EE 396 Design Project
Ball Beam System

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Objective :

To design a control system for a ball and beam apparatus that can maintain the position of the ball at a specified location on the beam, despite of any change in the position of the ball along the beam.

Introduction :

The ball and beam system is a classic example of a control system that is used to demonstrate various concepts in control theory. The system consists of a ball that rolls on an wooden beam, and a control mechanism that maintains the position of the ball at a specific location on the beam. The control mechanism can be implemented using various algorithms, including proportional, integral, derivative (PID) control.

In this project, we aimed to design and control a ball and beam system using a PID controller. The objective was to develop a system that could maintain the position of the ball at a specific location on the beam, despite disturbances or changes in the system parameters. We used a microcontroller, servo motor, ultrasonic sensors and other components to design the system.

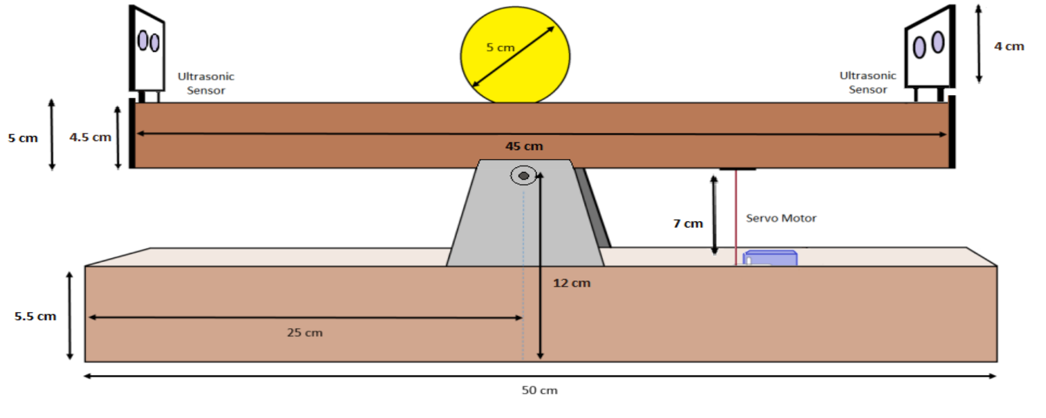
Material Required :

1. Arduino Uno
2. Servo Motor
3. Two Ultrasonic Range Finder
4. Small Bread Board
5. Jumper Wire
6. Plywood
7. Plywood Paint
8. Pencil
9. Sandpaper
10. Hacksaw Blade
11. Ball
12. 9V Adapter

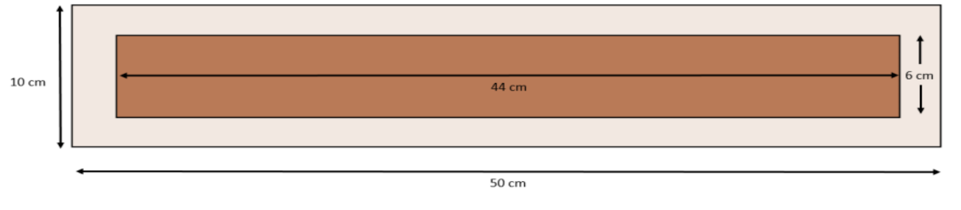
Physical Setup :

To create the physical ball beam system, we will utilize plywood as the primary material. The plywood pieces will be fastened together using nails to form permanent joints. The dimensions of the ball beam setup are illustrated in the accompanying figure.

1. The length of the beam on which the ball is resting is 45 cm. The width of top beam is less than the width of the lower beam. This ensures that that the top beam does not touch the bottom beam when it is at an inclined position.
2. Servo-motor is placed in such a way that the shaft connected to the top beam is almost at right-angles to ground when the beam is at balanced position.
3. The position of both the ultra-sonic sensors is set in such a way that that the transmitted waves from the sensor hits the center of the ball because wrong sensor placement can lead to erroneous readings which will make it difficult for us to tune the controller parameters.
4. To ensure the system operates smoothly and accurately, it is crucial to prevent any horizontal movement of the top beam. To achieve this, we will be using bearings to hold the spindle in place, while a pencil will be used as the spindle itself to prevent any horizontal movement of the top beam. We will fix the top beam firmly to the spindle to prevent unwanted vibrations that could interfere with tuning the controller parameters accurately. The combination of the bearing and pencil will ensure that the top beam is securely held in place, and we can expect the ball beam system to operate smoothly and accurately during our experiment.
5. To prevent the ball from colliding with the sensor, we will be installing a small barrier in front of the sensor. This barrier will ensure that the ball remains within the boundaries of the ball beam system and does not interfere with the accuracy of the sensor measurements.



Front view of the ball beam balancing system



Top view of the ball beam balancing system

Modeling and Dynamics

The ball and beam system may be broken down into smaller systems, and when these systems work together, the ball appears to be moving smoothly on the beam and vice versa so knowing the contributions and coordination of each component becomes crucial from the perspective of mathematical analysis hence the system's equation of motion and transfer function must be developed from the perspective of control and the same is implemented below.

Transfer function of a Ball Beam System

The ratio of the output and input Laplace transforms is used to define the transfer function of any system. Newtonian mechanics can be used to get the equation for the motion of the ball on the beam. Combining the transfer functions of the following subsystems will yield the transfer function:

(i) Beam tilt to ball position

(ii) Input voltage of the motor to its angle of rotation and tilt angle of the beam.

Think about Fig. 1 The ball on the beam is moving both in translation and in rotation. Now, assuming that the ball's translational acceleration is $\ddot{x}$ and that force F is given by

$$F_{tx} = m\ddot{x} = m\frac{d^2x}{dt^2}, \qquad (1)$$

$$Where\ m\ is\ the\ mass\ of\ the\ Ball.$$

$$The\ rotational\ torque\ T\ of\ the\ Ball = J\frac{dw}{dt}$$

$$Where\ w\ is\ the\ angular\ velocity.$$

$$J = Moment\ of\ Inertia\ of\ the\ Ball$$

$$Rotaional\ Force\ F_{rx} = \frac{T}{R} = \frac{J}{R^2}\ddot{x}$$

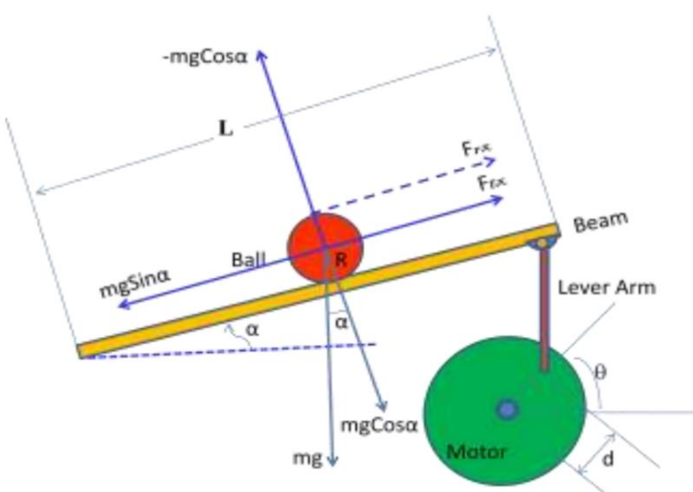


Fig. 1 Ball and Beam System with Newton balances of forces

As shown in Fig. 1 we have

$$F_{rx} + F_{tx} = -mgsign\alpha$$

$$\left(\frac{J}{R^2} + m\right)\ddot{x} = -mgsin\alpha \qquad (2)$$

The geometry of the lever arm section, as depicted in Fig. 2, can be used to determine the relationship between θ and α. The lever mechanism, which consists of lever arms SP = A and OS = d, is attached to the beam at P. Assume that the motor arm OS goes to T and the beam's end P moves to Q in such a way that ∠SOT = θ and ∠PO1Q = α.

