Ball and Beam Control Systems

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SUBMITTED TO:

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Internship Guide

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I would like to extend my heartfelt gratitude to all those who have made my summer internship at NIT Trichy an enriching and memorable experience.

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This internship has been a significant milestone in my academic and professional journey, and I am sincerely grateful to everyone who contributed to making it a success.

Thank you.
Piyush Shukla

CERTIFICATE

This is to certify that Piyush Shukla has successfully completed the Summer Internship at National Institute of Technology, Tiruchirapalli under the guidance and supervision of Dr. S. Mageshwari. During this period, Piyush has demonstrated diligence, commitment, and a keen interest in the assigned tasks and projects. The internship work included working on Ball and Beam Control Systems.

Dr. S. Mageshwari

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ABSTRACT

This Project presents an in-depth study of the Ball and Beam Control System, a fundamental control theory problem. The project focuses on non-model-based control methods implemented using MATLAB, SIMULINK, and GUI..
The Ball and Beam system, known for its inherent instability, is an excellent platform to explore various control strategies and their effectiveness.

We employed several analysis tools to evaluate the system's performance, including Bode Plot, Root Locus, Pole-Zero Map, and Step Response. These Plots provided insights into the system's frequency response, stability, and transient behavior. Through simulations, we gained a comprehensive understanding of the dynamic characteristics and control challenges of the Ball and Beam system.

This work contributes to the practical knowledge of control system design and analysis, providing a robust framework for future research and applications in similar control systems.

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Ball and Beam Control Systems

1. Introduction:

The ball and beam system is also called ‘balancing a ball on a beam’ ,since it is relatively easy to build, model and control theoretically. The system includes a ball, a beam, a motor and several sensors. It is generally linked to real control problems such as horizontally stabilizing an airplane during landing and in turbulent airflow. There are two degrees of freedom in this system. One is the ball rolling up and down the beam, and the other is the beam rotating from its one end. Ball and beam system is a very interesting system by its nonlinear dynamics and its under-actuated phenomenon. These types of systems have a wide range of industrial applications including passenger's platform balancing for comfort in luxury cars, control of rocket and aircraft vertical take-off and liquid carrying tankers on the roads where liquid behaves like a ball on a beam. It is ideal laboratory equipment to test classical, modern and advanced control system theory.

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.

This project aims to model and control the Ball and Beam System using various Controllers in MATLAB -SIMULINK.

2. OBJECTIVES OF THE PROJECT

- To thoroughly understand the dynamics and control principles of the Ball and Beam system.
- To develop and validate a mathematical model for the Ball and Beam system.
- To simulate the system in MATLAB SIMULINK for performance analysis.
- To design and implement control strategies using PID controllers.
- Demonstrate the importance and applications of Ball and Beam systems in control theory and engineering.
- Provide recommendations for future research and improvements in Ball and Beam control systems.

3. Theory

The purpose of this study was to demonstrate how feedback influences the response of a control system by constructing a PID controller. A control system is a device that manages and regulates the behavior of a particular system. The system in our case is the ball balance beam. In this system, a beam must be able to balance a ball and return the ball to the center of the beam if moved.

There are two different types of systems: Open loop and Closed loop.

- Open loop systems have no feedback and are simply based on the input.
- Closed loop systems use feedback to improve the control of the system.

The principle being tested by this experiment is how feedback can improve the system. This is achieved by the construction of a PID controller.

The PID controller is a type of feedback controller where P stands for proportional, I for integral, and D for derivative.

- The “P” term is responsible for producing an output value that is proportional to the current error that the system is calculating.
- The “I” term is essentially the sum of all the instantaneous errors and is responsible for eliminating the steady state error.
- The “D” term is responsible for predicting the future system behavior and using the predicted behavior to improve the time and stability of the system.

When all three parts are put together in one controller, the system should be able to achieve a steady state of oscillation. The output of the system is reliant on each part of the PID controller and each term has a corresponding gain that accompanies it.

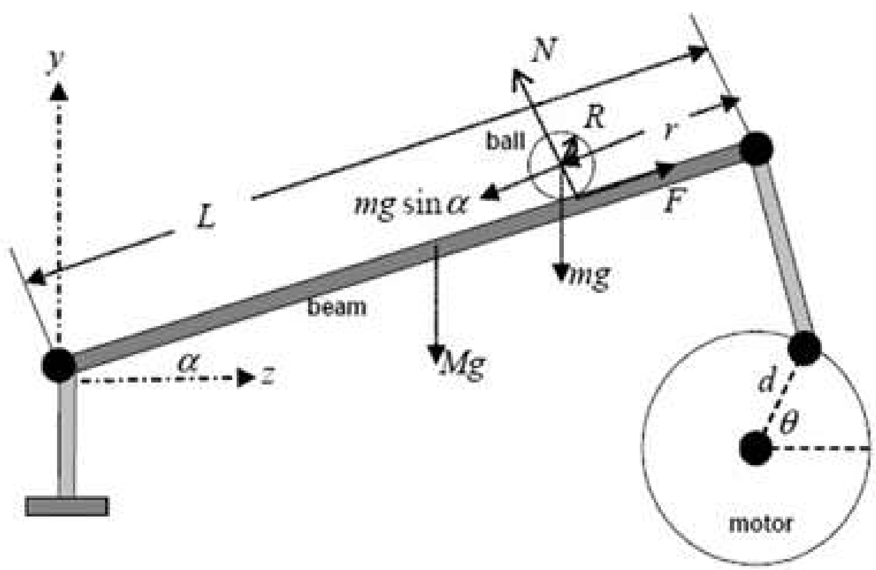
1. The “P” produces a proportional gain and this value has a direct result on response speed and percent overshoot.
2. The “I” produces an integral gain, which when combined with the proportional gain can produce an increase in rise time and settling of the system.
3. The derivative gain that is produced by the “D” term will help to decrease the overshoot value and settling time.

DESIGN CRITERIA :

- Settling time should be less than 3 seconds.
- Overshoot less than 5 percent.

SYSTEM MODELING

In order to acquire a ball and beam system dynamic equation, Lagrange approach is used to find the ball position of the system. It is based on the energy balance of the system. The Lagrange approach is used to acquire the motion equations for the ball and beam system.



