PERFORMANCE ANALYSIS OF BALL BALANCER SYSTEM USING FUZZY CONTROLLERS

DISSERTATION

SUBMITTED IN PARTIAL FULLFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF

MASTER OF TECHNOLOGY
IN
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Submitted by:
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CANDIDATE'S DECLARATION

I, Nikita, Roll No(s). 2K21/C&I/03 student of MTech (Control & Instrumentation), hereby declare that the project Dissertation titled "PERFORMANCE ANALYSIS OF BALL BALANCER SYSTEM USING FUZZY CONTROLLERS" which is submitted by me to the Department of ElectricalEngineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the thesis titled "PERFORMANCE ANALYSIS OF BALL BALANCER SYSTEM USING FUZZY CONTROLLERS" which is submitted by Nikita, 2K21/C&I/03 [Electrical Engineering Department], Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the projectwork carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

In this thesis, a 2DoF ball balancer system using a PD-tuned fuzzy logic controller is shown. The influence of differences in the ball's radius while maintaining a constant mass as well as variations in the ball's mass while maintaining a constant radius are both examined in this study. The analysis also looks at how gravity affects important time domain characteristics including settling time, rising time, and delay time. Additionally, the study investigates how the parameter values of the derivative and proportional controls inside the fuzzy controller are impacted by gravity.

The Ball Balancer System has a complex transfer function and is characterised by its instability and nonlinearity. Different techniques have been used over time to manage this system. The properties of ball position, ball plate angle, and actuation voltage in the ball balancer system are investigated in this research using a fuzzy logic controller. Between the Ball Balancer System using the PD adjusted Fuzzy Logic Controller and the Classical PD Controller, the time domain features such as rise time, peak time, settling time, and delay time are compared.

The thesis also covers how to regulate the ball's location in a two-degree-of-freedom ball balancer system using the Mamdani and Sugeno fuzzy inference systems. Nonlinearity, instability, and a convoluted transfer function all define this system. Fuzzy logic is one intelligent control technology that makes it easier to regulate and track the position of complex nonlinear systems. The Mamdani FIS and Sugeno FIS are compared to see how well they function in terms of ball location, ball plate angle, and actuation voltage. To compare the two fuzzy systems, variables including rising time, peak time, settling time, delay time, and peak overshoot are used.

All the work in this project is accomplished through simulation of the ball balancer system using MATLAB/Simulink software and results and waveforms have been

recorded accordingly.

ACKNOWLEDGEMENT

I have taken efforts and dedication in this thesis. However, it would not have been possible withoutthe kind support and help of many individuals and organizations. I would like to extend my sincerethanks to all of them.

I am highly indebted to Professor Bharat Bhushan and Sh. Abhishek Chaudhary, my supervisor for their guidance and constant support as well as for providing necessary information regarding the project & also, for his supportin completing the project.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2DoF	Two Degree of Freedom
PID	Proportional-Integral-Derivative
PIDNN	Proportional-Integral-Derivative-Neural-Network
DEPSO	Differential Evolution Particle Swarm Optimization
PSO	Particle Swarm Optimization
BP	Back Propagation
SMC	Sliding Mode Control
FOSMC	First Order Sliding Mode Control
PD	Proportional-Derivative
LPF	Low Pass Filter
GKYP	Generalized Kalman–Yakubovich– Popov
CMAC	Cerebellar model articulation controller
2DBB	Two DoF Ball Balancer
MPC	Model Predictive Control
LQR	Linear–Quadratic Regulator
FLC	Fuzzy-Logic Control
GA	Genetic algorithm
SA	Simulated Annealing
ISE	Integral Square Error
IAE	Integral Absolute Error
ITSE	Integral of Time Square Error
ITAE	Integral of Time Absolute Error
ANN	Artificial Neural Networks
ANFIS	Adaptive Neuro Fuzzy Inference System
CSA	Cuckoo Search Algorithm
LTR	Loop Transfer Recovery
ACO	Ant Colony Optimization
USB	Universal Serial Bus

IDBB	One DoF Ball Balancer
SCADA	Supervisory Control and Data Acquisition
PI	Proportional-Integral
K	Gain
NB	Negative Big
NM	Negative Medium
NS	Negative Small
ZE	Zero Error
PS	Positive Small
PM	Positive Medium
PB	Positive Big

LIST OF SYMBOLS

$T_{bb}(s)$	1DBB transfer function
$T_s(s)$	SRV02 plant transfer Function
$V_{m,x}(s)$	Input servo motor voltage for x-axis
$V_{m,y}(s)$	Input servo motor voltage for y-axis
$\theta_{l,x}(s)$	Servo load gear angle
$\theta_{l,y}(s)$	Servo load gear angle
$X(s)$	Ball position on x-axis
$Y(s)$	Ball position on y-axis
$V_m(s)$	Input servo motor voltage
τ	Torque
m_{ball}	Ball's mass
$x(t)$	Ball Position
F	Net force
$F_{x,t}$	Inertial force of ball
$F_{y,t}$	Force due to translation
g	Acceleration due to gravity
γ_b	Ball's angle
r_b	Radius of the ball
J_b	Moment of Inertia
$F_{x,r}$	Force due to rotation
$X_d(s)$	Position obtained
$C_{bb}(s)$	Transfer function of 1DBB compensator,
$E_s(s)$	Steady state error
$C_s(s)$	Transfer function of SRV02 compensator
$k_{p,bb}$	Proportional gain of ball balancer system
$k_{i,bb}$	Integral gain of ball balancer system
$k_{d,bb}$	Derivative gain of ball balancer system

CHAPTER 1
INTRODUCTION

1.1 OVERVIEW

Based on the type of systems, control systems can be classified as linear and nonlinear. While a linear system is the one which follows the principle of superposition and homogeneity, a nonlinear system may be defined as a system on which the principle of superposition and homogeneity are not applicable.

Almost every system existing in real world is a nonlinear system while the idea of linear system is only applicable in theory under specific assumptions. Nonlinear systems gain value in the area of research because of their complex nature along with wide range of applications in real world. One such nonlinear system is a ball balancer system. The nonlinear dynamic equations are tough to solve therefore they are usually approximated using the linear equations.

Mostly every practical system is nonlinear system. A system is nonlinear if the principle of superposition does not apply. Additivity and homogeneity. Some of the nonlinear phenomena are friction, saturation, backlash. While linear control is valid for only small range. Nonlinear control is valid for wide range of operation and can handle systems with hard non-linearity.

Nonlinear systems can also deal with uncertainties such as parameter changing due to ambient temperature, pressure, etc. A few examples of nonlinear systems are inverted pendulum, robot arm manipulator, negative resistance oscillator, helicopter levitation system, unmanned aerial vehicles, automatic guided vehicle, power assisted e-bicycle etc.

1.2 BALL BALANCER SYSTEM

A two degree of freedom ball balancer system comprises of a plate and a ball, which are used for balancing purpose. The ball is kept on the surface of the plate where it is free to move in all the directions. The plate is made to move about a mid-point which makes to ball to move. A USB camera is placed overhead which acts as a vision system for measuring the position of the ball. Two servos, Rotary Servo Base Unit devices are placed just below the plate and joined to the sides of the plate with the help of two degree of freedom gimbals. The ball is balanced on the plate by adjusting its tilt angle. The tilt angle is adjusted by controlling the position of the servo load gears.

The laboratory setup of 2 degree of freedom ball balancer system comprises of a camera, data acquisition device, ball and plate, VOLTPAQ-X2 power amplifier, SRV02-ET unit and a result analysis system. The plate is attached to the gimble from its centre and has 2 DoF for rotation and is free to tilt either in x direction or y direction. The objective of the system is to balance the ball on the surface of the plate so that it does not fall down when the plate tilts. The purpose behind using a 2 degree of freedom ball balancer system is stabilizing the ball at a position set by the user on the surface of the 2D plate.

A ball balancer system consists of a ball which is kept on a 2-dimensional plate which can freely move about a center point. The ball is then needed to be stabilized with the help of various controllers. The 2 DoF Ball Balancer system gains importance in research due to its inherently unstable and non-linear behavior. This nature of a ball balancer system helps in designing of robots which can be used for various purposes such as automatic controlling and position tracking on rough terrains, unmanned aerial and land vehicles, satellite position correction, etc.

1.3 MAMDANI FUZZY INFERENCE SYSTEM

Mamdani fuzzy inference was initially brought up as the technique for creating a control system using synthesizes of a certain combinations of linguistic control rules which are derived through skilled human operators. Here, the output of every rule is a fuzzy set.

As Mamdani systems contain more intuitive rule base which are easy to understand also, they are more-suited for expert system applications in which the rules are made using human expertise knowledge, like the medical diagnostics.

Hence, the mamdani systems are more intuitive, are more suited for use by human inputs, have an interpretable rule base and also have a wide acceptance.

The process inference mechanism of a Mamdani system is explained as well as outlined in the Fig. 1.1.

The result of every rule is obtained as a fuzzy set based on the output membership function along with the method of implication used in the FIS. The output fuzzy sets are merged in a common fuzzy set with the help of aggregation method of FIS. Thereafter, in order to calculate a concluding crisp output value, the collective output fuzzy set is gone through the process of defuzzification with the help of one of the techniques stated in method of defuzzification.

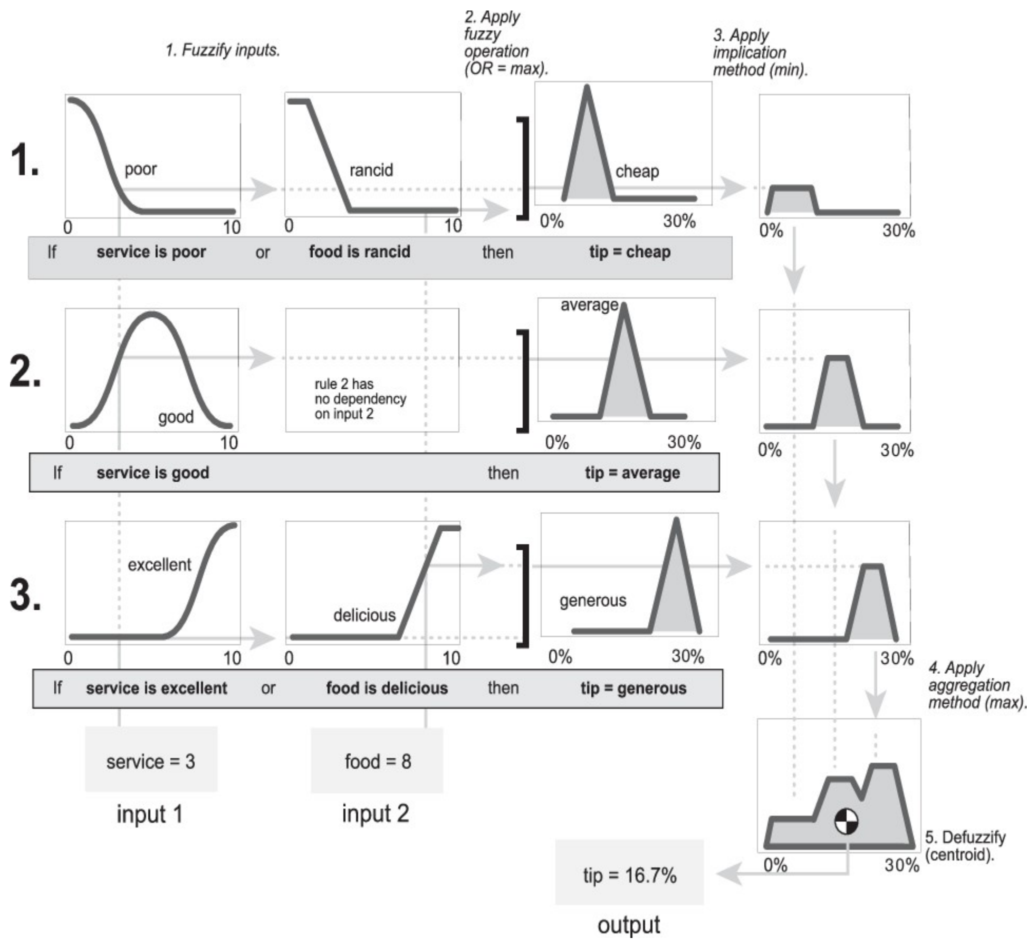


Figure 1.1 Example of Mamdani Fuzzy Inference System

1.4 TAKAGI SUGENO FUZZY INFERENCE SYSTEM

Sugeno fuzzy inference system which is additionally called as the Takagi-Sugeno-Kang fuzzy inference system, makes use of singleton output membership functions which can be a constant function or a linear function of the input. The process of defuzzification for a Sugeno system is comparatively more computationally structured in comparison with a Mamdani system, as it makes use of either a weighted average or weighted sum of a certain data points inspite of calculating a centroid of a 2D area.