$$OX = d\ cos\theta; TX = dsin\theta;$$

$$XS = OS - OX = d(1 - cos\theta)$$

$$O_1M = L\ cos\alpha; QM = L\ sin\alpha; MP = L(1 - cos\alpha)$$

$$TN = A\ sin\beta; QN = A\ cos\beta; MN = A\ cos\beta - L\ sin\alpha$$

$$TX = PS\ - PG = MZ - MN$$

$$\Rightarrow d\ sin\theta = A - A\ cos\beta + L\ sin\alpha$$

$$\Rightarrow d\ sin\theta\ - A(1 - cos\beta) - L\ sin\alpha = 0$$

$$\Rightarrow L\ sin\alpha = d\ sin\theta\ - A(1 - \cos\beta)$$

$$\Rightarrow \alpha = arc\ sin\left[\frac{d}{L}\ sin\theta\ - \frac{A}{L}(1 - cos\beta)\right] \qquad (3)$$

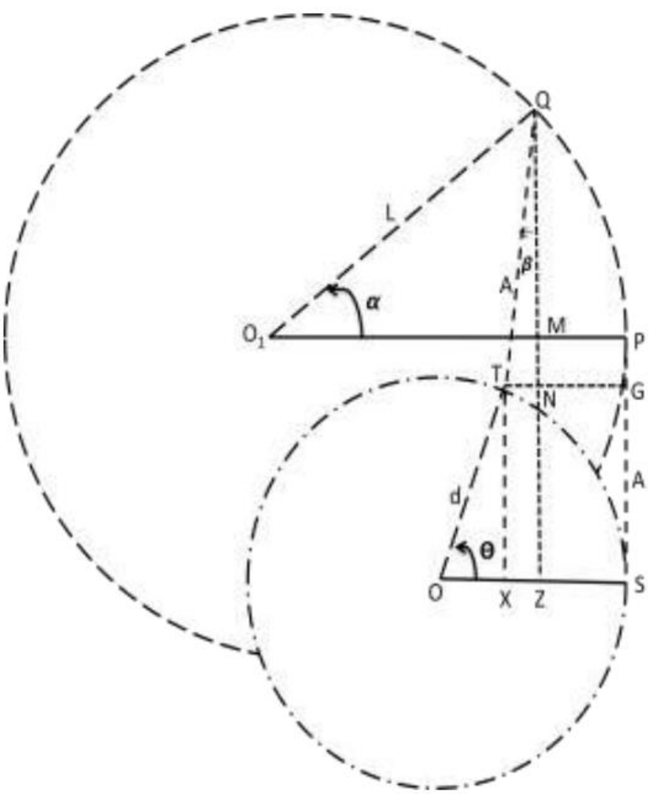


Fig. 2 *Relation between Motor angle and Beam anle*

Now,

$$TN + NG = XS$$

$$Asin\beta + MP = XS$$

$$Asin\beta + (L - Lcos\alpha) = d - dcos\theta$$

$$A\ sin\beta = d(1 - cos\theta) - L(1 - cos\alpha) \qquad (4)$$

Under restriction that the dependence of β on α is very weak.

$$A \sin\beta = d(1 - \cos\theta)$$

$$\Rightarrow \beta = arc\ sin\left[\frac{d}{A}(1 - \cos\theta)\right] \qquad (5)$$

And

$$\alpha \approx arc\ sin\left[\frac{d}{L}sin\theta\right] \qquad (6)$$

$$\alpha \approx \frac{d}{L}\theta\ , When\ \theta\ is\ small \qquad (7)$$

$$\dot{\alpha} = \frac{\frac{d}{L}cos\theta}{\sqrt{1-\frac{d^2}{L^2}(sin\theta)^2}}\dot{\theta}\ \ \&\ \ \dot{\beta} = \frac{\frac{d}{A}sin\theta}{\sqrt{1-\frac{d^2}{L^2}(1-cos\theta)^2}}\dot{\theta}$$

The motor angle, which is proportional to the input voltage, determines the beam angle.

$$\left(\frac{J}{R^2} + m\right)\ddot{x} = -mg\frac{d}{L}\theta, \qquad (\because sin\alpha \cong \alpha)$$

Assuming the initial condition then take the Laplace transform on both sides. We obtain

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

$$\frac{X(s)}{\theta(s)} = G_b(s) = \frac{-mg}{(\frac{J}{R^2}+m)}\frac{d}{L} * \frac{1}{s^2} \qquad (8)$$

The moment of inertia of ball is given by $J = \frac{2}{5}mR^2$.

<u>**The final transfer function $G_b(s)$ is given by -:**</u>

$$G_b(s) = \frac{X(s)}{\theta(s)} = -K\left(\frac{1}{s^2}\right) \qquad (9)$$

$$Where\ constant\ K = 7\frac{d}{L}$$

Transfer Function of Servo Motor

The applied input voltage Ea(s) to the DC servomotor determines the angle of rotation of the motor. The motor is connected to the pivot of the beam which determines the tilt of the beam, which in turn regulates the velocity of the ball on the beam thus motor's transfer function Gm(s) is obtained as follows.

We have used DC servomotor whose armature controller is DC motor model. The armature current in the armature regulated DC motor which regulates the shaft position and speed while maintaining a constant field current.

Fig. 3 depicts the circuit diagram of an armature-controlled DC motor.