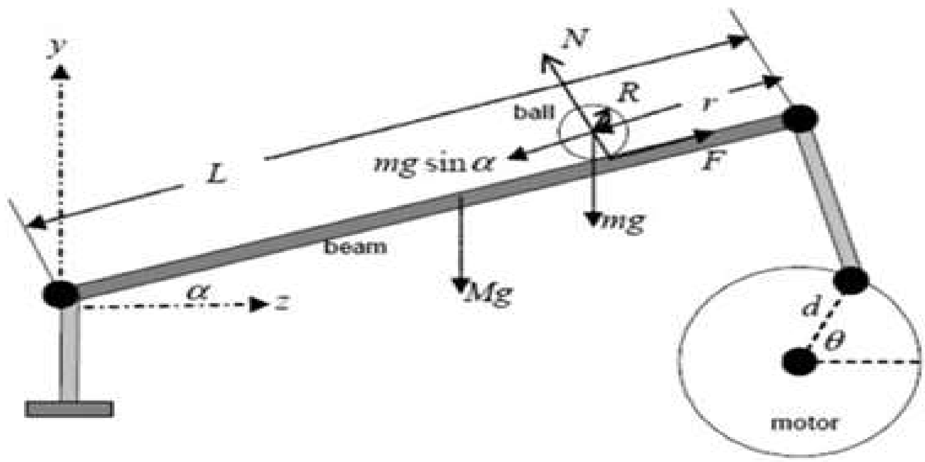
Where,

m ,mass of the ball 0.11 kg
R, radius of the ball 0.015 m
d, lever arm offset 0.03 m
g, gravitational acceleration 9.8 m/s^2
L, length of the beam 1.0 m
J,ball's moment of inertia 9.99e-6 kg.m^2
r, ball position coordinate
alpha, beam angle coordinate
Theta, Servo gear angle

SYSTEM EQUATIONS

The dynamic equation of the ball on the beam has been described by using Lagrange method as given below :

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



Linearization of this equation about the beam angle, **α** = 0, gives us the following linear approximation of the system :

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

The equation which relates the beam angle to the angle of the gear can be approximated as linear by the equation below :

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

Substituting this into the previous equation, we get :

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

Transfer Function :

Taking the Laplace transform of the equation above, the following equation is found :

$$\left(\frac{J}{R^2}+m\right)R(s)s^2=-mg\frac{d}{L}\Theta(s)$$

Rearranging we find the transfer function from the gear angle (θ(s)) to the ball position (R(s)).

$$P(s)=\frac{R(s)}{\Theta(s)}=-\frac{mgd}{L\left(\frac{J}{R^2}+m\right)}\frac{1}{s^2} \qquad [\frac{m}{rad}]$$

It should be noted that the above plant transfer function is a double integrator. As such it is marginally stable and will provide a challenging control problem.

MATLAB

The Transfer function can be implemented in MATLAB as follows:

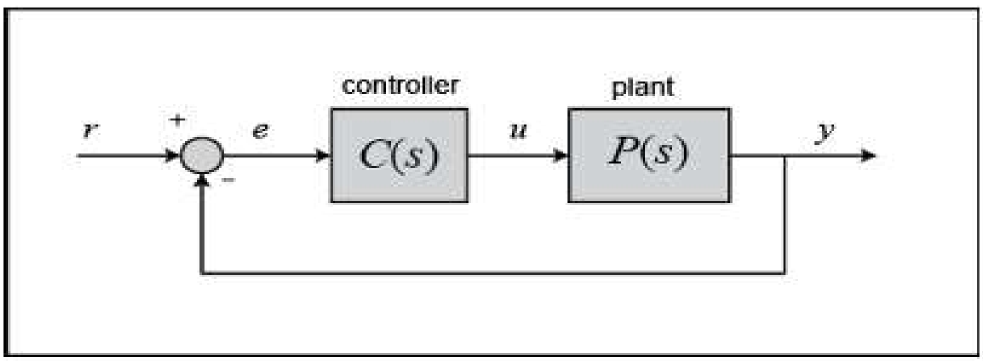
```
m = 0.111;
R = 0.015;
g = -9.8;
L = 1.0;
d = 0.03;
J = 9.99e-6;

s = tf('s');

P_ball = -m*g*d/L/(J/R^2+m)/s^2                    % P_ball = 0.21/(s^2)
```

Upon running the matlab file, The command window prompt shows the output as shown below :

```
Command Window
>> bb2

P_ball =

  0.21
  ----
  s^2

Continuous-time transfer function.
```

PID CONTROLLER

A proportional–integral–derivative controller (PID controller or three-term controller) is a control loop mechanism employing feedback that is widely used in industrial control systems and a variety of other applications requiring continuously modulated control. A PID controller continuously calculates an error value as the difference between a desired setpoint (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms (denoted P, I, and D respectively).



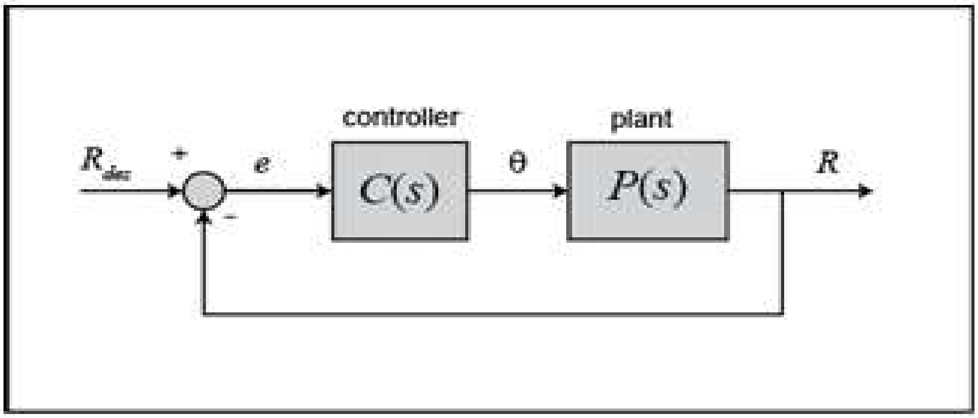
(e) - the tracking error
(r) - desired output
(y) - actual output
(u) - control signal
(Kp) - proportional gain
(Ki) - integral gain
(Kd) - derivative gain

The equation of PID controller is :

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

Closed-loop representation

The block diagram for this example with a controller and unity feedback of the ball's position is shown below:



First,study the response of the system shown above when a proportional controller is used. Then, derivative and/or integral control will be added if necessary.