Every rule present in a Sugeno system works as depicted in the Fig. 1.2, where it displays a two-input system having input values x and y.

Every rule gives rise to 2 values:

- z_i — Rule output level, which is a constant value or a linear function of the input values:

  $$z_i=a_ix+b_iy+c_i$$

  Here, x and y are the values of input 1 and input 2, respectively, and a_i, b_i, and c_i are constant coefficients. For a zero-order Sugeno system, z_i is a constant ($a = b = 0$).

- w_i — Rule firing strength derived from the rule antecedent

  $$w_i=AndMethod(F1(x),F2(y))$$

  Here, $F_1(...)$ and $F_2(...)$ are the membership functions for inputs 1 and 2, respectively.

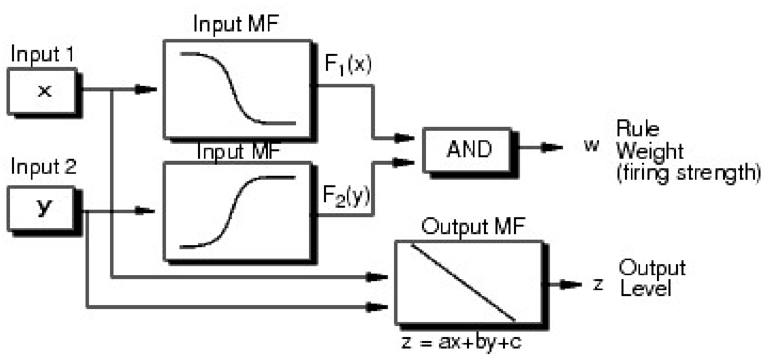


Figure 1.2 Rules for operating Sugeno system

The output of each rule is the product of w_i and z_i which is also the weighted output level.

An easy mathod to understand first-order Sugeno systems is to assume every rule as describing the position of a moving singleton. That is, the singleton output spikes can progress in a linear manner inside the output space, as per the input values. The rule firing strength then explains the size of the singleton spike.

The concluding output for the system is given by taking the weighted average of all rule outputs:

$$\text{Output} = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i}$$

here N is the number of rules.

The sugeno FIS are computationally more efficient and work fine with linear techniques like PID control and optimization as well as adaptive techniques. They ensure a continuous output surface and are more suited for mathematical analysis. The Fig. 1.3 displays a Sugeno system's fuzzy inference process.

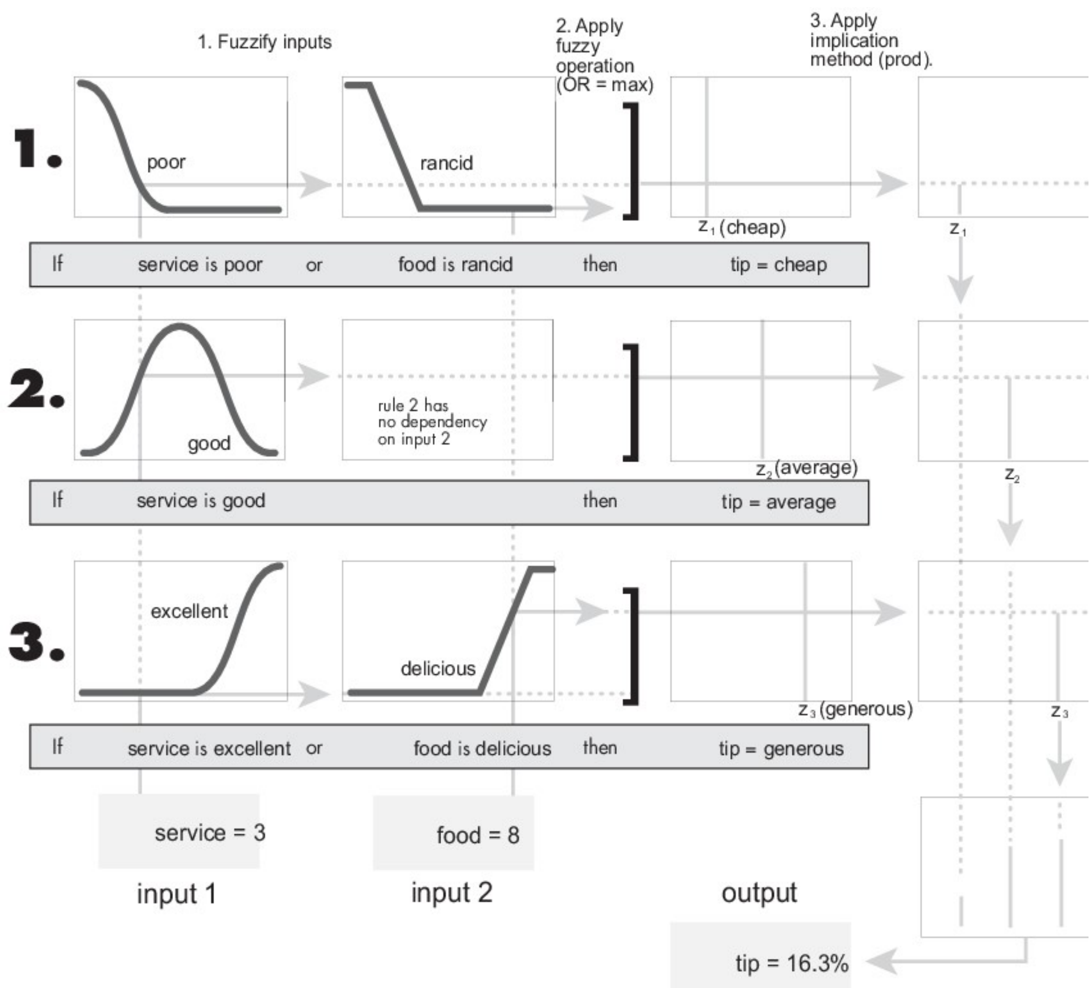


Fig. 1.3 Example of Sugeno Fuzzy inference system

1.5 OBJECTIVES OF THE PROJECT

The main objective behind designing a control system for the 2DoF ball balancer system is:

(i) Increase the stability of the system

(ii) Enhance the performance (steady state error, transient response (overshoot, speed response) of the system

(iii) minimize energy consumption

Desired performances of control design for the system are

(i) it should be robust to disturbance and parameter changing,

(ii) it should have a fast response and smooth curves

(iii) it should consume less energy

1.6 OUTLINE OF THE THESIS

The thesis is divided into the following chapters

Chapter 1 discusses a short description of what nonlinear systems are and their applications along with a small introduction of ball balancer system.

Chapter 2 discusses the literature review for the ball balancer system.

Chapter 3 gives a more detailed description of ball balancer system along with its transfer function and equations describing the system.

Chapter 4 discusses the types of controllers used such as PID and fuzzy logic controller.

Chapter 5 discusses the results obtained using the simulations that have been performed. Conclusion along with the future scope are given in chapter 6.

CHAPTER 2

LITERATURE SURVEY

2.1 LITERATURE SURVEY

In a ball balancer system, a camera is hung vertically opposite to the plate and is used to track the position of the ball for taking appropriate actions is taken by the controller. In order to detect the ball even when the light fluctuates frequently, blob analysis algorithm is utilized to help differentiate between the background and the foreground [3]. The main aim behind developing a control mechanism for ball balancer system is to train the system to keep an object in a balanced position on the unstable surface by adjusting the angle of inclination of the surface [4]. The objective here is to keep the ball near the set point and reduce the error between the set point and the current position [5].

The overhead camera provides feedback to the control system, and then accordingly control action is taken by the applied control strategy. The angle encoder collects the position of the motor as feedback [6]. Initial research on stabilizing the ball balancer includes using of a feedback compensation to stabilize the system [7]. With the help of mechatronic design principles, the system is realized using constraints such as performance, cost, functionality, extendibility, etc. With the help of the control scheme, the ball may be directed to follow any desired trajectory and not just be balanced at a single set point [8].

On-line training PIDNN controller making use of an enhanced DEPSO algorithm is proposed to track the trajectory of ball balancer system, to estimate input as well as the output parameters of the PID neural network, and to overcome the drawbacks of BP algorithm. Weighting factors of multi-layered forward neural network is trained using differential evolution based on enhanced PSO [10].

The modelling of a ball and plate system is done using the basis of First Principle's Method which is obtained from Newton-Euler method by balancing various forces along with the torques on motors, ball, plate as well as gears. Linearization is done for obtaining the state space model near the operating region, which is then utilized for discrete optimal control for trajectory tracking [15].

PID controllers based on Arduino microcontroller that use feedback signal for controlling the movement of the ball using linear potentiometer position sensor have been used [16]. The application of the cascaded fractional-order sliding mode controller along with the simple SMC for controlling the trajectory shows that FOSMC increases the speed of response and tracks the trajectory more accurately [17]. In order to achieve point-to-point control with circular trajectory control, a nonlinear PID is used that also helps in solving the bigger programming problems that consume larger computation time [11].

When the double feedback loop structure of the ball balancer system is designed such that, the inner loop uses linear algebraic method by solving Diophantine equations while the outer loop uses H-infinity sensitivity method, the system becomes more robust and the controllers show more adaptability [19]. Disturbance observer PD controllers are used to ensure efficient functioning of the Ball balancer system when subjected to environmental disturbances which is an updated type of ball and beam system [20].

When error integration is used while designing sliding mode controller, the system becomes more immune towards the external disturbances [21]. The use of a second order SMC shows the closed loop system as semi globally asymptotically stable above the top half plane taking into consideration that ball is always in contact with the arc [22]. To resolve the issue of coupling between the control loops as well as deal with the uncertainties, a novel design method is developed for optimal nonlinear controller using model reference technique. The optimal parameters are obtained using the invasive weed optimization technique [23].

The Proportional-Integral-Derivative controller design is proposed using the Kalman-Yakubovich-Popov Lemma. In this method, the I-PD controller is used to prevent the input signals which are large against the significant alterations made in the reference signal, followed by a LPF that is used in feedback for reducing the effect of noise from the camera in the high frequency range. The GKYP lemma technique is applied on the open loop transfer function. It also improves the steady state response [12].