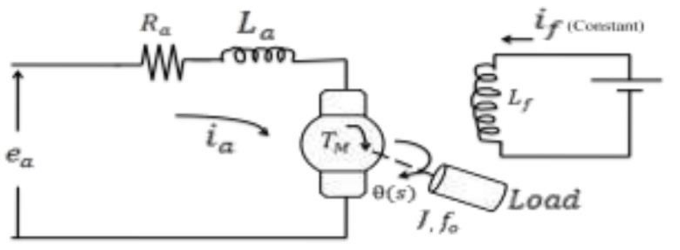


Fig. 3 *Armature controlled DC Motor*

Parameters shown in the Fig.3.are,

$R_a =$ *Resistance of armature*
$L_a =$ *Inductance of armature*
$T_M =$ *Torque produced by motor* (N_m)
$\theta =$ *angular displacement of motor shaft*

$J = (J_m + J_L)$ =Equivalent moment of inertia of load and motor

$f_0 =$ *Viscous friction coefficent of motor and load acting on motor shaft*

The torque TM produced by the motor is proportional to the airgap flux ϕ and the armature current, and it can be determined by the applied armature voltage e_a setup armature current i_a in the armature circuit.

$$T_M = k_1\, \emptyset\, i_a = k_1 k_f\, i_f\, i_a$$
$$= k_1 k_f i_f i_a = k_1 k_f i_f i_a = k_T i_a$$

where $k_1 = constant; k_f =$ constant

k_T is *the* motor constant

If we apply KVL in armature circuit gives we will get,

$$L_a \frac{di_a}{dt} + R_a i_a + e_b = e_a \qquad (10)$$

Here e_b is the back emf generated by the armature's spin in the magnetic field.

$$e_b = k_b \frac{d\theta}{dt}, \qquad (11)$$

where k_b is the back e.m.f. constant

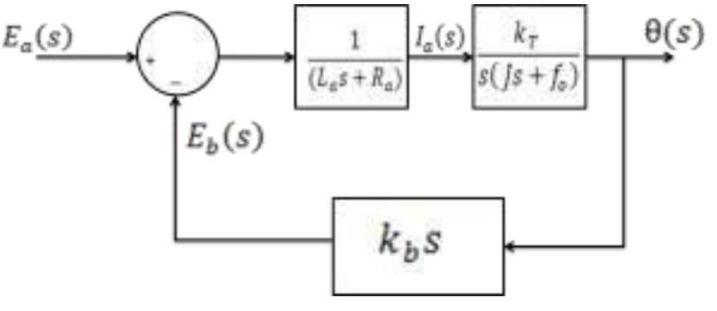
The motor's developed torque, denoted as TM, is utilized for rotating a load while resisting viscous forces. Hence, the torque equation can be expressed as follows:

$$J\frac{d^2\theta}{dt^2} + f_0\frac{d\theta}{dt} = T_M = k_T i_a \qquad (12)$$

Taking initial condition to be zero and obtaining the Laplace transform of equation (10), (11) and (12), we get

$$L_a s I_a(s) + R_a I_a(s) + E_b(s) = E_a(s)$$
$$(L_a s + R_a) I_a(s) = E_a(s) - E_b(s)$$
$$E_b(s) = k_b s\,\theta(s)$$
$$(Js^2 + f_o s)\theta(s) = k_T\, I_a(s) \qquad (13)$$

Now, we used this equation to represent block diagram of motor as shown in Fig.4.



$Fig. 4\ TF\ of\ DC\ Motor$

Putting $\frac{d\theta}{dt} = \omega = speed\ of\ motor$

We get,

$$J\frac{d\omega}{dt} + f_0\omega = k_t i_a, \qquad (14)$$

Laplace transform gives us :-

$$Js\omega(s) + f_o\omega(s) = k_T I_a(s)$$
$$(Js + f_o)\omega(s) = k_T\, I_a(s)$$

$$\therefore \omega(s) = \frac{k_T I_a(s)}{(Js+f_0)} \qquad (15)$$

On integrating $\frac{I_a(s)kT}{(Js+f_0)}$, we will obtain mean position $\theta(s)$ of the shaft. Thus fig. 5 shows the modified version of fig. 4

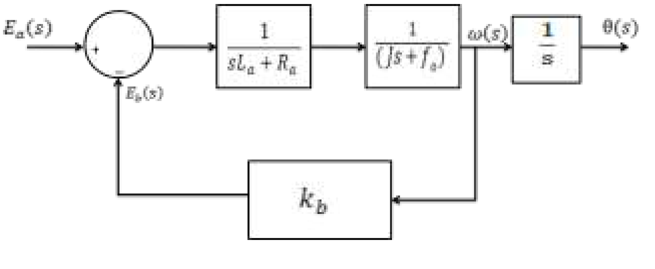


Fig.5 Modified block diagram of DC motor

The DC motor is an open loop system, yet the block diagram in Figure 5 includes a motor's built-in feedback loop for the back e.m.f. However, this feedback is represented as electric friction, which is proportional to the negative rate of change of position $\theta(s)$ of the motor. This feedback mechanism enhances the stability of the motor. The transfer function of the overall block diagram in Figure 5 can be expressed as:

$$G_m(s) = \frac{\theta(s)}{E_a(s)} = \frac{k_T}{s^3 jL_a + (R_a j + f_o L_a)s^2 + f_o R_a s + k_T k_b s}$$

Since La < 1,

$$G_m(s) = \frac{k_T}{s(R_a js + f_o R_a + k_T k_{b)}}$$

$$G_m(s) = \frac{\frac{k_T}{R_a}}{s(js+f)} \qquad (16)$$

$$where\ f = \pi f_o + \frac{k_T k_b}{R_a}$$

Appearance of term k_b in $f = f_0 + \frac{k_t k_b}{R_a}$ is known as electric friction.

$$G_m(s) = \frac{k_T/R_a f}{s\left(\frac{j}{f}s+1\right)} = \frac{k_m}{s(\tau s+1)}$$

Since $k_T = k_b$ in MKS units.

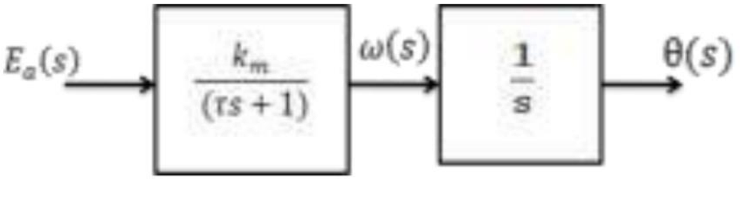
The transfer function for the speed can be given by

$$where\ k_m = \frac{k_T}{R_a f} = motor\ gain\ constant \qquad (17)$$

$$\frac{J}{f} = \tau = motor\ time\ constant$$

The parameters k_m and τ in the motor's block diagram represent the gain and time constants, respectively. These values depend on various motor parameters, including the armature resistance, back e.m.f. constant, and equivalent moment of inertia of the motor and load.

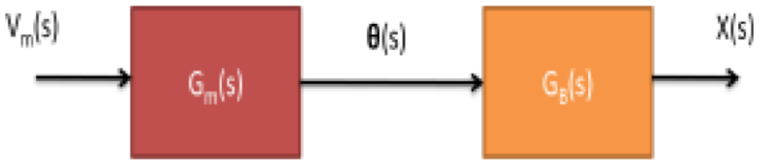
$$\frac{\omega(s)}{E_a(s)} = \frac{k_m}{(\tau s + 1)} \qquad (18)$$



$Fig. 6\ Simplified\ block\ diagram\ of\ DC\ Motor$

The block diagram clearly indicates that the DC motor acts as an integrating device in the servo system. It is coupled to the upper beam with the help of gear system and the output shaft.