Recall, that the transfer function for a PID controller is:

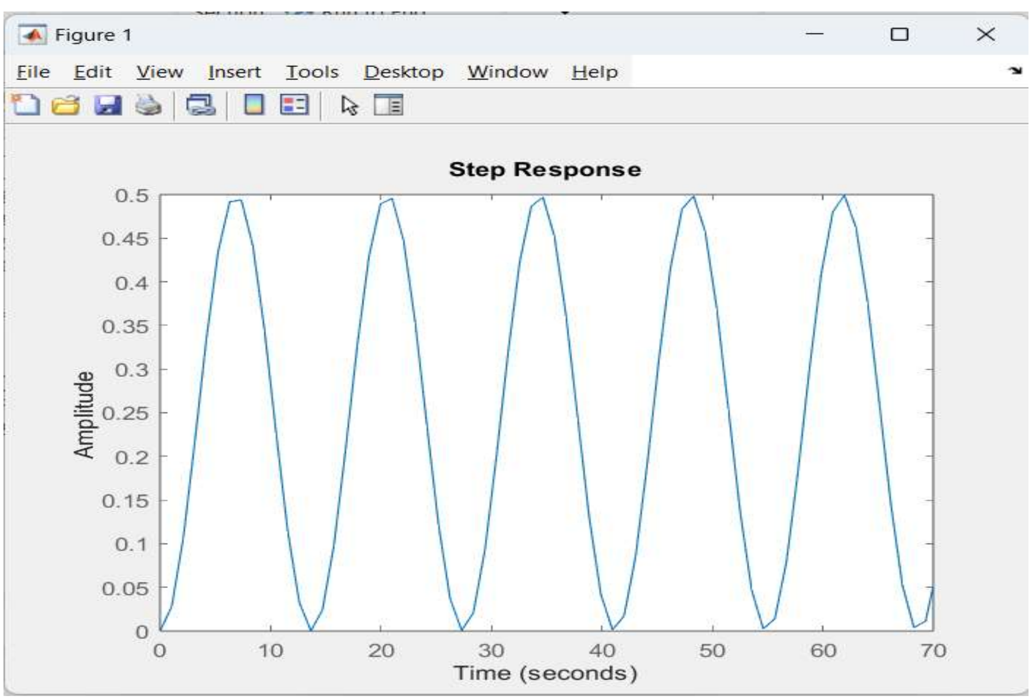
$$C(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s}$$

Proportional control

The closed-loop transfer function for proportional control with a proportional gain (Kp) equal to 1, we have modeled the system's response to a step input of 0.25m.

```
m = 0.11;
R = 0.015;
g = -9.8;
d = 0.03;
L =  1.0;
J =  9.99e-6;
s = tf('s');
P_ball = -m*g*d/L/(J/R^2+m)/s^2;

Kp = 1;
C = pid(Kp);
sys_cl=feedback(C*P_ball,1);
step(0.25*sys_cl)
axis([0 70 0 0.5])
```

The system remains marginally stable with the addition of a proportional gain. Change the value of Kp and note that the system remains unstable.



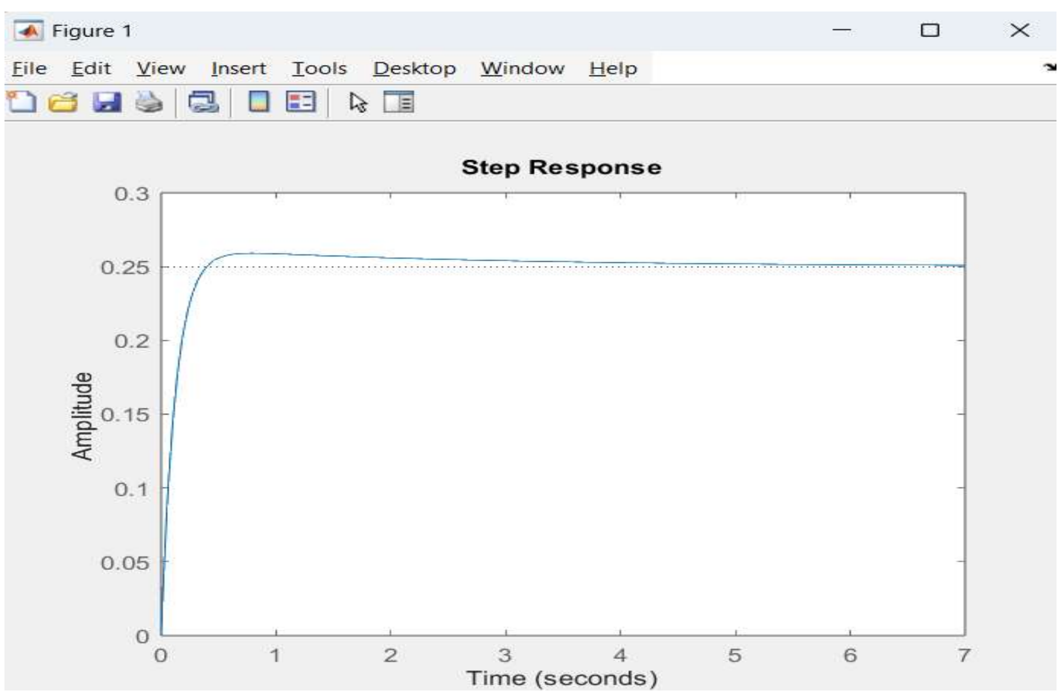
Proportional-derivative control

We tuned at various Kp and Kd to meet the desired overshoot criterion and settling time.

After tuning the gains a bit, the following step response plot can be achieved with Kp= 15 and Kd=40.

```
m = 0.11;
R = 0.015;
g = -9.8;
d = 0.03;
L =  1.0;
J =  9.99e-6;
s = tf('s');
P_ball = -m*g*d/L/(J/R^2+m)/s^2;

Kp = 15;
Kd = 40;
C = pid(Kp,0,Kd);
sys_cl=feedback(C*P_ball,1);
t=0:0.01:5;
step(0.25*sys_cl)
```

The Output for the matlab file is :