When the asymptotic stable dual PD control is used along with the nonlinear compensation, it helps to resolve the regulation problem by obtaining a novel nonlinear dynamic model [13]. For increasing the precision of system and obtain rapid and more accurate results, the overhead camera is replaced by a touch screen that captures the coordinates of the ball as well as of the servo motor underneath is replaced by a rotary pneumatic cylinder [14].

Classical methods like the PID control were then used for position tracking and controlling in the 2DoF Ball Balancer systems. But soon intelligent control started to come in picture. The Takagi Sugeno fuzzy controller is utilized to overcome the major drawbacks that a ball balancer system comes with, namely, plant nonlinearity and inter-axis coupling. This model is capable of capturing the nonlinear plant model dynamics using a smaller number of fuzzy rules while it also gives greater accuracy in comparison to the Mamdani fuzzy model [18]. Indirect adaptive control strategy, considered as a very successful control method lags behind in the identification phase. So, a novel indirect adaptive control technique using hierarchical fuzzy Cerebellar Model Articulation Controller (CMAC) neural network has been developed [9].

NiF and NiF-P have improved the performance remarkably in comparison to the classical PID control [24]. A comparative analysis among PID, SMC and also fuzzy controller shows that the performance of fuzzy controller is superior, followed by SMC and PID [25]. Further research was carried on motion planning of 6 parallel legged robots which could be used for moving on terrains which are irregular [26].

The application of optimal Linear quadratic Regulator control on 2DBB system resulted in minimization of quadratic cost function which then results in reduction of settling time and consequently less energy consumption. The work is then extended to trajectory tracking and asymptotic stabilization of four degree of freedom BB system [27]. Further, model predictive controller (MPC) is constructed using Laguerre functions and quadratic cost function which is alike the classical LQR for asymptotic stabilization of four degree of freedom BB system [28]. In order to achieve minimum tracking error along with a fast response, PID controllers and Lead/Lag compensators are used in a double loop feedback fashion [29].

With the advent of time, heuristic and metaheuristic techniques started replacing the classical control techniques mainly because the conventional PID and even the FLCs required the person designing the controller to have an expertise in parameter tuning. However, this was not the case with the metaheuristics. Metaheuristic optimization algorithms such as PSO, GA and SA tuned with Classical PID have proved to give improvised outputs when compared to traditional PID.

Comparative analysis depicts that when PID is tuned using particle swarm optimization, it exhibits better performance with regard to the ball position trajectory, the characteristics of the ball plate angle and also for the characteristics of the actuation voltage while also reducing the oscillations which were significant when PID was tuned using the genetic algorithm [30]. When the tuning for PSO - PID is done using the cost functions namely ISE, IAE, ITSE and ITAE, IAE is found to be best tuning parameter. PSO tuned PID controllers perform better than both the classical PID and Fuzzy Logic controller [31].

Nowadays, hybrid controllers have significantly improved the performance of the 2DBB system as they inherently utilize the characteristics of both the controllers. One such controller is ANFIS Controller that incorporates the benefits of both fuzzy logic controller and artificial neural network. Here, the ANN helps in training of the data while the FLC helps in linearizing the system even in absence of a proper mathematical model. ANFIS controller has given superior results by giving the least steady state error, settling time and vibration angle compared to FLC and ANN [32].

Heuristic techniques like PSO and Cuckoo Search Technique have been used in integration with the PID controllers. Performance indices used for evaluation are ITSE, ITAE, ISE and IAE. The transient performance analysis is done using PID based on H-infinity and also PSO-I-PD. Results show that response from CSA-PI-PD controller is fast and free from oscillations while it also stabilizes the system. Zero overshoot is obtained using CSA-PI-PD while the settling time has 72% reduction [33].

To overcome the difficulties faced while implementing Model Predictive Control on microcontrollers having limited performance, a new embedded MPC is designed that converts the quadratic programming problem into equivalent nonnegative least squares problem with enhanced calculation efficiency for improving the tracking performance for a 2DBB system [34].

While tuning the PID controller with Zeigler Nichols method, simple internal model control and genetic algorithm, the performance analysis carried upon set point tracking with reference as a square wave. This disturbance rejection depicts that genetic algorithm takes less time to settle and gives less overshoot and outstands simple internal model control Zeigler Nichols [35].

For enhancing the dynamic working along with the robustness, a novel LTR control strategy is designed wherein estimation of states is done using the extended Kalman filters and then for obtaining the optimal feedback gain matrix, the Jacobian matrix and Riccati equation is solved in real time. The performance of the ball balancer is improved using the principle of loop transfer function recovery [36].

The tuning of PID parameters is also done by improving ACO technique for ball balancing as well as position controlling. It helps to improve the transient response along with less steady state error, low RMSE and less peak time [37]. Wavelet based fuzzy controllers used in close loop with the system are used to overcome the non-linear and underactuated behavior of ball and plate arrangement. Discrete wavelet transform is used for denoising of error signal and also to tune the weights of the controller [38].

CHAPTER 3
BALL BALANCER SYSTEM

3.1 INTRODUCTION

The 2DBB system comprises of a plate and a ball, which are used for balancing purpose. The ball is kept on the surface of the plate where it is free to move in all the directions. The plate is made to move about a mid-point which makes to ball to move. A USB camera is placed overhead which acts as a vision system for measuring the position of the ball as sown in Fig. 3.1.

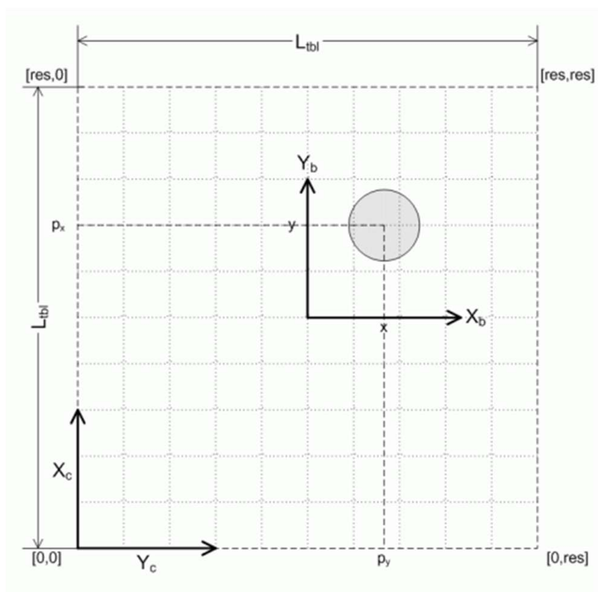


Fig. 3.1: Ball position on x-y plane

Two servos, Rotary Servo Base Unit devices are placed just below the plate and joined to the sides of the plate using the 2DoF gimbals. The ball is balanced on the plate by adjusting its tilt angle. The tilt angle is adjusted by manipulating the servo load gears position. Fig. 3.2. illustrates a typical Ball Balancer System.

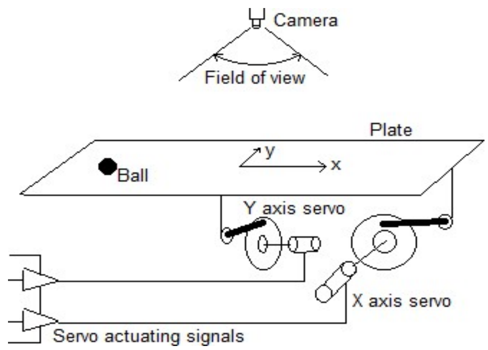


Fig. 3.2. Illustration of a typical Ball Balancer System

The laboratory setup of 2 DoF ball balancer system comprises of a camera, data acquisition device, ball and plate, VOLTPAQ-X2 power amplifier, SRV02-ET unit and a result analysis system. The plate is attached to the gimble from its centre and has 2 DoF for rotation while also being free to tilt either in x direction or y direction. The aim is to stabilize the ball on the surface of the 2D plate so that it does not fall down when the plate tilts. The purpose behind using a 2DBB system is balancing the ball at a point which set by user on surface of the 2D plate.

3.2 MATHEMATICAL MODELLING

3.2.1 Transfer Function

The modelling of the 2DBB is done with the use of first principles method [3]. Fig. 3.3 represents the block diagram of open loop structure of 2DBB system. The dynamics of input servo motor voltage along with the resultant load angle is found using transfer function of SRV02. $T_{bb}(s)$ represents the dynamics related to the servo load gear angle with respect to the ball position.

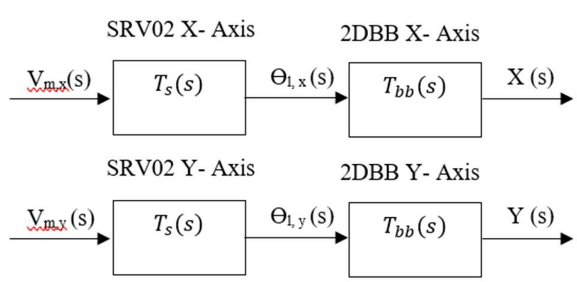


Fig. 3.3 2DBB open loop block diagram

The 2DBB system is a decoupled system, which means that actuator in x-axis does not affect the response obtained through y-axis. Also, as the plate is symmetric and the SRV02 device has same hardware, the dynamics of both the axis are similar in nature, and consequently modelling of only 1 axis is done. Fig. 3.4 represents the open loop block diagram for 1DBB.

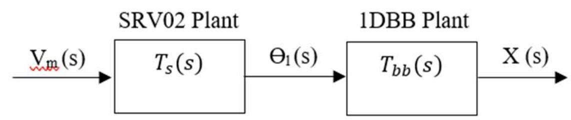


Fig. 3.4 1DBB open loop block diagram

The diagram depicting all the forces on the ball balancer system is as in Fig. 3.5. The transfer function relating SRV02 and 1DBB is written as

$$T(s) = T_{bb}(s)T_s(s) \tag{3.1}$$

Here, $T_{bb}(s)$ represents 1DBB transfer function, which may further be written as

$$T_{bb}(s) = \frac{X(s)}{\theta_l(s)} \tag{3.2}$$

Eq (2) shows the relationship between displacement of ball w.r.t servo load angle.

While the transfer function of SRV02 is written as

$$T_s(s) = \frac{\theta_l(s)}{V_m(s)} \tag{3.3}$$

3.2.2 Equations of Motion

The nonlinear time domain equation that describes the position of ball w.r.t the plate angle is

$$\frac{d^2}{dt^2}x(t) = f\big(\beta(t)\big) \tag{3.5}$$

Using Newton's second law on the ball, we get-

$$m_{ball}\left(\frac{d^2}{dt^2}x(t)\right) = \sum F \tag{3.6}$$

Here, m_{ball} represents the ball's mass.