By combining $G_m(s)$ and $G_B(s)$ we get overall open loop transfer function as $G(s)$. Which is depicted in Fig.7.



$Fig. 7$ TF of $Ball$ and $Beam$ $System$

So the overall transfer function of the Ball Beam System (G(s)) :-

$$G(s) = G_m(s). G_B(s)$$

$$G(s) = \frac{X(s)}{\theta(s)}$$

$$\boldsymbol{G(s) = \frac{K_m K}{s^3(1+\tau s)}}$$

Stability of this System without any controller

As indicated in Figure 8, the step response of this transfer function reveals that the system is unstable. When the beam is tilted, the ball rolls down due to the force of gravity and velocity depending upon tilt of the beam. To regulate motion of ball in beam we need to required a controller to stop fall down a ball as well position..

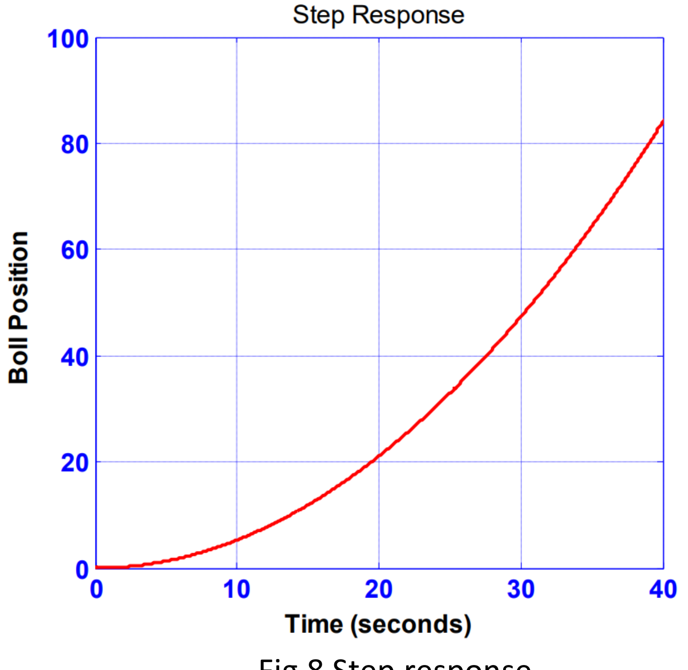


Fig.8 Step response.

ABOUT PID CONTROLLER

(PID) controller is a feedback control system that utilizes three distinct control actions. The system is combination of the proportional action, integral action, and derivative action to achieve stability in unstable systems.

To solve any PID control problem , the PID transfer function is represented in Laplace transform as

$$\boldsymbol{PID = K_p + \frac{K_t}{s} + K_d s}$$

Where

K_P = Proportional gain

K_I = Integral gain

K_D = Derivative gain

The PID controller operates in a closed-loop system that involves various variables. One of the critical variables is the error (e), which represents the difference between the desired input value (R) and the actual output (Y). The error is fed back to the PID controller, which computes both the derivative and integral of the error. The controller's output signal (u) is calculated as the sum of the proportional gain (Kp) multiplied by the magnitude of the error, the integral gain (Ki) multiplied by the error, and the derivative gain (Kd) multiplied by the derivative of the error. This approach allows the PID controller to adjust the system's control signal based on the error's magnitude, rate of change, and duration

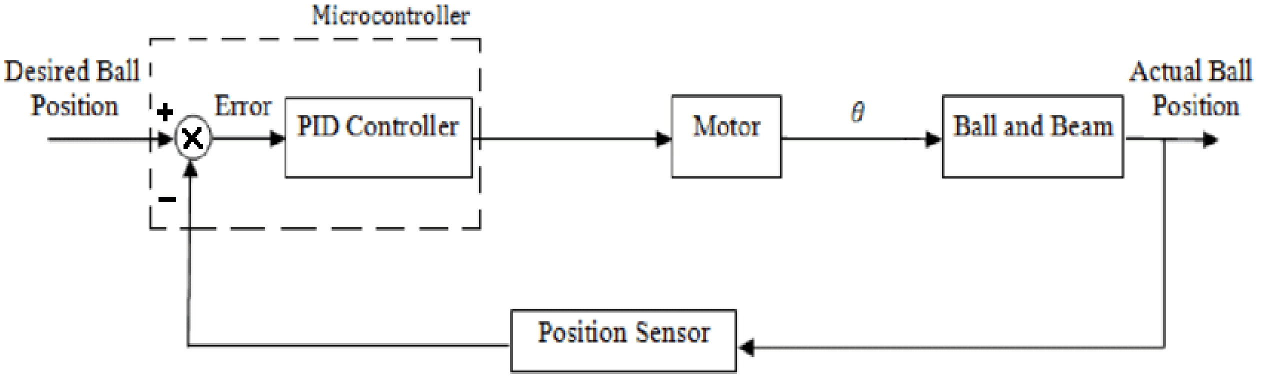
$$\mu = K_p e + K_i \int e\, dt + K_s \frac{de}{dt}$$

Control Loop Response	Rise Time	Overshoot	Settling Time	Steady-State Error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small Change	Decrease	Decrease	Small Change