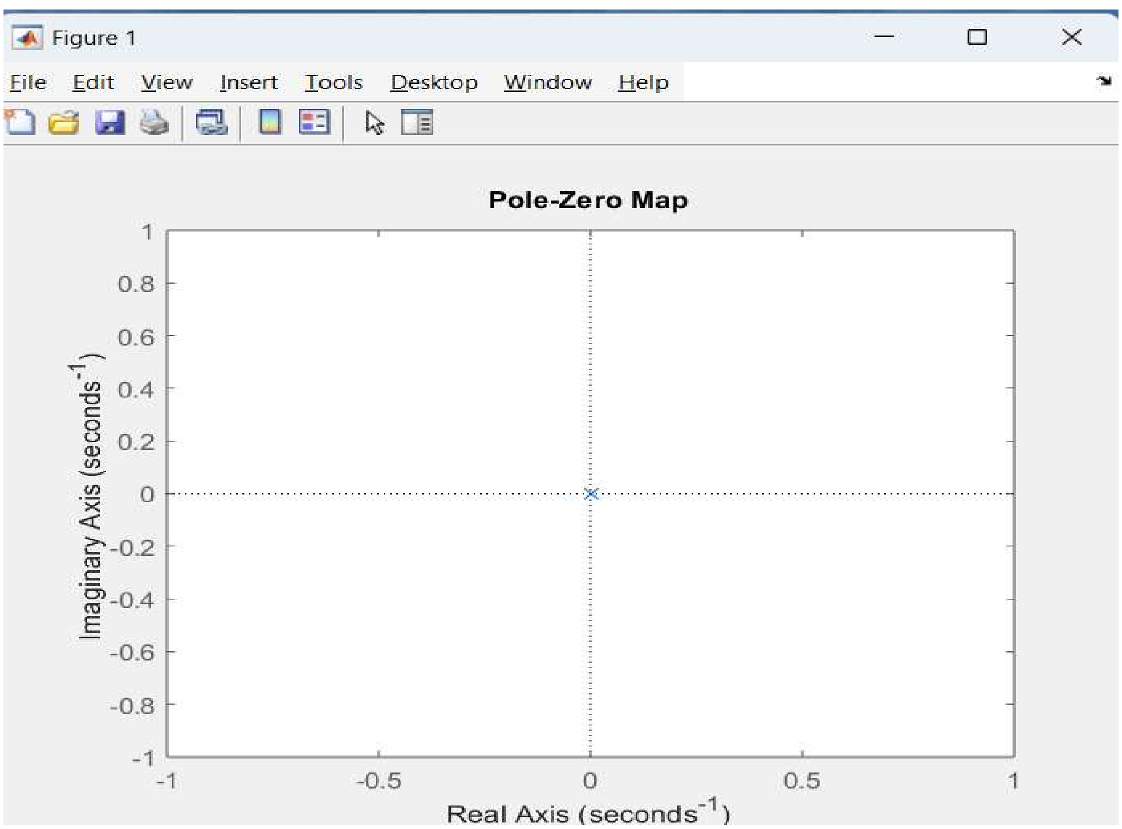
4. ANALYSIS

1. Pole - Zero Map

The Ball and Beam system is a type II system which has two poles at the origin, as seen in the pole/zero map below. Since the poles are not strictly in the left half plane, the open loop system will be unstable as seen in the step response below.

```
pzmap(P_ball)
```

The Pole - Zero plot Output is shown below :

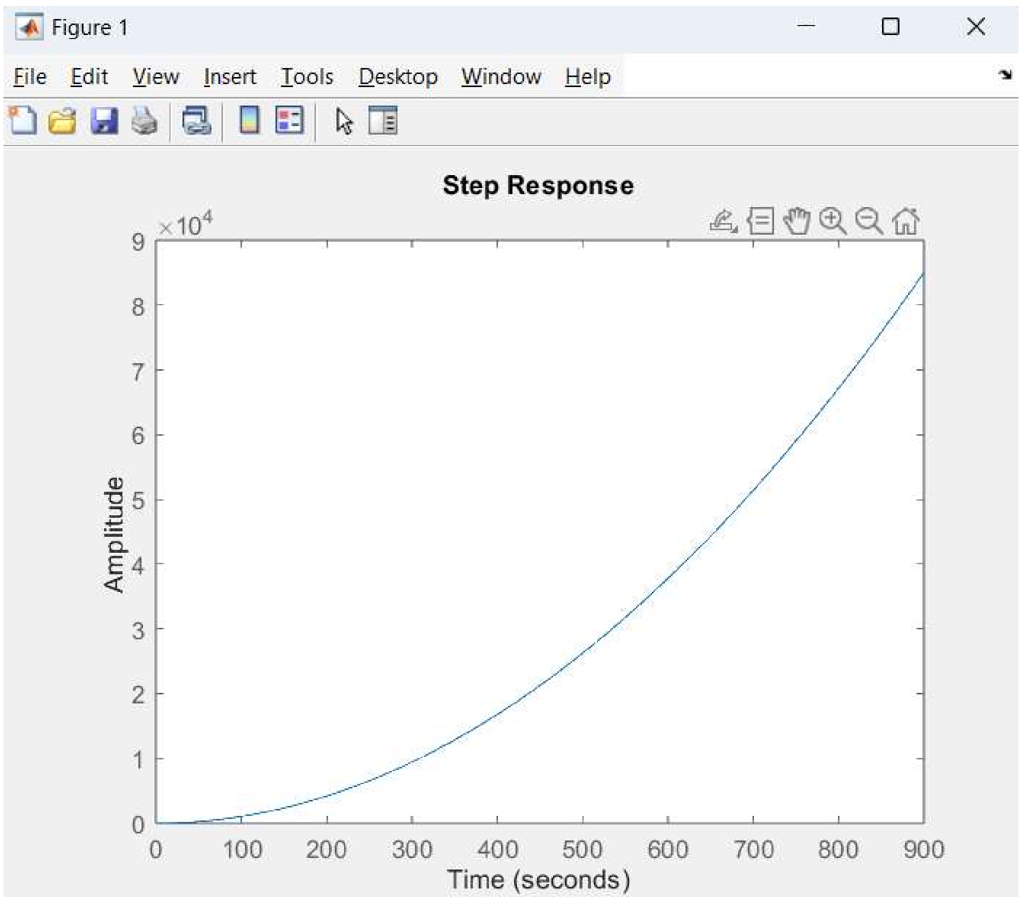


2. Open Loop Step Response

Now, we would like to observe the ball's response to a step input on the motor servo gear angle θ (1-radian step). To do this you will need to add the following line to your bb2.m-file.

```
step(P_ball)
```

The Step Response Output is shown below :