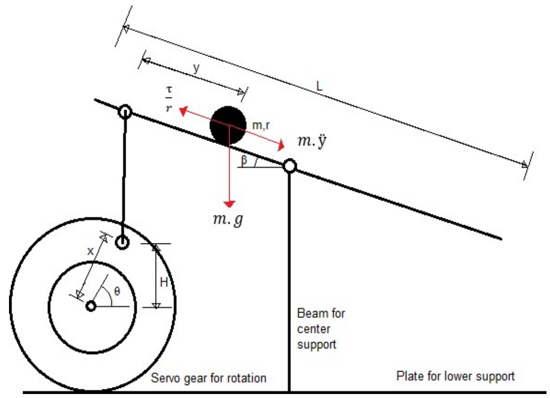


Fig. 3.5. Forces acting on the ball and beam system

The forces on the ball can be balanced as

$$m_{ball}\left(\frac{d^2}{dt^2}x(t)\right) = F_{x,t} - F_{x,r} \tag{3.7}$$

Here, $F_{x,t}$ represents the inertial force of ball while $F_{x,r}$ represents the force due to translation under the effect of gravity. The frictional force and viscous damping are not taken into consideration. In order to reach the state of equilibrium, equate the momentum of the ball with force acting as a result of gravity.

$$F_{x,t} = m_{ball}g\sin(\beta(t)) \tag{3.8}$$

Let, $\gamma_b(t)$ represents the ball's angle while r_b stands for the ball's radius. So, the angular displacement can be converted into linear displacement using the sector formula.

$$x(t) = \gamma_b(t)r_b \tag{3.9}$$

The rotational forces due to the ball's inertia can be written as

$$F_{x,r} = \frac{J_b\left(\frac{d^2}{dt^2}x(t)\right)}{r_b^2} \tag{3.10}$$

The acceleration of the ball in linear form is given as

$$\frac{d^2}{dt^2}x(t) = \frac{m_{ball}g\,sin(\beta(t))r_b^2}{m_{ball}r_b^2+J_b} \tag{3.11}$$

The relation of the angle of the table with the servo angle can be given as

$$sin\big(\beta(t)\big) = \frac{2\, sin(\theta_l(t)) r_{arm}}{L_{tbl}} \tag{3.12}$$

The linearized equation of motion for 1 DoF ball balancer system is

$$\frac{d^2}{dt^2} x(t) = \frac{2 m_b g \theta_l(t) r_{arm} r_b^2}{L_{tbl}(m_{ball} r_b^2 + J_b)} \tag{3.13}$$

Assuming zero initial conditions, the transfer function of one degree of freedom system is given by

$$T_{bb}(s) = \frac{K_{bb}}{s^2} \tag{3.14}$$

Where $k_{bb} = \frac{2 m_{ball} g r_{arm} r_b^2}{L_{tbl}(m_{ball} r_b^2 + J_b)}$

And combined 1DBB and SRV02 transfer function is obtained as

$$T(s) = \frac{K_{bb} K}{(\tau s + 1) s^3} \tag{3.15}$$

While the relation of the displacement of ball with the servo voltage to x-axis is

$$x(s) = \frac{K_{bb} K V_m(s)}{(\tau s + 1) s^3} \tag{3.16}$$

CHAPTER 4
CONTROLLER DESIGN

4.1 CONTROLLER

A controller is a device or algorithm that takes the sensor input while giving the control output. A comparison is made among the measured process variable along with the desired set point and calculation for the error signal is done. As per the error signal, the controller produces the control output to the actuator.

A controller is a component available within a control system which produces control signals for reducing any deviations of the real value when compared to the desirable estimate to nearly zero or least value that is possible. It manages the control action for the system for generating the precise output.

The technique of generating a control signal with the help of a controller is called control action.

The Fig. 4.1 underneath shows the block diagram for a controller:

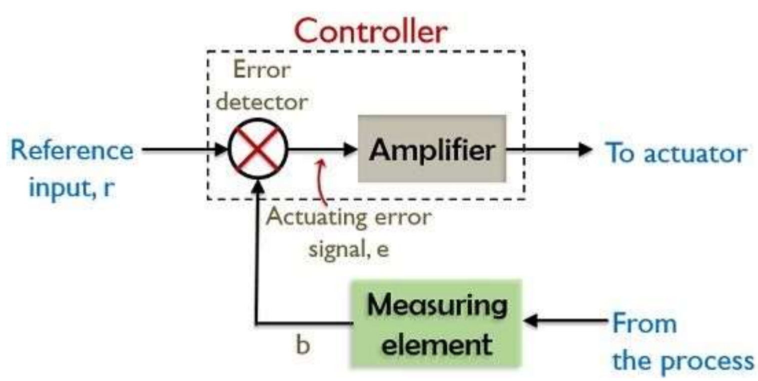


Fig. 4.1 Block Diagram for a controller

The divergence of the obtained output in comparison to the reference input gives the error signal that is required to be reduced with the help of a controller so the system can produce the desired output. A control system handles the system for providing any given output. Hence, the controller gives the required controlling to the system in order to get the required output.

A controller is a instrument which aims to reduce the deviation between the real value of a system and the required value of the system. Controllers are a crucial component in control engineering.

The major advantages of the controllers consist of:

1. They enhance the steady-state accuracy as they decrease the steady state error.
2. This leads to improved stability.
3. They reduce the undesirable offsets which are generated by the system itself.
4. They are capable of controlling the peak overshoot of system.
5. They help to reduce the noise signals generated through the system.
6. They are helpful in speeding up the slow response for a overdamped system.

Various types of such controllers are used in industrial gadgets like PLC and also Supervisory Control And Data acquisition systems. Mainly, there are two types: continuous and discontinuous controllers. Where in discontinuous controllers, there is the manipulated variable which gets changed among various discrete values. On the basis of different states the manipulated variable assumes, a difference is introduced in between two states, three states, and multi-state controllers. In comparison with the continuous controllers, the discontinuous controllers work on very simplistic, switching concluding controlling components.

The major characteristic of the continuous controllers is that the manipulated variable is capable of having any value which is in the range of output of the controller. As per the theory of continuous controller, three main controllers are there on the basis of which the complete control action is taken:

1. Proportional controllers.
2. Integral controllers.
3. Derivative controllers.

The combined version of these controllers is used in controlling the system in order to make the process variable equals the desired value. The above-mentioned controllers can be used to make into combinations to form new controllers:

1. PI Controller
2. PD Controller
3. PID Controller

4.2 PID CONTROLLER

Every controller has a particular application where they provide best results. Not every controller can be inserted with any system while expecting decent results –various criteria must be satisfied. In case of a proportional controller**,** two conditions that must be fulfilled are :

1. Smaller deviation
2. No sudden deviations

While using proportional controller, the output is varied directly with the error signal. Writing this in mathematical format,

$$A(t) \propto e(t) \tag{4.1}$$

Removing the sign of proportionality,

$$A(t) = K_p \times e(t) \tag{4.2}$$

here K_p stands for the constant of proportionality which is also the controller gain.

It is suggested to keep K_p more than one. In case the value of K_p is more than one (>1), then it enhances the error signal that is generated along with detecting the amplified error signal can be detected easily.

1. It helps to reduce the steady-state error, thereby increasing the stability of the system.
2. Makes response of overdamped system faster.

3. Sometimes offsets might occur in the system.
4. The contribute in increasing the peak overshoot.

While considering the integral controllers, the output is directly varied as per the integral of the obtained error signal. Because in an integral controller output is varies directly with the integration of the error signal, it can be written in mathematical format as,

$$A(t) \propto \int_{0}^{t} e(t)dt \tag{4.3}$$

Removing the sign of proportionality,

$$A(t) = K_i \times \int_{0}^{t} e(t)dt \tag{4.4}$$

Where Ki is an integral constant also known as controller gain.

The integral controller also called reset controller can put back the controlled variable to the accurate desired value succeeding a disturbance which is the reason it is called a reset controller. It also has ability of causing instability in the system by giving slow response for the error that is produced. Also, it is seen that the derivative controllers cannot be used in standalone and a combination should be made with other types of controllers as:

1. It does not help in improving the steady-state error.
2. It gives rise to saturation effects while also amplifying the noise signals which are generated by the system.

For a derivative controller the output is varied directly to the derivative of the obtained error signal. Because in a derivative controller output is varied directly to the derivative of the error obtained, it can be written in mathematical format as,

$$A(t) \propto \frac{de(t)}{dt} \tag{4.5}$$

Removing the sign of proportionality,

$$A(t) = K_d \times \frac{de(t)}{dt} \tag{4.6}$$

here, K_d stands for proportional constant or can be called controller gain.

The derivative controller also called the rate controller has a main benefit of a derivative controller which is improving the transient response for the system.

PI Controller is a made by combining the proportional and an integral controller where the output equals to the addition of proportional as well as the integral of the signal generated for error. Because in a PI controller output is varied directly to the addition of proportional of error along with the integral of the error signal, this can be written in mathematical format as,

$$A(t) \propto \int_0^t e(t)dt + A(t) \propto e(t) \tag{4.7}$$

Removing the sign of proportionality,

$$A(t) = K_i \int_0^t e(t)dt + K_p e(t) \tag{4.8}$$

here, K_i and k_p proportional constant and integral constant respectively.

Benefits along with the demerits are collective form of the merits and demerits of proportional and integral controllers individually. Using the PI controller, one pole can be introduced on origin while one zero is placed far from the origin. Because the pole is present at origin, it has more effect, therefore it results in reduction in the stability of the system; while the major merit of using it is that it helps in reducing the steady-state error on a very significant level, because of which it is useful in a wide range of applications as controllers. The Integral component helps in reducing the stability, which does not always imply instability for the system.

PD Controller is a collective version of proportional and a derivative controller where the output equals the addition of proportional and derivative of the signal obtained for the error. Because in a proportional and derivative controller output is directly proportional to the summation of proportional of error and differentiation of the error signal, in can be written in mathematical format as,

$$A(t) \propto \frac{de(t)}{dt} + A(t) \propto e(t) \tag{4.9}$$

Removing the sign of proportionality,

$$A(t) = K_d \frac{de(t)}{dt} + K_p e(t) \tag{4.10}$$

here, K_d and K_p stand for proportional constant and derivative constant. merits along with the demerits are collective of the merits as well as the demerits of proportional and derivative controllers individually.

With addition of a "zero" on an appropriate position in the OLTF helps in improving the stability, on the other hand adding a pole in the OLTF reduces the stability. Using the PD controller is similar to adding a zero in the OLTF.

In case a "zero" is is placed at a location which is at a distance from imaginary axis, its impact decreases

In case the "zero" exists on the imaginary axis, it is not acceptable. Usually, the Proportional-Derivative controller helps in improving the transient response while Proportional-Integral controller helps in improving the steady-state response in a control system.

The PID controller is usually helpful in control utilization in the industry for regulating the temperature, pressure, or any other variables present in the processes.

In order to design a PID Controller, following steps can be followed:

In order to design a PID Controller for a system, some basic steps that can be followed in to get the required performance are:

1. Get the transient response of CLTF for determining the scope of improvement.
2. Add the P controller, find an appropriate the value of 'K' using suitable method
3. Use the integral part for reducing the steady-state error.
4. Use the derivative part for increasing the damping, reducing overshoot and transient time.
5. Sisotool which is present in MATLAB software is useful for tuning the parameters properly so as to get a required response.

For a ball balancer system:

The ball balancer system is created using a cascaded control system. The ball balancer arrangement's closed loop block diagram is depicted in figure. The SRV02 Controller and SRV02 Plant make up the inner loop, and the 1DBB Controller, a ball balancer, and unity feedback make up the outer loop. The controller receives the error and outputs it to the inner loop. This results in an output when used with the ball balancer's transfer function. If it does not match the expected output, it is communicated back to the controller using unity feedback, who then takes the necessary action.

While the outer loop attempts to regulate the plate's inclination angle. In order to determine the needed position of the ball, the compensator in the outer loop determines the servo load angle using the ball position data. The inner loop controls both the input voltage and angle variation. The inner loop of the system is the servo position control system.

The required motor voltage is calculated using the servo compensator for load angle for tracking the load angle. Fig. 4.2 shows the cascaded control system used to control ball position in the x-axis of the combined SRV02 and 2DBB plant. Here, $C_{bb}(s)$ represents the transfer function of 1DBB compensator, $C_s(s)$ represents the transfer function of SRV02 compensator, $T_s(s)$ represents the SRV02 plant transfer function and $T_{bb}(s)$ represents the transfer function of 1DBB plant. Figure 4.3. shows the PID Compensator with derivative set-point weighting.