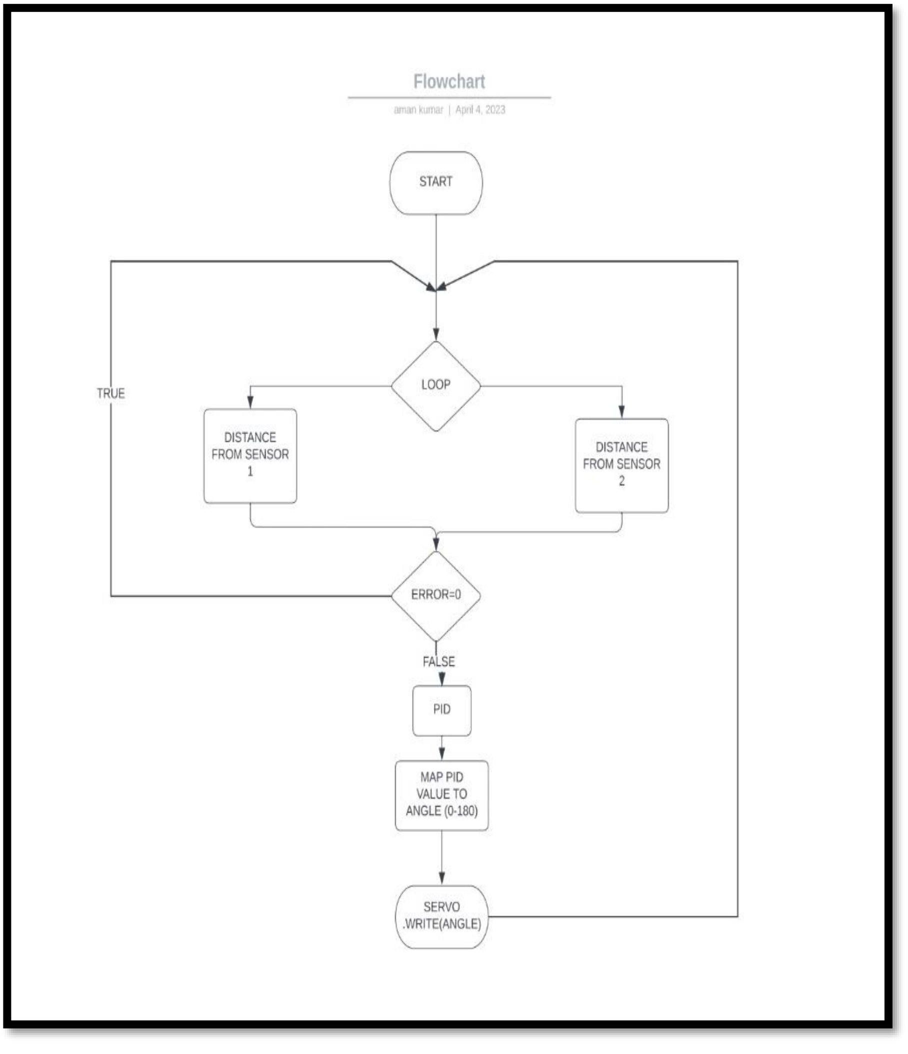
DESIGNING OF PID CONTROLLER AND ALGORITHM

We will be designing a PID controller for a ball beam balance system using an Arduino microcontroller. The PID controller will use the algorithm, given in Fig. , to adjust the angle of the beam in response to the position of the ball on the beam. We will program the Arduino with the algorithm and implement the PID controller on the hardware. We will also tune the PID parameters to achieve a stable and fast response of the ball on the beam, and test and refine the controller as needed. This showcase the capabilities of an Arduino microcontroller in control systems engineering and demonstrate the application of PID control to a real world system.

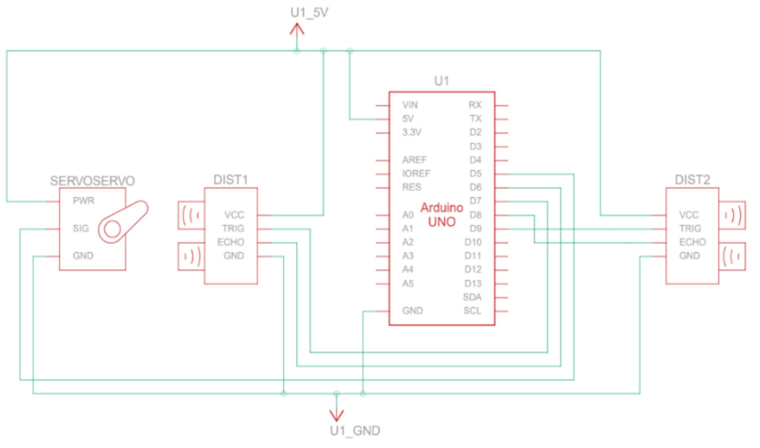
Block Diagram With Controller



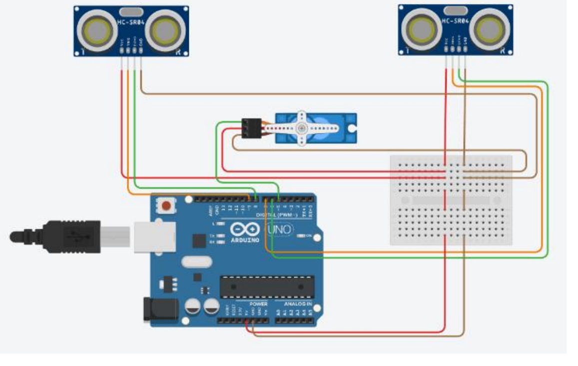
ALGORITHM



CIRCUIT DIAGRAM :



TINKERCAD SIMULATION OF THE CIRCUIT :



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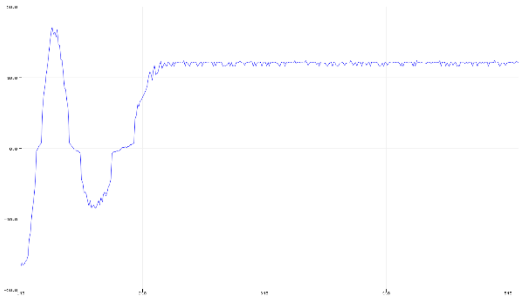
HARDWARE IMPLEMNTATION :

TUNING PID USING INPUT AND OUTPUT CHARACTERSTICS

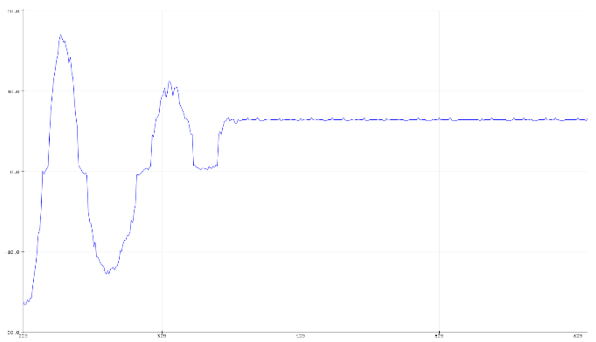
Varying Kp keeping both Ki and Kd to zero.

At the correct value of Kp, the system response will be stable, fast, and free of oscillations or overshoot. The controller will be able to quickly and accurately respond to changes in the input or reference signal, bringing the output to the desired setpoint with minimal error.

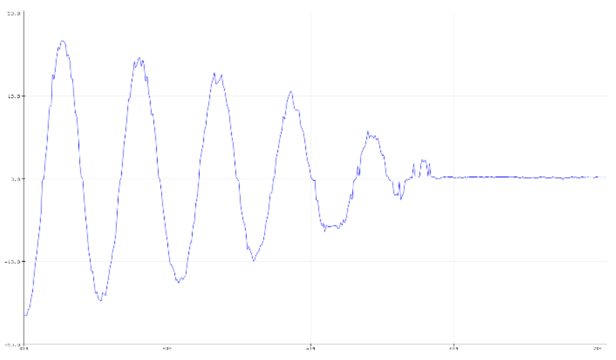
Case 1: Kp=5, Kd=0, Ki=0



Case 2: Kp=15, Kd=0, Ki=0

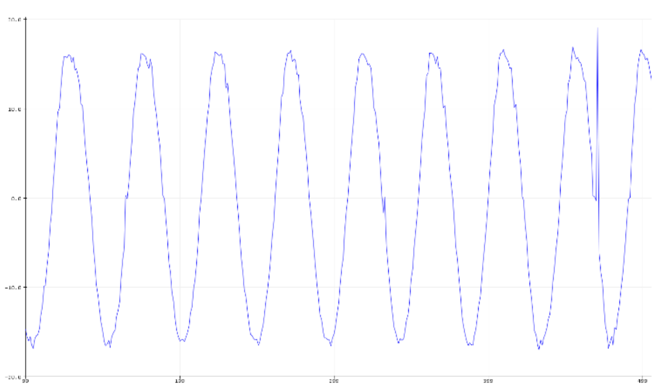


Case 3: Kp=35 ,Kd=0, Ki=0



The above condition has been found to be true for Kp = 35, therefore, it is appropriate to set Kp to 35 in the system.