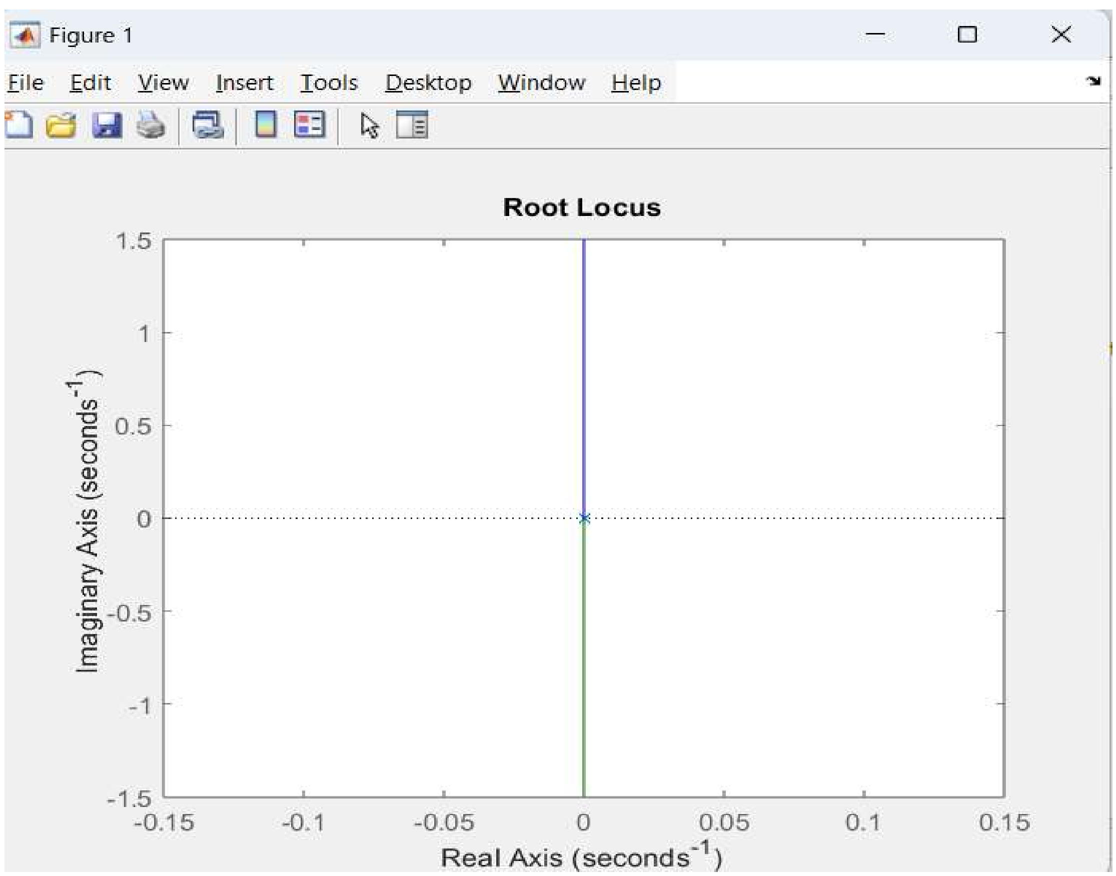
From this plot it is clear that the system is unstable in an open-loop causing the ball to roll right off the end of the beam. Therefore, some method of controlling the ball's position in this system is required.

3. Root Locus

The main idea of the root locus design is to estimate the closed-loop response from the open-loop root locus plot. By adding zeros and/or poles to the original system (adding a compensator), the root locus and thus the closed-loop response will be modified. Let us first view the root locus for the plant in an open loop.

```
rlocus(P_ball)
```

The Root Locus Plot Output is shown below :



As you can see the system has two poles at the origin which go off to infinity along the imaginary axes.

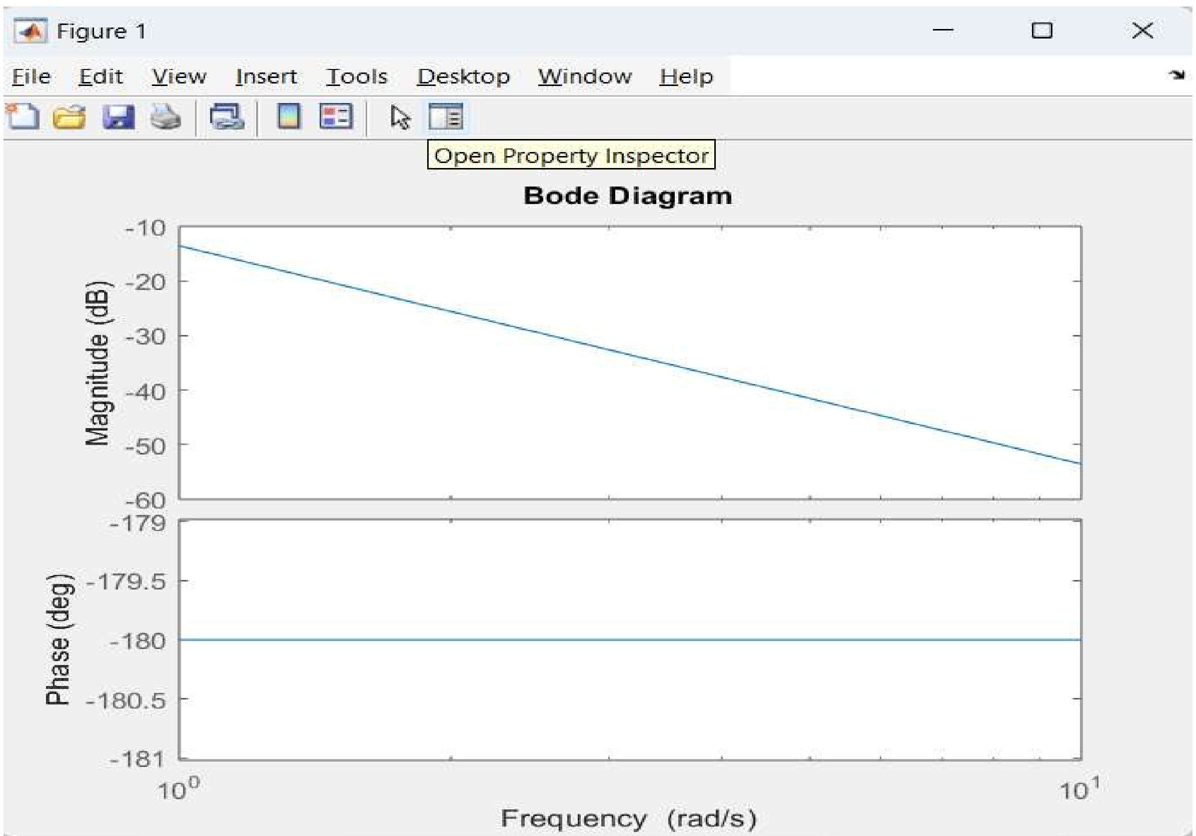
4. Bode Plot

The main idea of frequency based design is to use the Bode plot of the open-loop transfer function to estimate the closed-loop response.