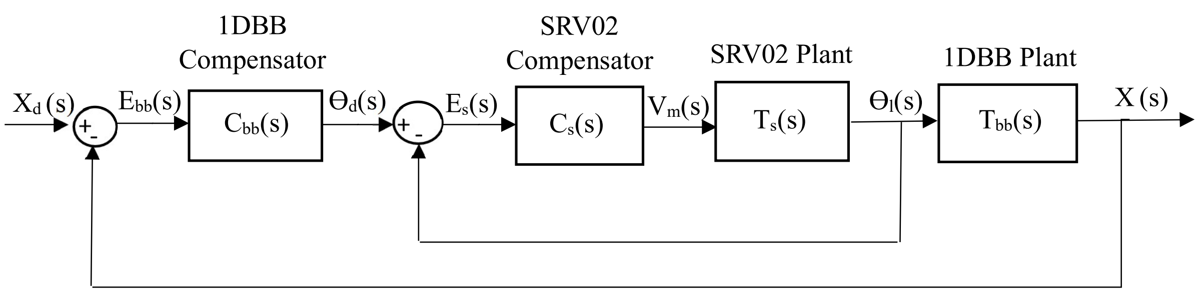


Fig. 4.2 Cascade control system used to control ball position in the x-axis of the combined SRV02 and 2DBB plant

Let, $\theta_l(t) = \theta_d(t)$ (4.1)

The closed loop equation for Proportional-Integral-Derivative controller in time domain is given as

$$\theta_d(t) = k_p\big(x_d(t) - x(t)\big) + k_d\left(b_{sd}\left(\frac{d}{dt}x_d(t)\right) - \left(\frac{d}{dt}x(t)\right)\right) + k_i\int \big(x_d(t) - x(t)\big)\, dt \qquad (4.2)$$

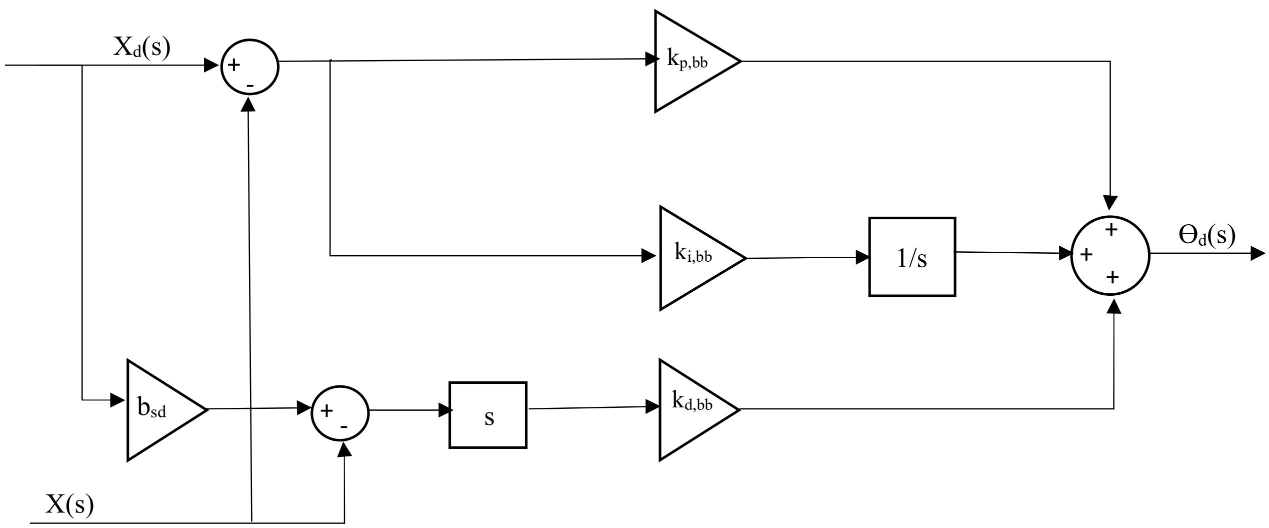


Fig. 4.3. PID Compensator with derivative set-point weighting

The steady state error is given as-

$$E(s) = X_d(s) - X(s) \qquad (4.3)$$

4.3 FUZZY LOGIC CONTROLLER

Systems with a high degree of nonlinearity are typically controlled by fuzzy logic controllers (FLC). The majority of physical and electrical systems are often rather non-linear. Fuzzy Logic controllers are a useful option for researchers for this reason.

In FLC, a precise mathematical model is not required. It can manage non-linearities, process inputs based on prior knowledge, and exhibit more disturbance insensitivity than the majority of other non-linear controllers.

Fuzzy sets, or classes of objects where the change from membership to non-membership is smooth rather than abrupt, are the foundation of FLC.

In recent research, FLC has performed better than other controllers in complicated, nonlinear, or undefinable systems for which there is good empirical knowledge. Because of this, fuzzy sets' boundaries can be hazy and imprecise, which makes them suitable for approximation models.

Determining the input and output variables based on prior experiences or practical knowledge is a crucial phase in the fuzzy controller synthesis process.

This is carried out in accordance with the controller's anticipated function. Although the states of the controlled system, their errors, error variation, and error accumulation are normally the variables chosen, there are no common guidelines for choosing those variables.

Fuzzy logic uses information similar to that of a human to make decisions. Instead of using accurate data with clearly defined bounds, it used imprecise data. A rule basis, a fuzzifier, an inference mechanism, and a defuzzifier are the four main parts of a fuzzy controller. The defuzzification process transforms the formed conclusions back into numeric values, whereas the fuzzification process transforms the numerical data input into a form that the fuzzy system may use to draw conclusions. Two variables have been used as inputs in the controller created for the study in the paper. The first of these is error, and the second is a change in error. While the output variable was chosen to be the control. The outer loop's modelling framework is the Sugeno Fuzzy.

The defuzzification process is carried out using the centre of gravity method. Seven linguistic variables—mf1, mf2, mf3, mf4, mf5, mf6, mf7—are used in the analysis. Error and change in error have the same range of numbers, which is [-0.2, 0.2]. The 2DBB System's single axis control, whose block design is shown in Fig. 4.4, uses fuzzy logic control.

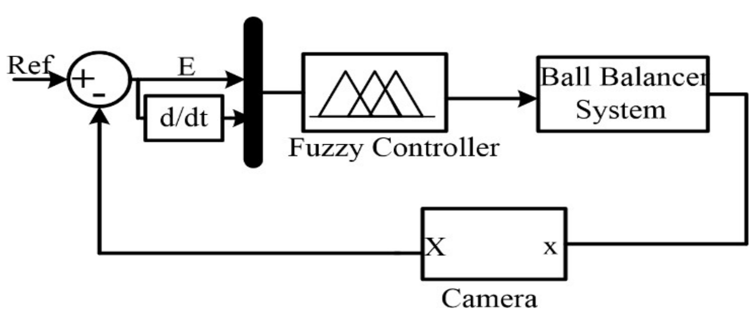
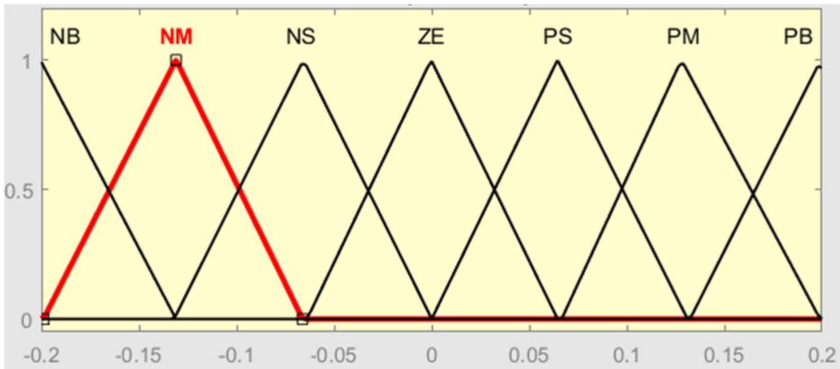


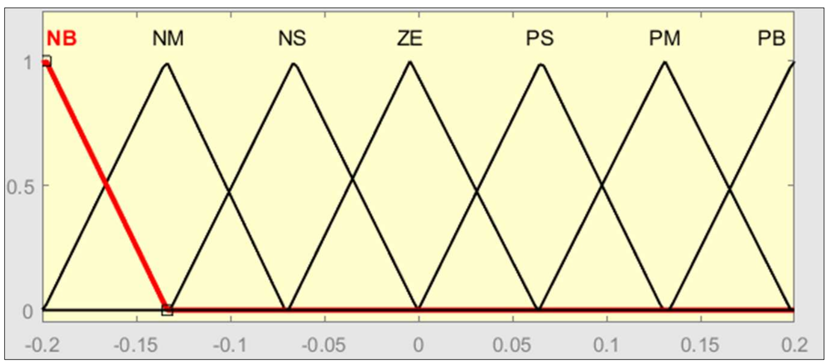
Fig. 4.4. Block Diagram for 2 DoF Ball Balancer System controlled using Fuzzy Logic

The membership function plots for the error and change in error which are the input variable and control, which is the output are as shown in Fig. 4.5.



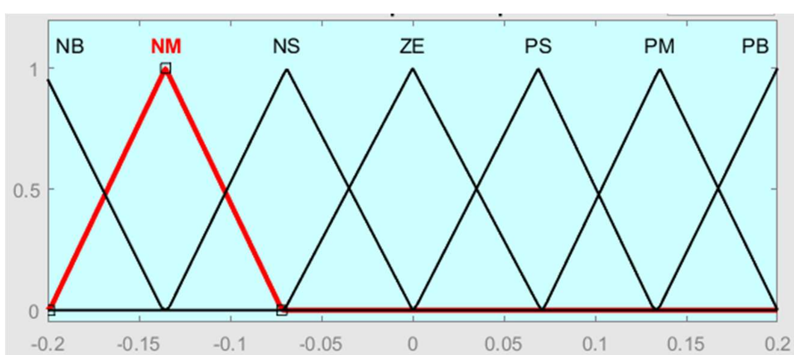
Input variable “error”

(a)



Input variable “change in error”

(b)



Output variable “control action”

(c)

Fig. 4.5. Plots of membership function for (a) error (b) change in error (c) control action

In Fig. 4.6 below, the surface produced by 49 if-then rules intended to regulate the fuzzy control utilising the 7 linguistic variables NB, NM, NS, ZE, PS, PM and PB is depicted. The two inputs provided to the controller are represented by the x- and y-axes. The control is represented by the z-axis.