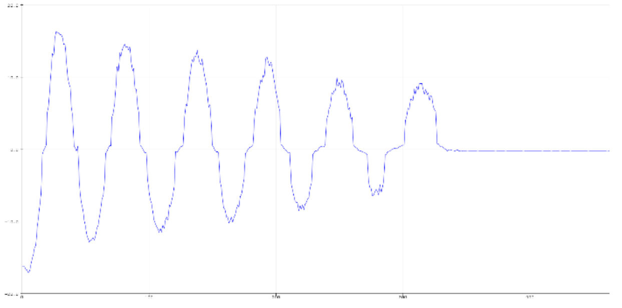
Case 4: Kp=55,Kd=0,Ki=0



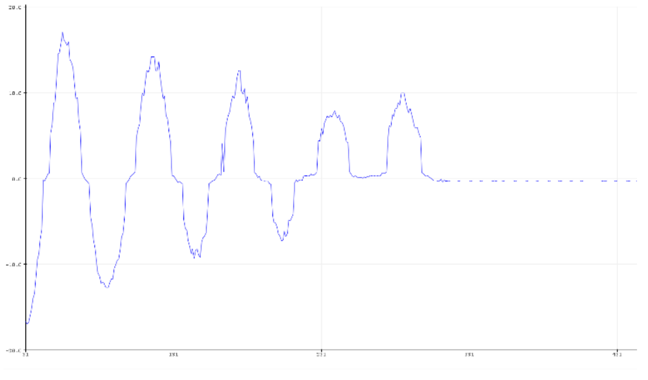
Now varying Kd, keeping Kp = 35 and Ki = 0.

The correct values of Kp and Kd will result in a system response that is fast, stable, and free of overshoot and oscillations. The controller will be able to quickly and accurately respond to changes in the input signal, bringing the output to the desired setpoint with minimal error and settling time.

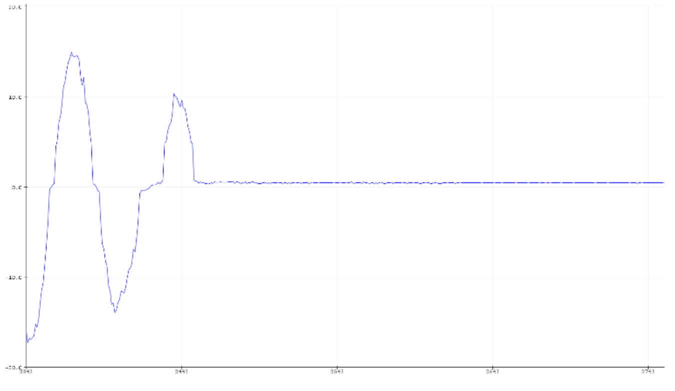
Case 1: Kp=35, Kd=20, Ki=0



Case 2: Kp=35, Kd=100, Ki=0

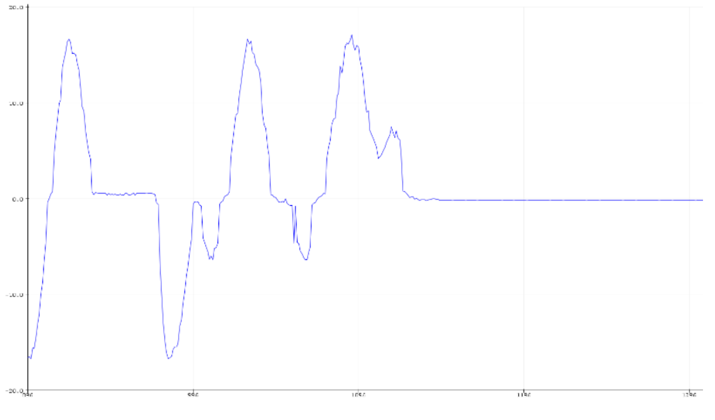


Case 3: Kp=35, Kd=420 , Ki=0



The above condition has been found to be true for Kp=35 and Kd =420, therefore, it is appropriate to set Kp to 35 and Kd to 420 in the system.

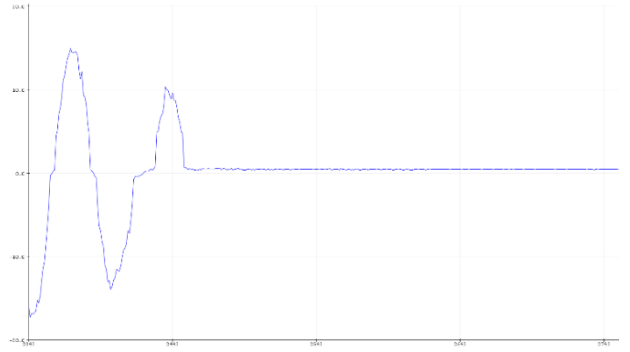
Case 3: Kp=35, Kd=420, Ki=0



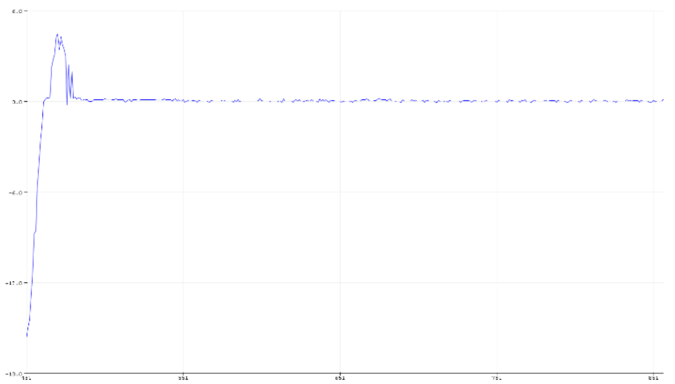
Now varying Ki, keeping Kp = 35 and Kd = 420.

When all three gains are set correctly, the system should respond quickly to changes in the input signal, settle smoothly to the desired setpoint with minimal overshoot or oscillations, and maintain a stable output. The system should also be able to compensate for disturbances or changes in the input signal, and eliminate any steady-state error.

