Change its gain value to " d/L ". Connect the output of the gain block to the third input of the Mux block. Label this line "alpha". Insert a Derivative block and place it underneath the alpha signal line. Tap a line off the output of the Gain block and connect it to the input of the Derivative block. Connect the output of the Derivative block to the fourth input off the Mux block. So, overall model will show like in following way in fig(c) Ball and Beam Model in Simulink this overall model forms total theoretical project model which energise with step input and generates the final response that is open loop response as its own behaviour.

Open-Loop Response: To generate the open-loop response, it is helpful to first contain this model in a subsystem block. Insert Subsystem block and open the Subsystem block and copy the previous model named ball.mdl and paste in it. Then Close the Subsystem window. You will see the Subsystem block in the untitled window with one input terminal labelled 'theta' and one output terminal labelled 'r'.

(a) Obtaining Transfer Function Of System:

Before obtaining a step response, we must set the physical parameters as taken and entered them in MATLAB command window.

m=0.187;	L=0.4;
R=0.02;	J=9.99e-6;
d=0.03;	

Now insert step signal block and connect it to input of subsystem block. then insert scope block and connect it to output of subsystem block. This whole assembly represents the open loop model of system. Now run the simulation and open the scope block, it shows the response as given above in Fig (d) Open Loop Response of Ball and Beam Model. it shows in exponential form which directly increases towards to infinity. From this plot it is clear that the system is unstable in open-loop since exponentially increasing response causing the ball to roll right off the end of the beam. Therefore, some method of controlling the ball's position in this system is required. So some control has to be given to system in order to stabilize the system. For this purpose, we must extract the transfer function of the system from the parameters taken.

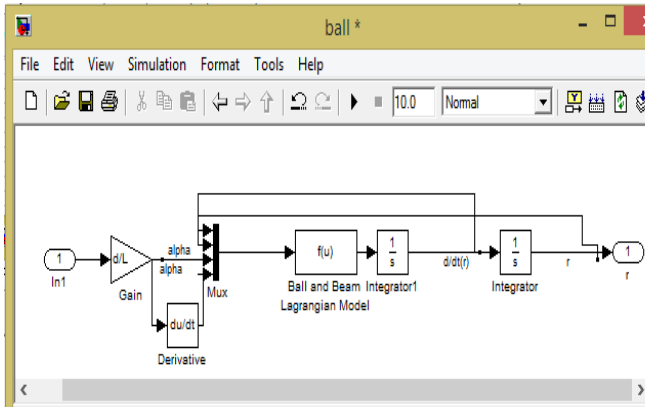
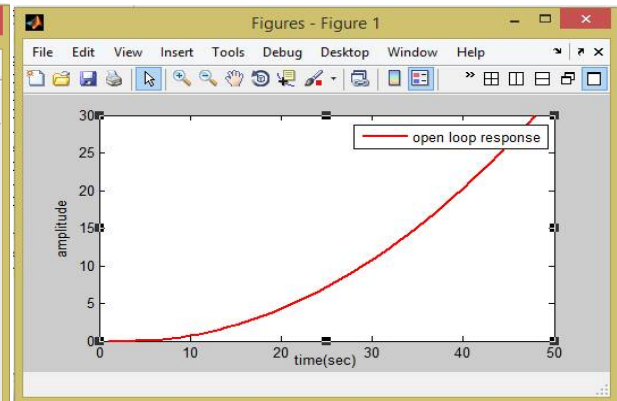


Fig (c) Ball and Beam Model in Simulink



Fig(d) Open Loop Response of Ball and Beam Model

Extracting The Linear Model Into Matlab:

The Simulink model can be extracted into an equivalent state-space or transfer function model in MATLAB. This is done through the use of In1 and Out1 blocks and the MATLAB function *linmod*.