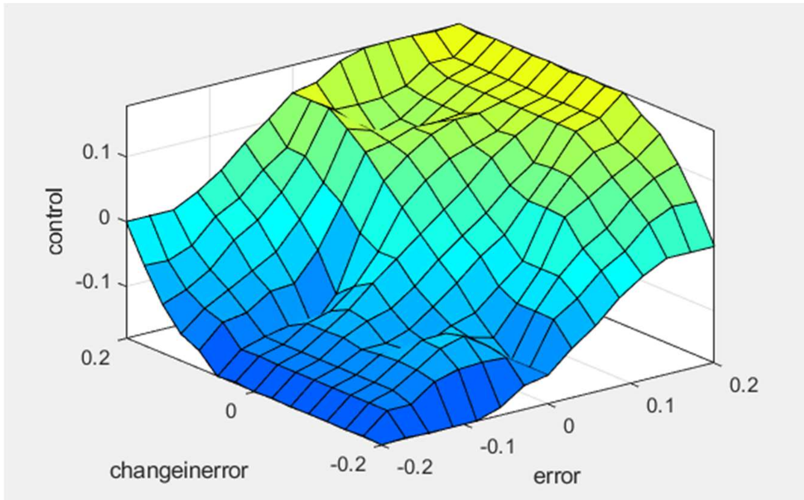


Fig. 4.6. Surface generated using Fuzzy Controller

4.4. TYPES OF FUZZY CONTROLLER

Fuzzy logic makes decisions using human-like comprehension, particularly when working with ambiguous or imprecise input. Instead of exact data with distinct borders, it functions with imperfect data. A fuzzy controller is made up of four basic components: a rule-base, a fuzzifier, an inference mechanism, and a defuzzifier. While the fuzzification process converts the numerical data input into a form that the fuzzy system may use to draw conclusions, the defuzzification process converts the produced conclusions back into numeric values. The fuzzy controller is modelled using the rules created to tell the system how to control and map input to output.

There are two input variables and one output variable in the developed fuzzy controller. The inputs and output of the Mamdani fuzzy model are error and change in error. The inference process is constructed with 49 if-then rules, and the defuzzification technique employed is centroid. The input and output variables both employ triangular membership functions. The error and velocity are the input variables for the sugeno fuzzy model, and the angle is the output variable. While the output variable has a membership function of the constant type, the two input variables have a triangle membership function. Wtaver is the defuzzification technique employed. The controller design for the same is depicted in the following figures (Fig. 4.7(a) and 4.7(b)).

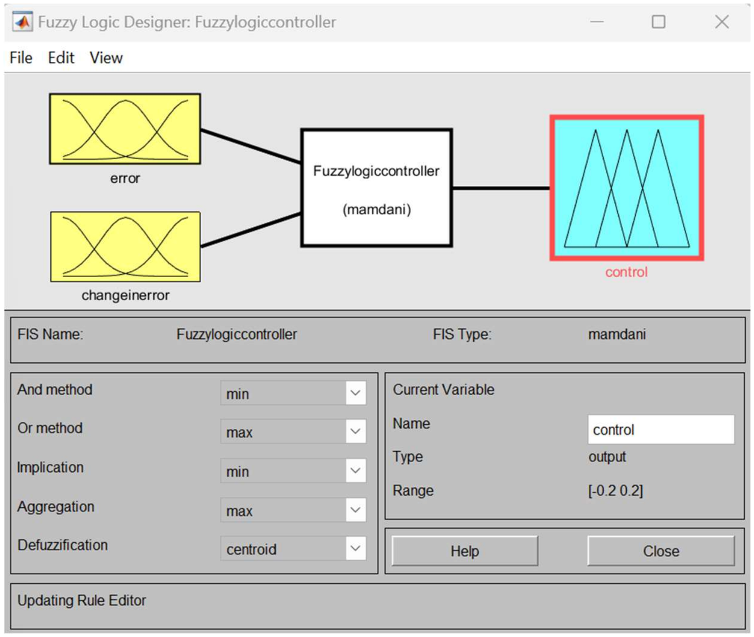


Fig. 4.7. (a) Fuzzy logic controller design using Mamdani fuzzy model

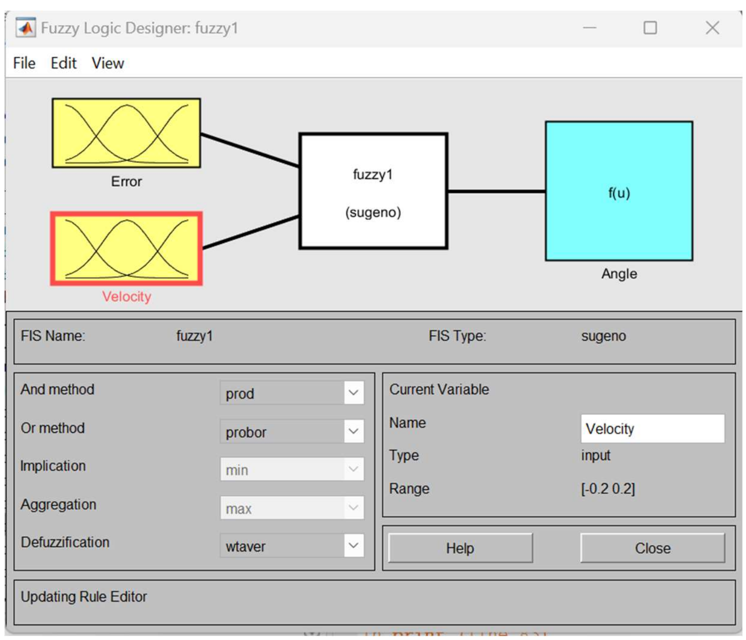


Fig. 4.7. (b) Fuzzy logic controller design using Sugeno fuzzy model

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Effect of Parameter Change

Simulations have been performed on the MATLAB/ Simulink environment using a PD tuned fuzzy logic controller for a 2DBB system. Figure 5.1 shows the simulation model of 2DBB System. The main components are SRV02 position model, 2DBB nonlinear model and the PID controller design.

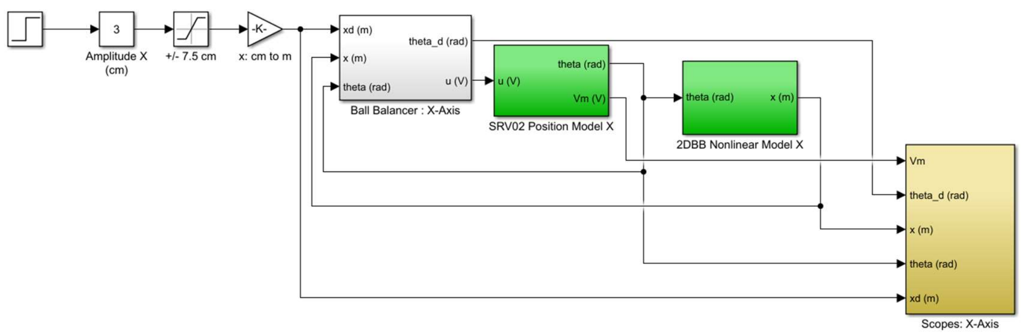


Fig 5.1 Simulation model of 2DBB System

The graphs obtained for plate angle control, position control and actuation voltage using the PD Tuned Fuzzy Logic Controller are as shown in Fig. 5.2. (a), (b) and (c) respectively.

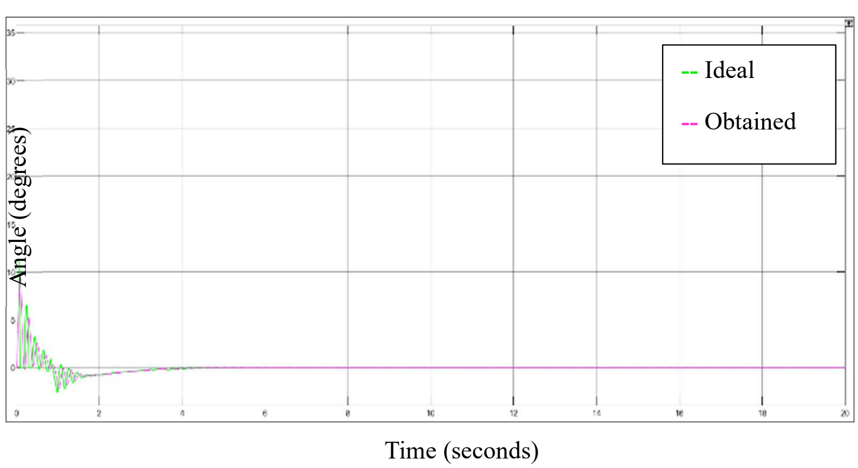


Fig. 5.2. (a) Characteristics of ball plate angle control using PD Tuned Fuzzy Logic Controller

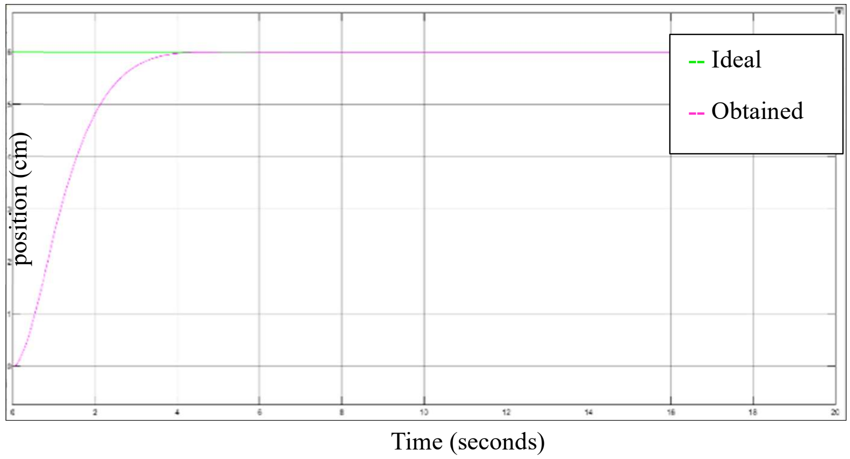


Fig. 5.2. (b) Characteristics of position control of ball using PD Tuned Fuzzy Logic Controller

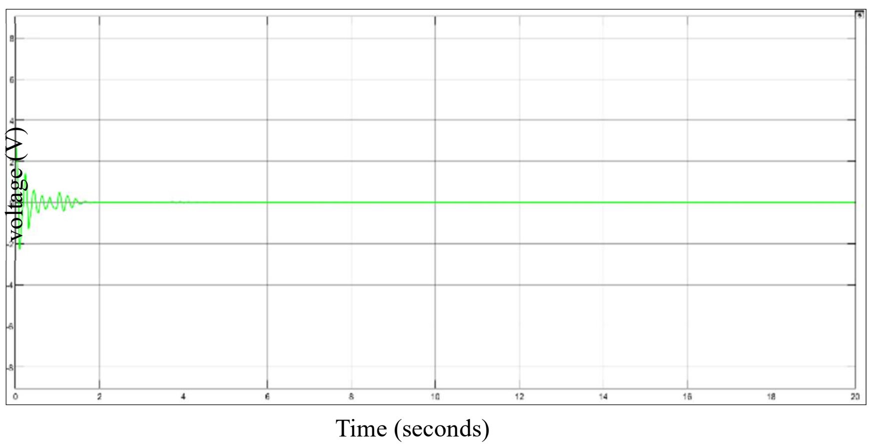


Fig. 5.2. (c) Characteristics of actuation voltage using PD Tuned Fuzzy Logic Controller

Effect of Change in Mass of the Ball on the 2DBB System

The mass of the ball has been varied keeping the radius and other factors constant. The following observations have been recorded based on the change.

The readings have been recorded for 2.5%, 5%, 7.5%, 10%, 25%, 50%, 75%, 100% and 125% change in mass considering 0.04kg as the initial mass and 0.0196 m radius. No change has been observed in either the ball position and ball plate angle characteristics or the controller gains. The time domain specifications are also not altered and are same as shown in Table 4 for FLC.

The values of the PD gains also remain constant and are as follows-kp_bb = 3.45 rad/m

kd_bb = 2.11 rad.s/m

where, kp_bb is the proportional gain for the ball balancer system and kd_bb is the derivative gain for the ball balancer system. The observations for the same are recorded as per the Table 1.