Case 1: Kp=35, Kd=420, Ki=0

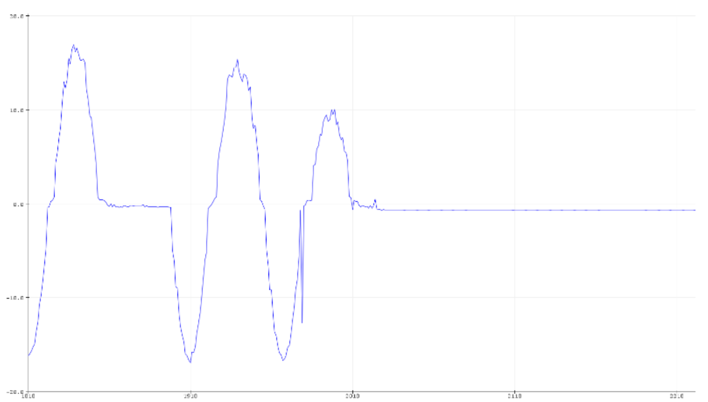


Case 2: Kp=35, Kd=420, Ki=0.015



The above condition has been found to be true for Kp=35, Kd=420 and Ki=0.015, therefore it is appropriate to set Kp to 35, Kd to 420 and Ki to 0.015 in the system.

Case 3: Kp=35, Kd=420 , Ki=0



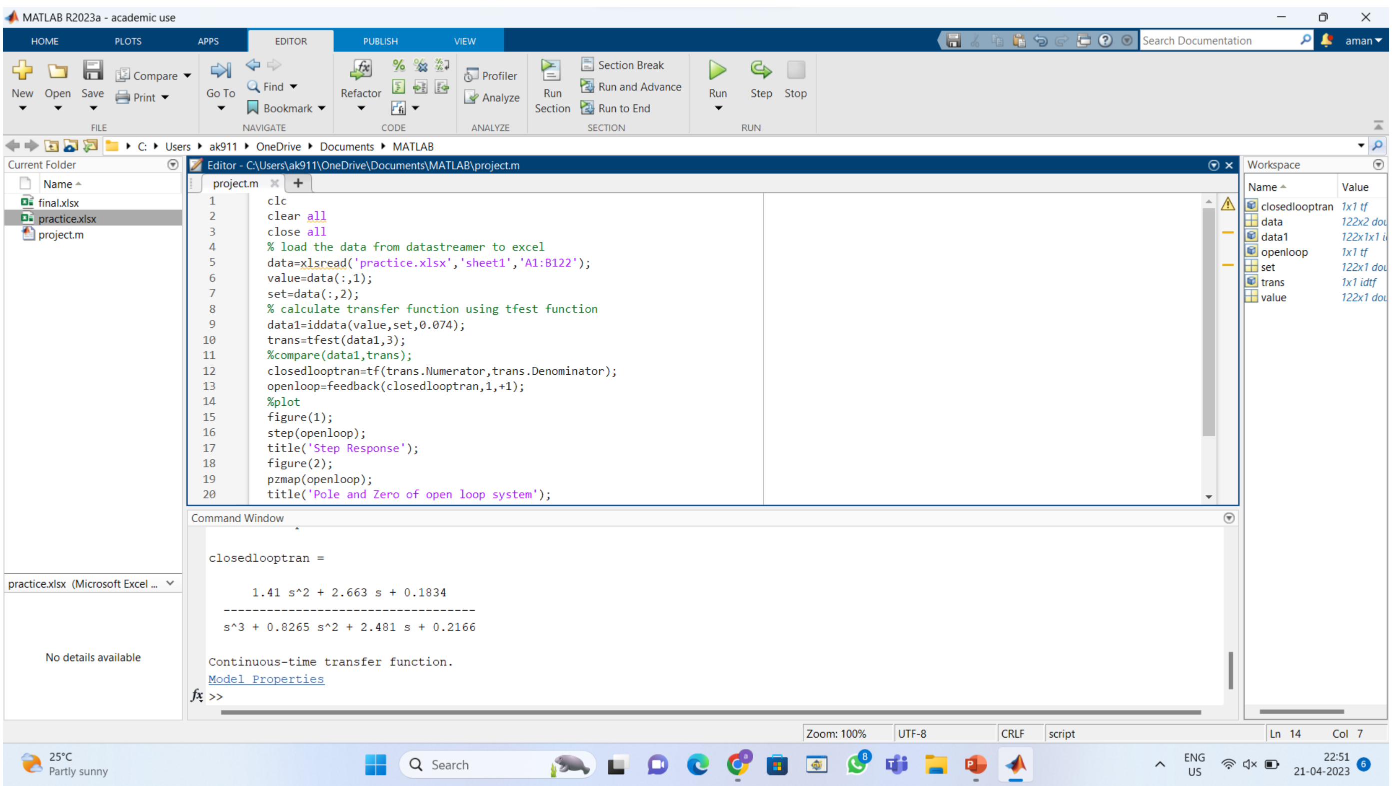
After several rounds of experimentation and analysis, we found that setting the proportional gain (Kp) to 35, the derivative gain (Kd) to 420, and the integral gain (Ki) to 0.015 produced the desired system behavior. These values were selected based on the specific characteristics of the system being controlled and were determined through a systematic tuning process.

OBTAINING CLOSED LOOP TRASFER FUNCTION OF THE CONTROLLED SYSTEM USING INPUT AND OUTPUT CHARATERSTICS

We obtained the transfer function of the system by taking input and respective output data from an Arduino microcontroller and using MATLAB for analysis.

To collect the data, we utilized Excel Data Streamer, which enabled us to stream real-time data from the Arduino to Excel. With the data in Excel, we were able to analyze the system response and derive the transfer function.

In MATLAB, we used the "tfest" function. This function estimates the transfer function of a system based on input/output data in the time or frequency domain.

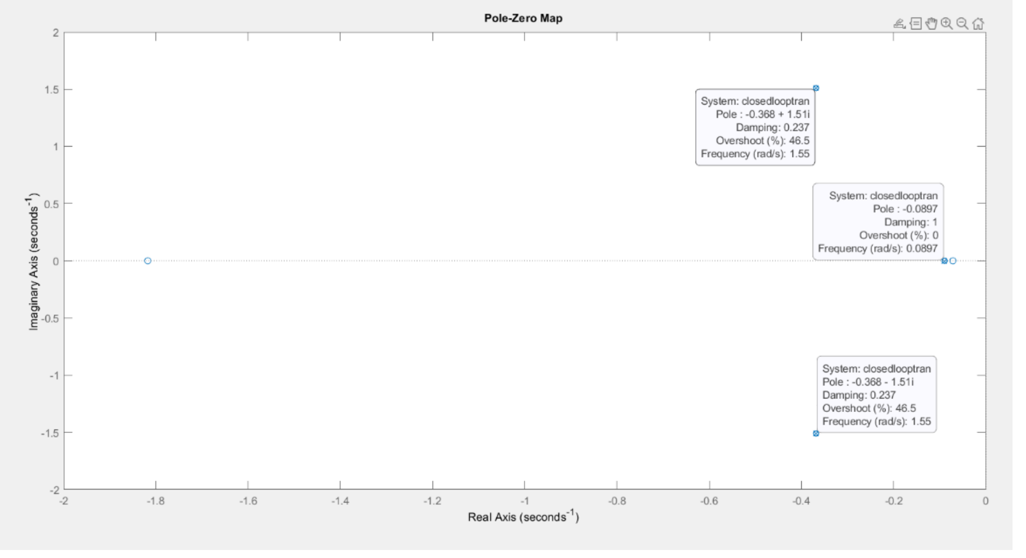


$$T(s) = \frac{1.41s^2+2.66s+0.1834}{s^3+0.8265s^2+2.481s+0.2166}$$

Poles are at (-0.37+1.5j), (-0.37-1.5j), (-0.089+0j).