For this purpose, enter the following commands in MATLAB's command window. You will see the following output providing the open-loop model of the system [5].

```
[A,B,C,D] = linmod('ball')
[num, den] = ss2tf(A,B,C,D)
```

And getting the transfer function-

$$\frac{0.0546}{s^2}$$

VI. BUILDING PID CONTROLLER FOR THE SYSTEM

As we seen earlier the system is non-linear. So we have need a controller to make it linear and force it to work desirably. To design the PID controller further steps are to be followed. Insert a step block and keep the step time as zero. Insert an PID block and set initial values of k_p , k_i and k_d as zero. Insert scope and signal constraint block from sink and Simulink design optimization library respectively. Insert a transfer function block and implement the transfer function found in above case there. The main purpose of signal constraint to set the constraint to get the response as per our desire. We can set the constraints for the response in that pallet. Now go to signal constraint palate, set the response constraints and start the simulation. The signal constraint shows various step responses in reference to ideal step response curve and finally it settled as ideal step response curve which is shown below [5]. And it gives closed loop response as shown in below fig(e) as well as the final settled response obtained in scope is shown below in fig(e).

During the process, It optimise the k_p , k_i and k_d values with changing number of iterations. Finally, it gives the optimum values of k_p , k_i and k_d within specified tolerance.

In this way, we have finally got this k_p , k_i and k_d values. Which we have used as gain parameters in 'my.PID' wallet of Arduino. The obtained values of k_p , k_i and k_d are given below

$$K_p = 2.3392$$

$$K_i = - 0.2228$$

$$K_d = 41.0787$$

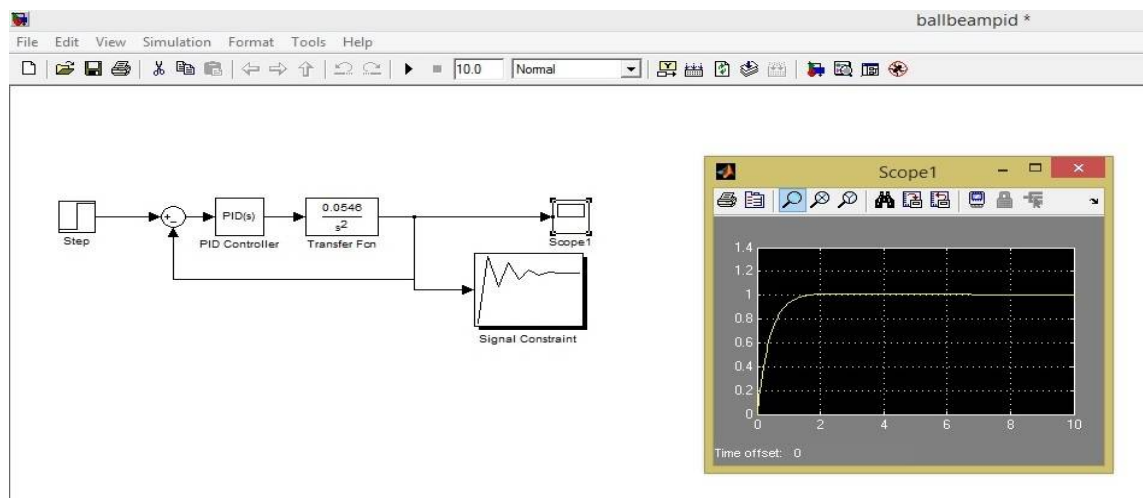
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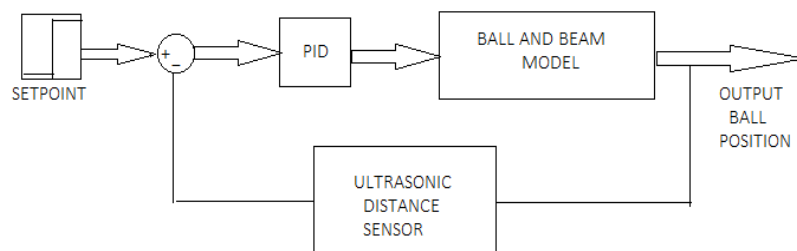
This Fig(e) Building of PID controller for the system and its controlled closed loop response demonstrates building of PID controller for the system and response of system after PID action is consequences on the ball and beam mathematical model and generates final system controlled response that is closed loop response of the system.



Fig(e) Building of PID controller for the system and its controlled closed loop response

VII.CONNECTION AND WORKING

Basically it operates as in closed loop control system shown in fig (f) Block Diagram of Ball and Beam Control System in which, Set point gives as reference signal to PID controller takes corrective action according to feedback signal received by ultrasonic sensor and controls the ball and beam model as final balls position to set point.