Table 1. Observation Table for Variation in Moment of Inertia with change in Mass of the Ball

S. No.	Mass of ball (kg)	Moment of Inertia of the Ball ($kg.m^2$)
1.	0.04	0.00000614
2.	0.41	0.00000630
3.	0.42	0.00000645
4.	0.43	0.00000660
5.	0.44	0.00000676
6.	0.05	0.00000768
7.	0.06	0.00000921
8.	0.07	0.00001075
9.	0.08	0.00001229
10.	0.09	0.00001382

Effect of Change in Radius of the Ball on the 2DBB System

The radius of the ball has been varied keeping the mass of the ball constant. The following observations have been made based on the change in radius.

The readings have been recorded for 5%, 10%, 15% and 20% change in radius of the ball considering 0.0196m as the initial radius and 0.04 kg mass. No change has been observed in either the ball position and ball plate angle characteristics or the controller gains. The time domain specifications are also not altered and are same as shown in Table 4 for FLC. The values of the PD gains also remain the same and are as follows-

kp_bb = 3.45 rad/m

kd_bb = 2.11 rad.s/m

where, kp_bb is the proportional gain for the ball balancer system and kd_bb is the derivative gain for the ball balancer system. The observations for the same are recorded as per the Table 2.

Table 2. Observation Table for Variation of Moment of Inertia With Change In Radius Of Ball

S.No.	Radius of Ball (m)	Moment of Inertia of the Ball ($kg.m^2$)
1.	0.0196	0.00000614
2.	0.02058	0.00000677
3.	0.02156	0.00000743
4.	0.02254	0.00000812
5.	0.02352	0.00000885

Effect of Change in Gravity on the Ball Balancer System

The gravitational constant has been varied for studying the effect of gravitational constant on the control and balancing of the ball on the ball balancer system. It has been found that the proportional and derivative controller gains change with change in the value of gravitational constant.

It has been noticed that with increase in gravity the value of the proportional gain and derivative gain decreases while the model gain increases. On the other hand, with decrease in gravity, the proportional gain and derivative gains increase while the model gain decreases. The dependence of all the 3 parameters on gravitational constant is approximately linear.

Also, it has been obtained that the characteristics of the position of the ball, ball plate angle control as well as the actuation voltage remain the same until a critical point which is found to be 9.2 m/s^2. Below this value, the characteristics and behavior of the system changes drastically.

It is seen that the change in mass of the ball produces no change either in the time domain characteristics of the ball or the control action. In the same way, the change in radius of the ball produces no change either in the time domain characteristics of the ball or the control action. The observations for the same are recorded as per the Table 3.

Table 3. Observation Table for Variation of PD Controller Gains and Model Gain with change in Gravitational Constant

S.No.	Gravitational Constant (m/s^2)	Proportional Gain (rad/m)	Derivative Gain (rad.s/m)	Model Gain (m/s^2/rad)
1.	10	3.38	2.07	1.11
2.	9.9	3.42	2.09	1.10
3.	9.81	3.45	2.11	1.09
4.	9.7	3.49	2.13	1.08
5.	9.65	3.51	2.14	1.07
6.	9.6	3.52	2.15	1.06
7.	9.5	3.56	2.17	1.05
8.	9.4	3.6	2.2	1.04
9.	9.3	3.64	2.22	1.03
10.	9.2	3.68	2.25	1.02
11.	9.1	3.72	2.27	1.01
12.	9.0	3.76	2.29	0.998

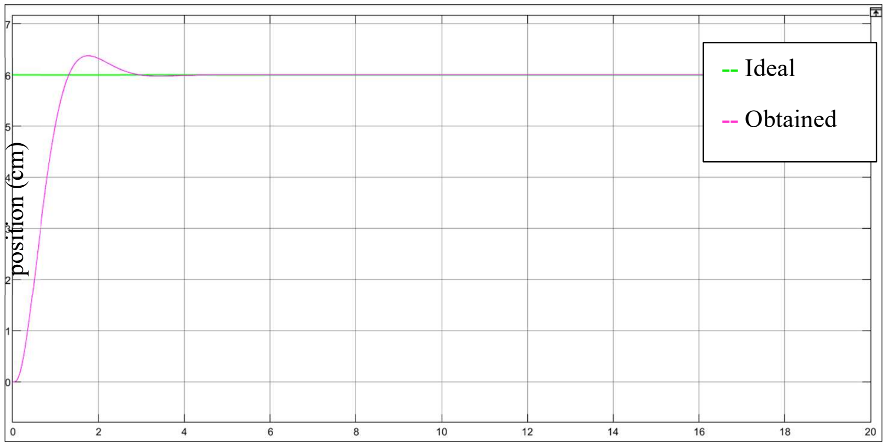
Also, the impact of gravity has been observed. The change in gravitational constant produces significant changes in the characteristics of ball position control, ball plate angle control and actuation voltage after it crosses a critical point. The change in gravitational constant also affect the controller gain i.e., proportional gain and the derivative gain. The model gain varies proportionally with the gravitational constant while the controller gains vary inversely with the change in gravitational constant.

Comparison of PD tuned Fuzzy Logic Controller with the Classical PD Controller

The PD Controller i.e., proportional- derivative controller has been used to study the characteristics of the Ball Balancer System. PD controllers are useful because the derivative controller is anticipatory in nature while the proportional controller is used for reducing steady state error. While the proportional controller output varies as per change in inputs, the derivative controller output behaves with respect to the rate at which the error changes with time. While the proportional controller is used for decreasing the rise time, the derivative controller helps in reducing the peak overshoot.

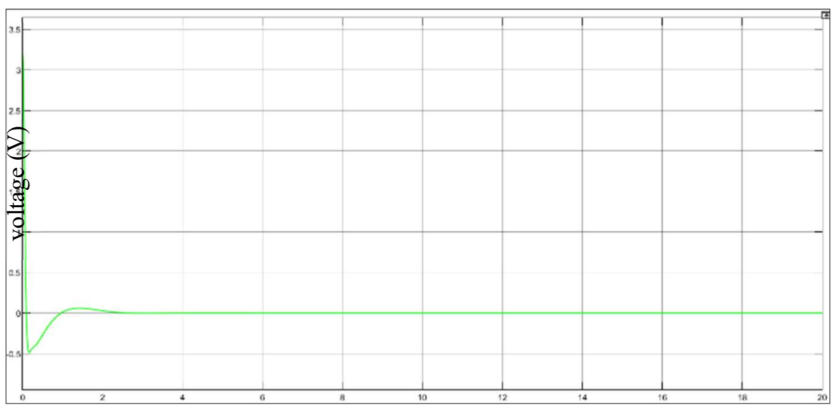
The graphs showing the characteristics for the ball plate angle control, ball position control and actuation voltage are as depicted in Fig. 5.3 (a), (b) and (c) respectively. The model is simulated for a time period of 20 seconds.

Fig. 5.3. (a) Characteristics of ball plate angle control of the Ball Balancer System using PD Controller



Time (seconds)

Fig. 5.3 (b) Characteristics of the ball position control of the Ball Balancer System using PD Controller



Time (seconds)

Fig. 5.3 (c) Characteristics of actuation voltage of the Ball Balancer System using PD Controller

The graphs in figure 5.3 are compared with those in figure 5.2. It is observed that using a fuzzy controller the curve reaches the final set point value more early as compared to the classical PD controller. Table 4 shows the time domain specifications for the ball balancer system using fuzzy logic controller and classical PD controller for ball position characteristics It can be analyzed by observed using the graphs and the time domain specification table that the curves obtained using fuzzy controllers are smoother as they have lesser oscillations and lower peak overshoots which makes then more stable and desirable as compared to the classical. They also take lesser time to reach their final value which makes them more efficient.

Table 4. Time Domain Specifications for the Ball Balancer System using Fuzzy Logic Controller and Classical PD Controller for ball position characteristics

Time Domain Specification	**Fuzzy Logic Controller**	**Classical PD Controller**
Rise Time	0.376	1.318
Peak Time	4.354	1.754
Settling Time	3.686	4.499
Delay Time	1.167	0.643

The settling time as well as rise time is less for the PD Tuned fuzzy controller. Also, the PD controller gives higher overshoot as compared to the fuzzy controller, which indicates that the fuzzy controller is a more stable controller and reaches the final value faster than the classical PD Controller.

5.2 Comparison of Mamdani and Sugeno Fuzzy Inference System

This section describes the results obtained after evaluating the working of the system using the simulation results. The performance of the fuzzy logic controller is evaluated and a comparison is done between the mamdani and sugeno FIS.

The following graph shows the characteristics for ball position for two degree of freedom ball balancer system. Fig. 5.4 shows the ball position characteristics, Fig. 5.5 shows the ball plate angle characteristics while the Fig. 5.6 shows the actuation voltage characteristics. The time domain analysis for the same is done as in Table I.