The bode plot for the original open-loop transfer function.

```
bode(P_ball)
```

The Bode Plot is plotted below :

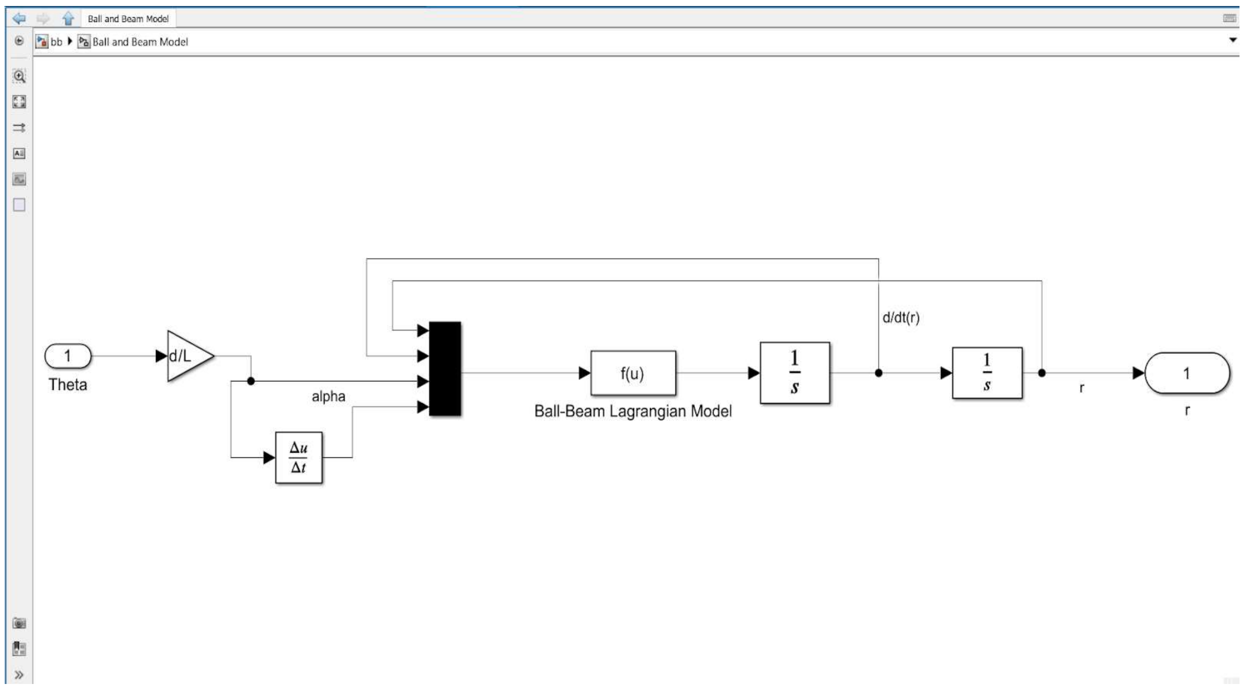


We can see that the phase margin is zero. Since the phase margin is defined as the change in open-loop phase shift necessary to make a closed-loop system unstable this means that our zero phase margin indicates our system is Unstable.

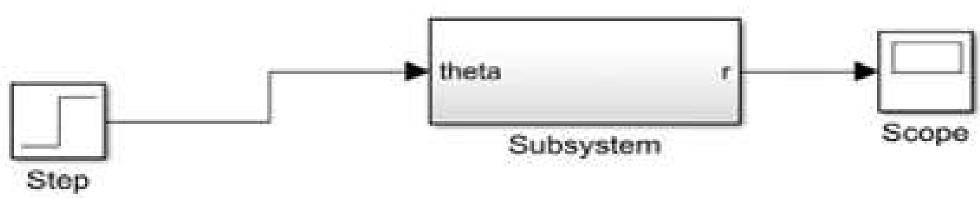
5. SIMULINK MODEL

- Open Loop response

This is the Subsystem of the Simulink model.



Working into a subsystem and checking the Open-Loop Response.

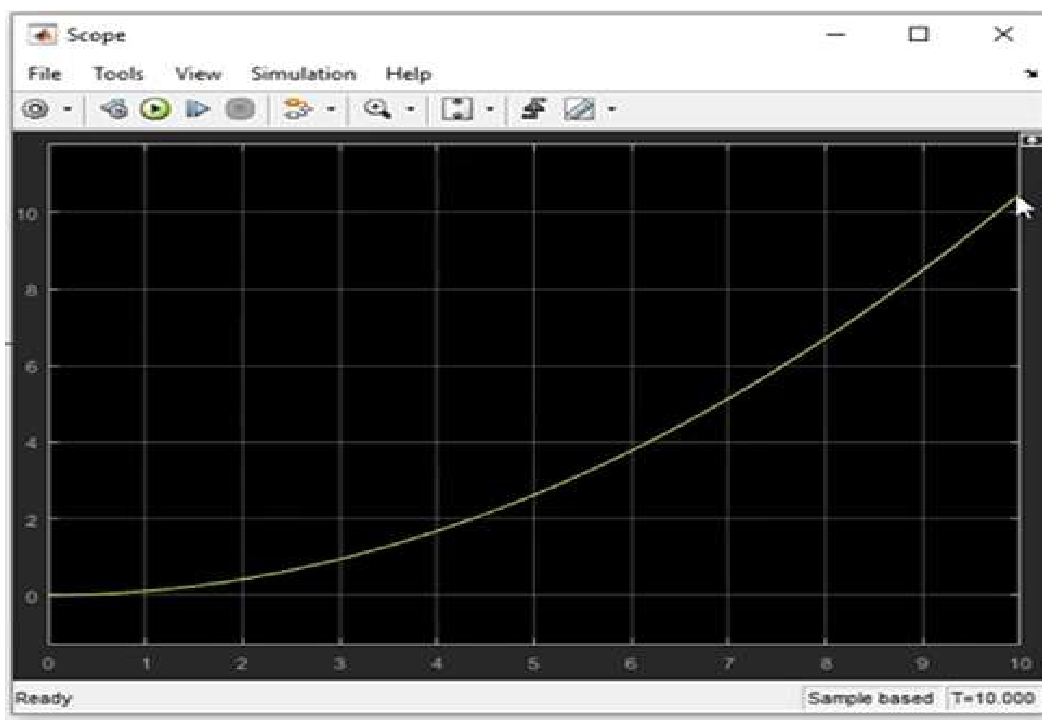


Assign values of constants in command window:

Workspace

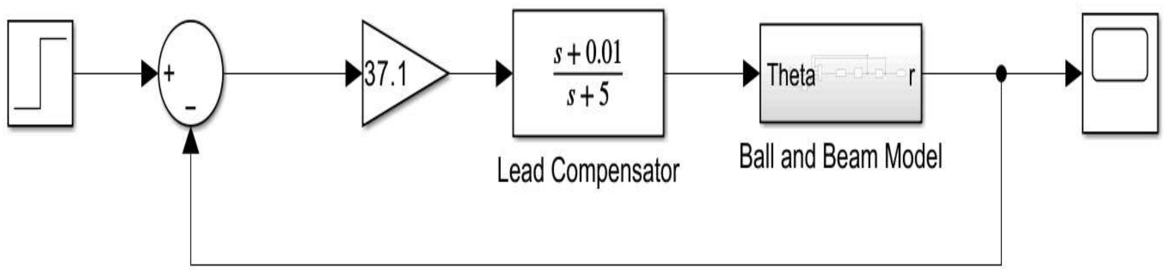
Name	Value
d	0.0300
g	-9.8000
J	9.9900e-06
L	1
m	0.1110
R	0.0150