Fig(f) Block Diagram of Ball and Beam Control System

As Arduino-uno base used as predesigned PID controller of the system. Also we have developed program code in Arduino IDE software 1.6.8 for the control mechanism of this system. In this configuration, +5v and ground (GND) supply directly connected to servo motor and ultrasonic sensor for its proper working. Normally, Ultrasonic range sensor used with input signal as PWM pulses in on-off sequence from pin no. 3,5,6,9,10,11 of arduino board for trigger itself. Since transmitter generates sound wave with very low frequency passes in air medium and reflected back from balls position to the receiver. Which also gives very low strengthen signal at receiver side which is also PWM signal at same pin no. on Arduino Uno. Hence we can't get analog parameter that directly indicates the distance of the ball position. Hence for that purpose we have directly given trigger signal from analog pin A0 of arduino board and received echo with analog pin A1. In this way we could directly obtained the real time simulation in arduino in serial

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plotter option provided in that version of same software. Thus, in terms of servo actuation we have provided control signal to servo motor from pin no. 9 i.e. PWM signal which is suitable for servomotor.

Basically this system referred as very non-linear system. Its main objective to design accurate controller and apply different control strategies for that system in order to get better control over the system and stabilize it in less amount of time. As per setup and objective which has to be achieved we have developed the programming code. In which First of all, set the maximum and minimum range for balls position to rolls over the beam that is min is 2cm and maximum is 40cm and also set the limits of the angle of rotation that is in range between -45 to +45. Moving towards the controller, which has near about perfect values of the K_p , K_i and K_d as we had calculated from tuning which will consider as it got better control over the system but whenever it loses the control over system then we had to change the gain parameters according to system stabilization.

Initially controller requires the initial position of the motor for that purpose we had to measure the initial angle of the servomotor and gives it to the controller for better control because, until controller didn't know the initial angle of the servomotor It cannot be get control over the system. Normally, all of the 'ball on beam balancing control system' project has used encoder. Which directly acts as angle sensor for servomotor and it gives directly initial angle to PID controller. But, because of the cost effective reason we could not implement the position sensor as encoder. Hence for that solution we have developed another technique which helped directly to indicate servomotor angle. Which is also cheap technique to measure the angle of the servomotor.

Potentiometer directly connected to the one of the analog input pin of arduino (A1) as varying analog input resistance among the circuit of power supplying to servomotor. And servomotor connected to PWM output pin no. 8 which vary the pulse width according to input resistance changes through POT. As the wiper of the POT rotates from 0 to 360 degree it changes its resistance proportionally. As resistance changes servomotor rotates from angle 0 to 180 degree. And normally this value in arduino plots as 0 to 1023 then it mapping to 0 to 180 degree that is movement in angle of rotation. Basically, this 0 to 180degree value plotted as input analog value of POT resistance. And hence according to that movement of the wiper it directly calibrated as angle of the servomotor.

VIII.RESULT

As we have worked our configuration, we have attained stability in 92 sec. with our system at 15 cm set-point. We had simulated our system with 'Serial plotter' function in arduino which shows real time varying parameter with respect to the time as shown in below. The process of taking the distance measurements by ultrasonic sensor and comparing the same with setpoint continues until ball attains desired position. From the above resulted closed loop response in Simulink of Matlab we have calculated theoretically analytical transient parameters and practically worked analytical transient parameters which shown in below table no.1 Theoretically and Practically Calculated Transient parameters.

The Transient Parameters are given below,

Table No.1 Theoretically and Practically Calculated Transient parameters

Sr. No.	Transient Parameter	Analytical values	Practical value
1.	Delay time(T_d)	0.27	0.27
2.	Rise Time(T_r)	0.8	0.8
3.	Time Constant	0.44	0.44
4.	Settling Time(T_s)	9.2	92

The values obtained above are same as we obtained by simulation in MATLAB except settling time is much larger. since this are the practically obtained values and for such high settling time there are many causes like values of

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PID parameters k_p , k_i , k_d or variation in system parameters, imperfect mechanically designed system with wear and tear at joints etc.

IX.CONCLUSION

Thus from our project we have concluded that the Ball and Beam system is most non-linear system available to us after aeroplane and it is best platform to check the controller performance. If any controller works well with system then that controller is fine. But, if any controller doesn't respond as per our desire then some modifications are needed in the same. Also the controller we have designed is not that perfect since it took lot of time to attain steady state because of it affected by many constraints like PID parameters k_p , k_i , k_d , absolutely correct system parameters, mechanical design consideration etc.

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