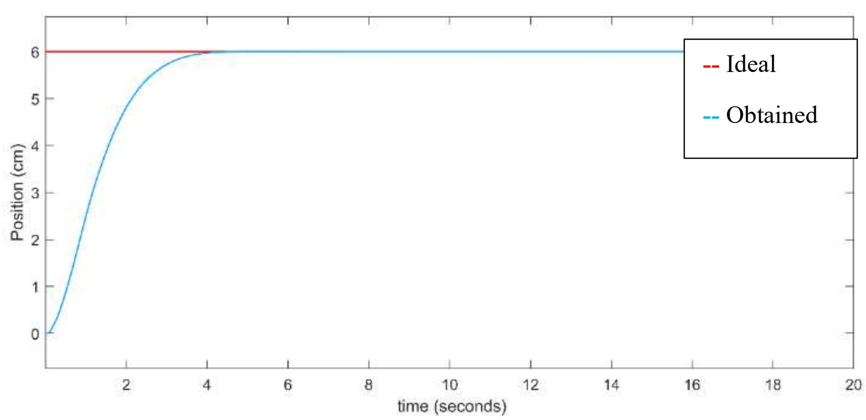


Fig. 5.4. (a) Ball position characteristics for 2DBB system using Mamdani FIS

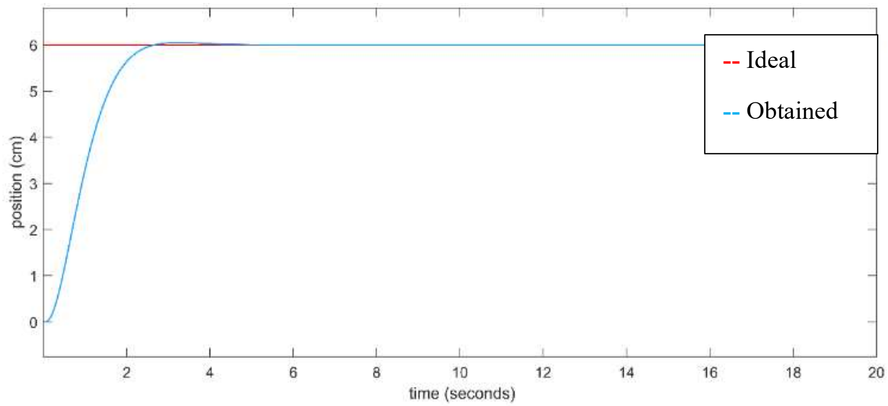


Fig. 5.4. (b) Ball position characteristics for 2DBB system using Sugeno FIS

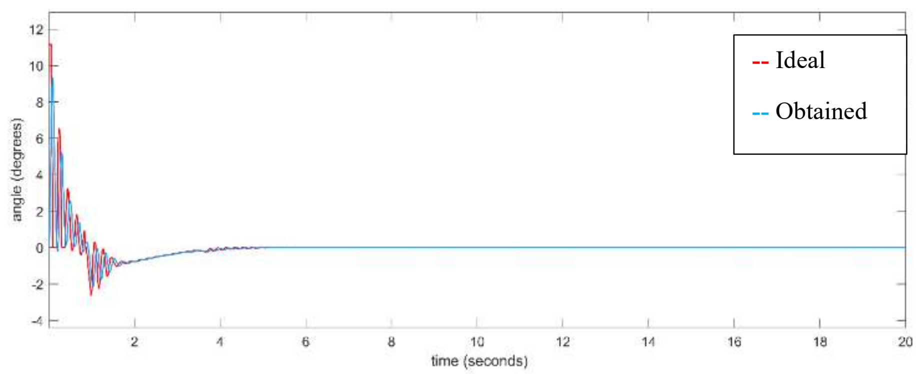


Fig. 5.5. (a) Ball plate angle characteristics for 2DBB system using Mamdani FIS

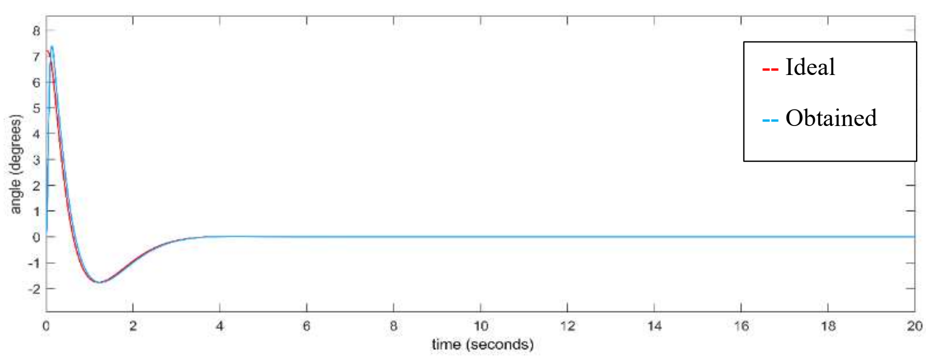


Fig. 5.5. (b) Ball plate angle characteristics for 2DBB system using Sugeno FIS

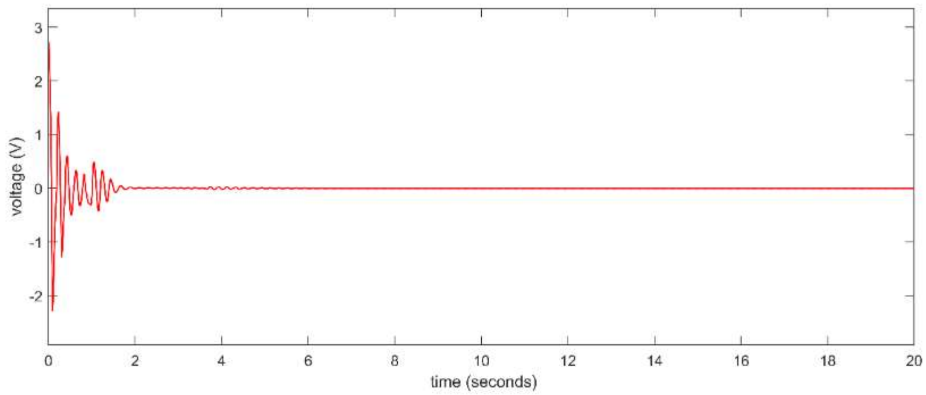


Fig. 5.6. (a) Actuation voltage characteristics for 2DBB system using Mamdani FIS

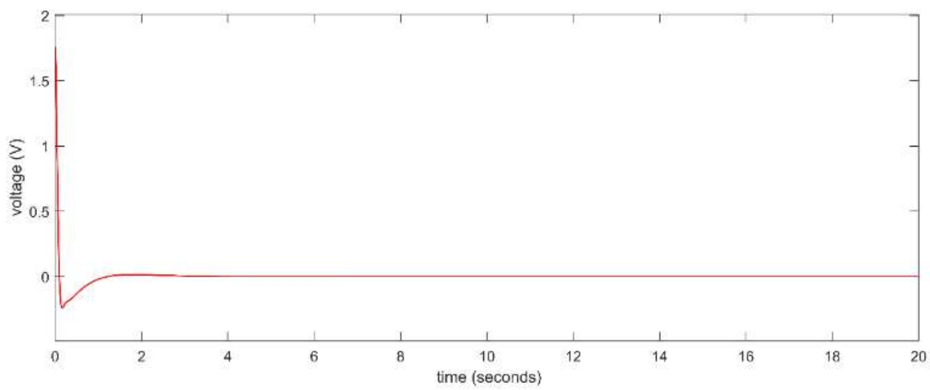


Fig. 5.6. (b) Actuation voltage characteristics for 2DBB system using Sugeno FIS

The time domain specifications are specified in Table 5. The time domain analysis shows that the rise time, peak time, delay time and settling time is less while using the sugeno fuzzy model. This shows that the curve reaches the steady state and also its peak faster as compared to the mamdani fuzzy model and also has a more stable transient response. This means that the sugeno fuzzy model is superior than the mamdani fuzzy model.

Furthermore, the surface generated using the two fuzzy models are shown as in Fig. 5.7. figure 5.7 (a) shows the surface generated using mamdani fuzzy model while figure 5.7 (b) shows the surface generated using Sugeno fuzzy model.

It is observed that while using the sugeno fuzzy model, the surface obtained with error, change in error and control action on the respective three axes, a smoother surface is obtained in comparison to the mamdani fuzzy model.

Table 5 Comparative Time Response Analysis

Time domain specification	Mamdani Fuzzy	Sugeno Fuzzy
Rise time	2.09945	1.44491
Peak time	4.6	3.242
Delay time	1.1654	0.9239
Settling time	2.93732	2.06316
Peak overshoot	0	0.04834

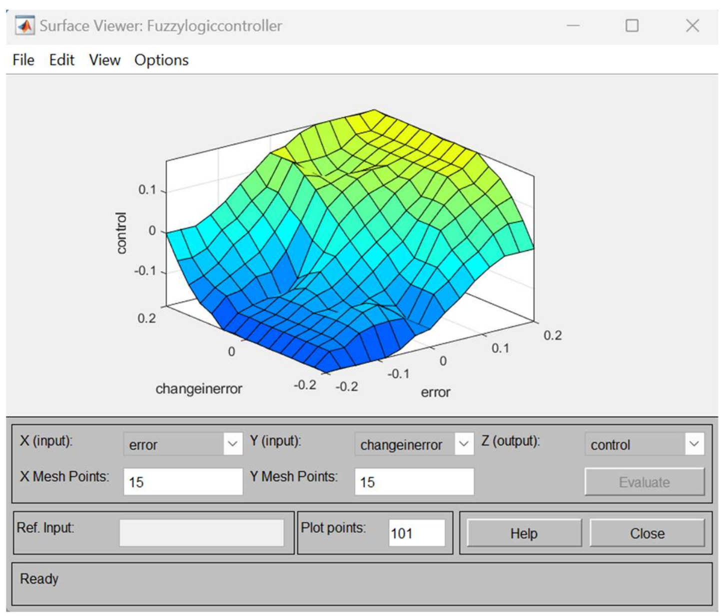


Fig. 5.7 (a) Surface generated using mamdani fuzzy model

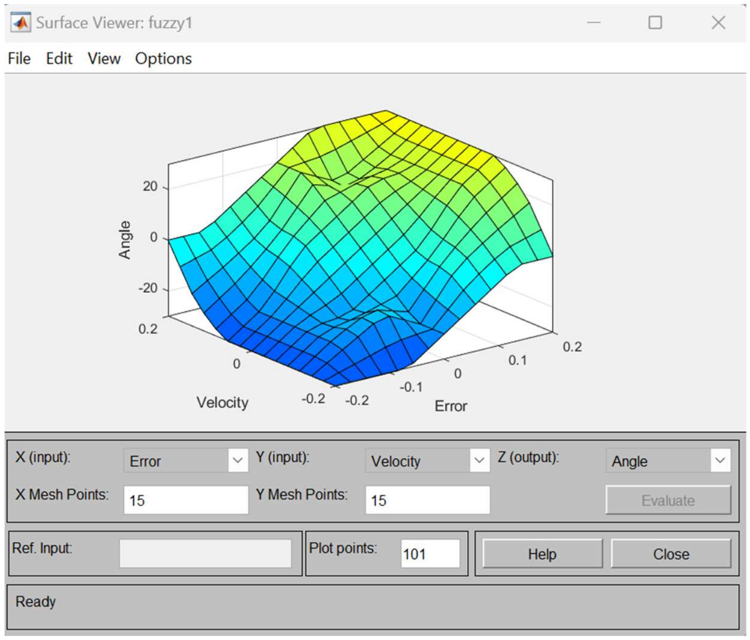


Fig. 5.7. (b) Surface generated using Sugeno fuzzy model

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

The mathematical modelling of the 2DBB System is successfully done, and fuzzy controller is used for controlling the ball position and the results obtained are compared with the classical PD controller. The impact of radius of ball, mass of ball and gravitational constant has been studied on the controller. It is seen that the change in mass of the ball produces no change either in the time domain characteristics of the ball or the control action. In the same way, the change in radius of the ball produces no change either in the time domain characteristics of the ball or the control action. Also, the impact of gravity has been observed. The change in gravitational constant produces significant changes in the characteristics of ball position control, ball plate angle control and actuation voltage after it crosses a critical point. The change in gravitational constant also affect the controller gain i.e., proportional gain and the derivative gain. The model gain varies proportionally with the gravitational constant while the controller gains vary inversely with the change in gravitational constant. The model is simulated for a time period of 20 seconds. The time domain specifications do not change with change in either mass or the radius of the ball. On comparing the results of PD tuned fuzzy controller with the classical PD Controller, it can be observed that the settling time as well as rise time is less for the PD Tuned fuzzy controller. Also, the PD controller gives higher overshoot as compared to the fuzzy controller, which indicates that the fuzzy controller is a more stable controller and reaches the final value faster than the classical PD Controller. The research can further be extended to observe the effect of parameter variation by implementing the changes of the hardware system and studying the characteristics in the real time.

A comparison has been done between the mamdani fuzzy model and sugeno fuzzy model to compare and evaluate the performance of the two fuzzy models. The ball position, ball plate angle and the actuation voltage characteristics have been studied to draw conclusions. Time domain analysis has been done to compare the two models on the basis of various parameters such as rise time, peak time, delay time, settling time and peak overshoot. It has been found that sugeno fuzzy model gives better steady state and transient response while mamdani fuzzy model gives no overshoot. The response generated using the sugeno fuzzy model is more stable and hence superior. For the actuation voltage and ball plate angle characteristics also, there are less oscillations using the sugeno fuzzy model, which increases the stability. The surface generated using the sugeno fuzzy controller is also smoother than the surface generated using the mamdani fuzzy model.

6.2 FUTURE SCOPE

The research can be continued to discover the impact of parameter change by implementing the work of the hardware system along with carrying out a study for the characteristics in the real time. Different algorithms can be used to study the changes that occur in various parameters on changing the algorithm and more optimized results can be obtained. Similarly, fuzzy controller can be integrated or used in hybrid with some other algorithms to train the system to balance the more with more accuracy and precision. Results from different algorithms can be compared and analyzed to study the patterns more effectively.

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LIST OF PUBLICATION OF CANDIDATE’S WORK

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