The Output (Scope) comes as follows :

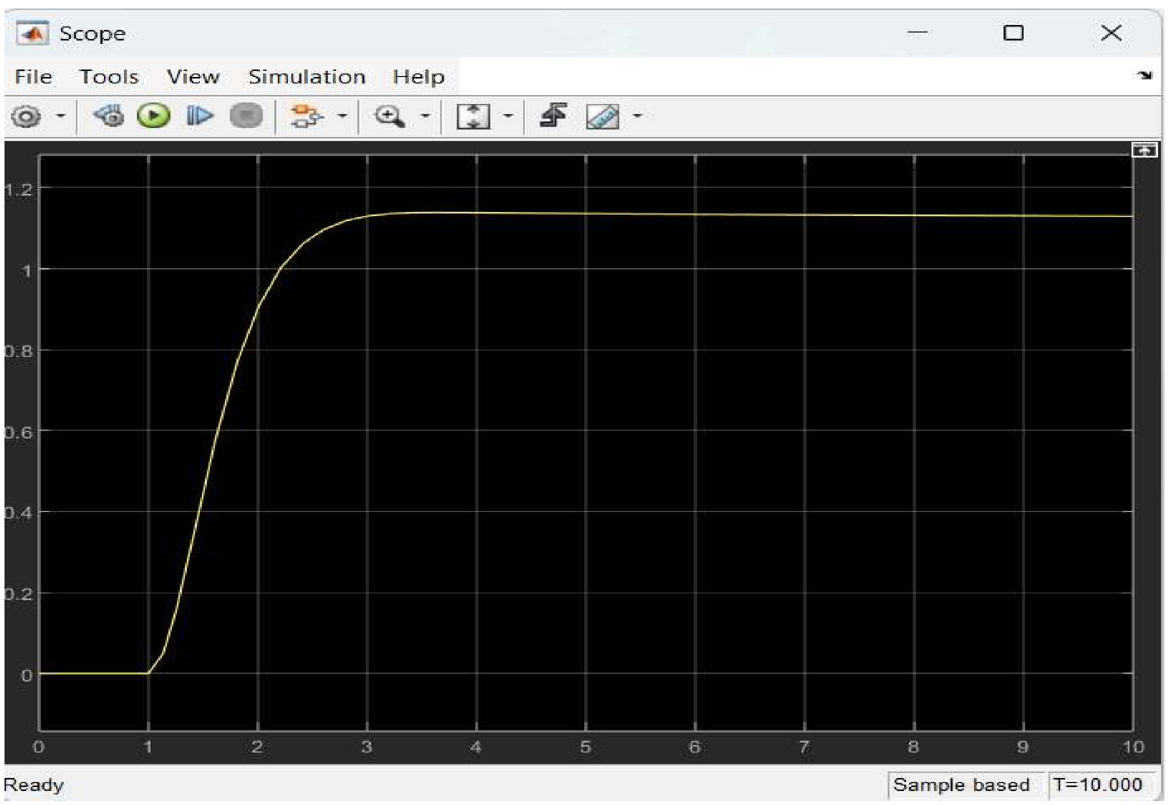


The system is unstable. So we need to add a controller to make the system stable.

- Root Locus Controller design



The Output (Scope) is shown below :

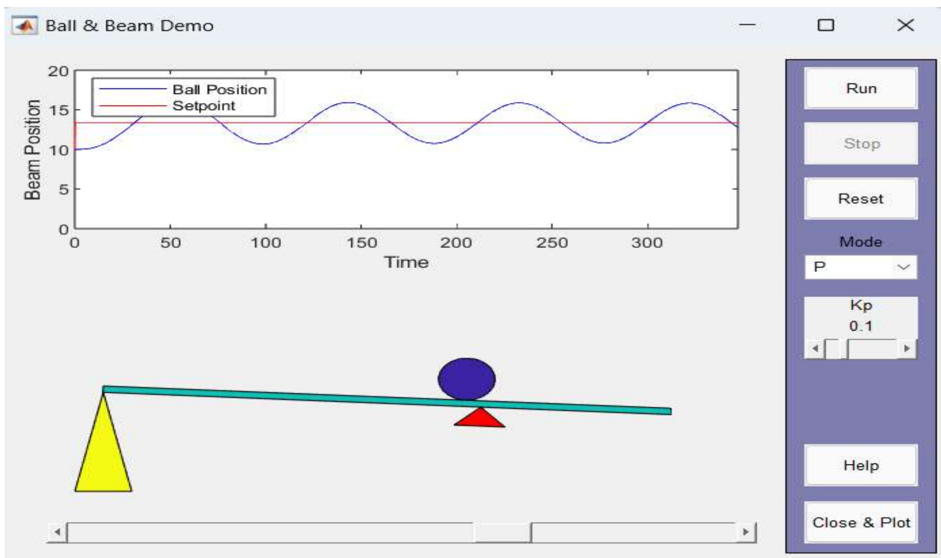


<u>Thus ,the system is stable.</u>

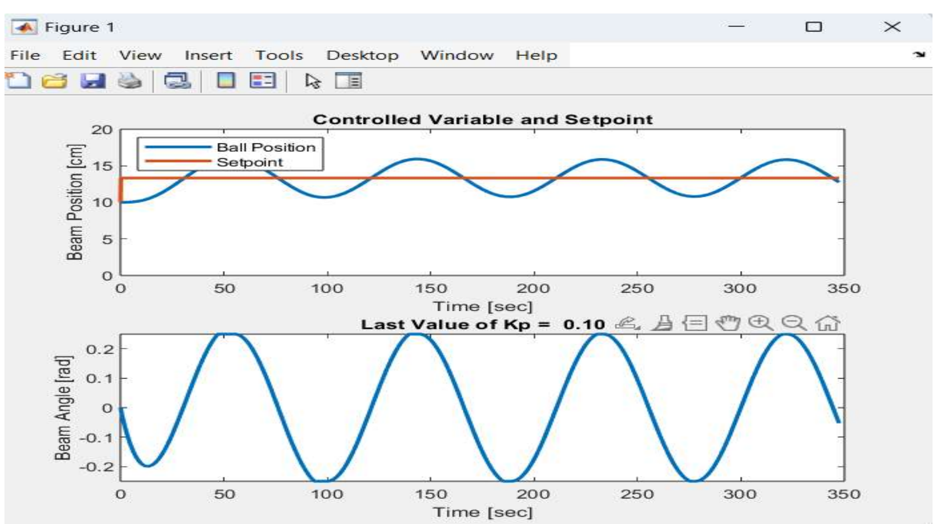
6. Graphical user interface (GUI)

The ball and beam system offers an interactive demonstration of Proportional (P) and Proportional-Derivative (PD) control techniques applied to a ball and beam experiment.