Since all four poles of the transfer function are located on the left-hand side of the complex plane, we can conclude that the system is stable. This property ensures that the system will respond to inputs in a predictable and reliable manner, without exhibiting oscillatory or unstable behavior.

We can verify this from the pole zero location of the Transfer Function.



OBSERVATIONS :

When changing the values of Kp, Ki, and Kd in a ball beam system, we can observe different behaviors in the system's response. Specifically:

Changing Kp: Increasing Kp can make the system more responsive and decrease its settling time, but it can also increase overshoot and oscillations. Decreasing Kp can make the system less responsive and increase its settling time, but it can also decrease overshoot and oscillations.

Changing Ki: Increasing Ki can help to correct any steady-state error in the system, but it can also increase overshoot and oscillations. Decreasing Ki can reduce overshoot and oscillations, but it can also increase settling time and make the system less responsive.

Changing Kd: Increasing Kd can help to dampen out any overshoot or oscillations in the system, but it can also increase settling time and make the system less responsive. Decreasing Kd can decrease settling time and make the system more responsive, but it can also increase overshoot and oscillations.

By observing the system's response to changes in Kp, Ki, and Kd, we can determine the optimal values of these parameters to achieve the desired performance of the ball beam system. This process involves testing the system with different parameter values, evaluating the system's response, and adjusting the parameters until the desired performance is achieved.

CONCLUSION :

The ball and beam system's mathematical model was formulated by applying both physical and electrical principles, and then simplified according to its relevant parameters.

The parameters (Kp, Ki, and Kd) were determined through manual tuning from the ball beam system model to achieve optimal system response. Experimental results revealed that the best controller parameters for the system were Kp =35, Ki=0.015, and Kd=420.The system's accuracy was evaluated by testing its ability to track the ball's position at three different locations, and it was discovered that altering the set point did not have any impact on the accuracy.

CHALLENGES FACED :

1. **Vibrations at the Joint :** The first challenge that we encountered was to prevent horizontal movement of the upper beam and minimize vibrations at the joints, so we used pencil as a spindle with a bearing inside a plywood to create a fixed joint for a ball beam system that was experiencing vibration issues. This helped to improve stability and precision by reducing friction and wear on the joint.
2. **Height of the sensor :** To obtain accurate measurements of the distance between the ball and the beam, it was necessary to position the ultrasonic sensor at a specific height such that it points directly at the center of the ball. To address this challenge, we designed a holder for the sensor that allows for the height to be adjusted as needed to ensure precise alignment with the ball.
3. **Incorrect Readings of the Sensor :** To address the issue of an ultrasonic sensor giving incorrect readings after 20 cm, we used two ultrasonic sensors in a binary format. This involves using one sensor to detect the distance up to 20 cm, and the second sensor to detect distances beyond 20 cm. By combining the readings from the two sensors, we obtained a more accurate measurement of the distance.
4. **Loose Gear :** The gear joint in the servo motor is loose, preventing the motor from attaining a fixed position and causing errors in the angle of tilt of the beam. This looseness is a property of the motor's manufacturing and cannot be removed.
5. **Placement of Motor :** One challenge we faced was determining the optimal placement of the motor in relation to the joint. Fixing the motor too close to the joint resulted in increased moment, but also introduced unwanted vibrations into the system. On the other hand, fixing the motor too far from the joint helped reduce vibrations, but limited the range of movement. To overcome this challenge, we carefully experimented with different motor placements to find the right balance between moment and vibration.
6. **PID Tuning :** The final challenge we encountered was in tuning the PID parameters for the system. Achieving optimal PID tuning can be challenging due to the complex interaction between the proportional, integral, and derivative gains, and their effects on the system's response. Finding the right balance among these parameters to achieve the desired system behavior, such as fast response time, minimal overshoot, and stable oscillation, can be challenging and may require multiple iterations and adjustments. However, with thorough experimentation and analysis of the system's input-output response, we were able to successfully tune the PID parameters to achieve satisfactory system performance.

MAJOR LEARNINGS :

1. **Using Carpentry Instruments :** We learned how to use various carpentry tools and techniques during the development of our ball-beam balance project, as we used wooden ply as our primary material for the mechanical model. This included the use of saws, drills, nails, sandpaper, rulers, measuring tapes, levels, and clamps. Proper tool maintenance and safety were also emphasized throughout the project.

2. **How to remove unwanted vibrations and movements in the system :** We learned that unwanted movement in the upper beam and vibrations at the joints could introduce errors in our ball-beam system. To prevent this, we used a pencil as a spindle with a bearing inside a plywood to create a fixed joint for the ball-beam system. This helped to minimize vibrations and reduce friction, improving stability and precision in the system. Overall, this experience taught us the importance of identifying and addressing sources of unwanted movement and vibrations in mechanical systems. By implementing solutions such as bearings and spindles, we can improve the accuracy and reliability of our systems.

3. **How to obtain correct reading from sensors :** To address the challenge of obtaining accurate readings from the ultrasonic sensor, we visualized the sensor's output using the serial plotter. This helped us to identify and address any irregularities in the readings caused by rapid changes in distance. By adjusting the sensor's parameters (height) based on real-time data analysis, we were able to obtain more reliable and accurate readings. This experience taught us the importance of real-time data analysis and visualization in sensor-based projects.

4. **How to obtain sufficient friction in real objects :** To maintain the balance of our ball-beam system, we roughened the surface of both the ball and beam using Hacksaw blade to increase friction. Through experimentation, we found that a slightly rough surface helped to stabilize the system and prevent excessive movement, but too much friction could cause the ball to stick and impede its movement. Overall, we gained valuable knowledge and experience in maintaining and controlling friction in real-world applications.

5. **Experimental Tuning PID Controller :** To tune the PID parameters for our ball-beam system, we experimented with different values of proportional, integral, and derivative gains. We adjusted the PID parameters multiple times by analyzing the system's input-output response until we achieved the desired behavior. This experience taught us patience, attention to detail, and a better understanding of how to apply control theory in practice.