Through this graphical user interface (GUI), users can visualize and understand the dynamics and control strategies employed to maintain the ball's stability on the beam.

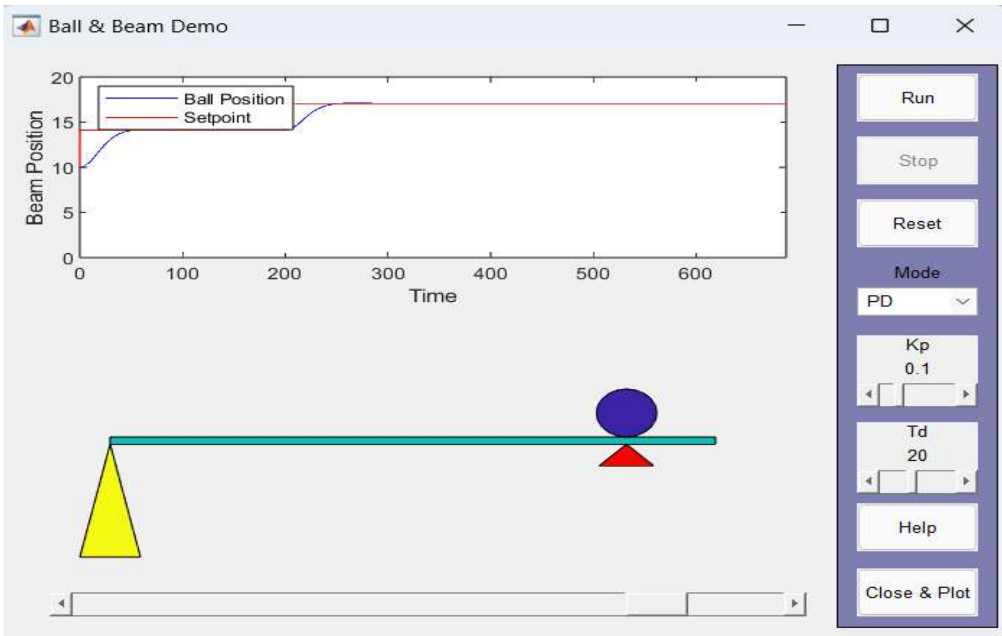


This GUI is only at a P controller, At Kp = 0.1 the plot is marginally stable and it is just revolving around the setpoint.

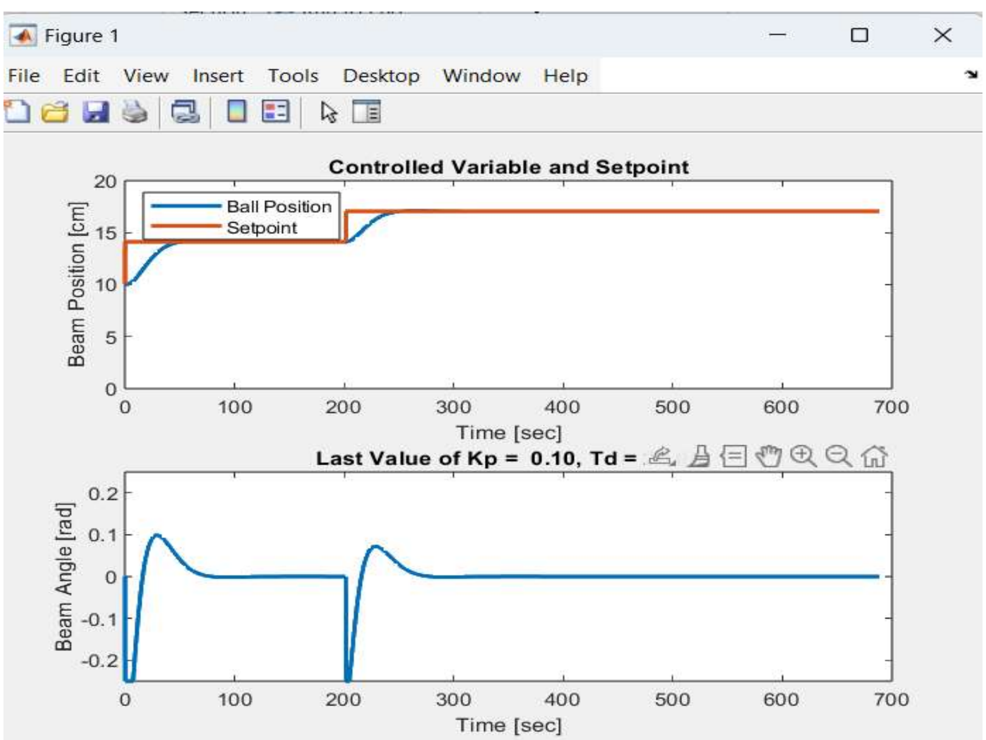


Proportional - derivative Controller

After Tuning at different Kp(proportional constant) and Td (derivative time), Controller is tuned at a Kp = 0.1 , Td = 20 to be stable at desired setpoint.



In the plot , the Ball position is Stable at the Setpoint.



7. CONCLUSIONS

The Ball and beam system was studied and modeled using the Lagrange method. Different controller methods including PID Controller,Root locus controller were simulated in MATLAB SIMULINK .

- In the Proportional Controller, The system remains Marginally stable with the addition of a proportional gain. Change the value of Kp and note that the system remains Unstable.

- In the Proportional - derivative Controller, After tuning the gains at various Kp and Kd values, At Kp= 15 and Kd=40 we got the desired settling time and overshoot, and the system is Stable.

- We plotted different plots such as Pole-Zero Map, Open loop step response, Root locus and Bode plot for Open loop System for type - II system.

- A Simulink model is modeled for Open loop and Closed loop system,

  For an Open loop system , The System is unstable.

  For Closed loop system, The System becomes Stable.

- In Graphical User Interface (GUI), an Animated ball and beam system was designed using MATLAB for P and PD controllers.

  For P controller at Kp = 0.1, the system is Marginally Stable and as we increase the value of Kp the plot between Ball Position and Time gets wide i.e Time period increases as we increase Kp.

  For PD controllers at Kp =0.1 and Td= 20, the ball is Stable and we obtain the desired output.

8. REFERENCES

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