Design and Implementation of Soft Computing Technique on Ball Balancer System

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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MASTER OF TECHNOLOGY
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Submitted by:

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DESIGN AND IMPLEMENTATION OF SOFT COMPUTING TECHNIQUE ON BALL BALANCER SYSTEM

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CANDIDATE'S DECLARATION

I, Apoorv Surana, Roll No. 2K19/C&I/01, student of M.Tech. (Control & Instrumentation), hereby declare that the project Dissertation entitled "Design and Implementation of Soft Computing Technique on Ball Balancer System" which is submitted by me to the Department of Electrical Engineering, 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 Project Dissertation titled "Design and Implementation of Soft Computing Technique on Ball Balancer System" which is submitted by Apoorv Surana, Roll No. 2K19/C&I/01, Department of Electrical Engineering, 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 project work 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.

Place: New Delhi
Date: 22/10/2021

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SUPERVISOR
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ABSTRACT

This project presents design and control of a 2D Ball Balancer Arrangement using PID controller tuned with Particle Swarm Optimization (PSO), Simulated Annealing (SA) and Genetic algorithm (GA). The project also compares the results of proposed control techniques with Classical PID controller and Fuzzy logic controller (FLC). The Ball Balancer Arrangement is a non-linear system with complex plant transfer function. Classical control methods such as Classical PID and Fuzzy logic controller are also able to control the Ball Balancer Arrangement but manual tuning and rule base optimization is slow and inefficient. PSO, SA and GA are heuristic algorithms which can find the best solution without the need of human experience. Heuristic algorithms improve the solution in every iteration based on cost function minimization. The comparative analysis of PSO, SA and GA tuned PID and their comparison with Classical PID and FLC is shown in terms of delay time, rise time, and settling time and the study demonstrates that PSO tuned PID controller performs the best. The designing and simulation have been successfully performed in MATLAB/ Simulink environment.

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ABBREVIATIONS

S. No.	Abbreviation	Description
1	PID	Proportional, Integral and Derivative
2	NiF	Neuro-inference Fuzzy
3	NiF-P	Neuro-inference Fuzzy-Proportional
4	PSO	Particle Swarm Optimization
5	SA	Simulated Annealing
6	GA	Genetic Algorithm
7	FLC	Fuzzy Logic Controller
8	ISE	Integral Square Error
9	IAE	Integral Absolute Error
10	ITSE	Integral Time Square Error
11	ITAE	Integral Time Absolute Error

LIST OF SYMBOLS

S. No.	Ball Balancer Arrangement Variables	Symbol
1	Ball Position (Arm distance from Ball)	y
2	Servo gear angle with horizontal plane	θ
3	Applied voltage to servo for actuation	v_m
4	Mass of ball	m
5	Force due to gravity	$F_{x,t}$
6	Inertial force of ball	$F_{x,r}$
7	Gravitational constant	g
8	Plate angle with horizontal plane	β
9	Ball torque	τ
10	Radius of the ball	r
11	Moment of inertia of the ball	J
12	Length of plate	L
13	Distance between gear shaft and coupling joint	x

S. No.	Controller Variables	Symbol
1	Proportional Gain	K_P
2	Integral Gain	K_I
3	Derivative Gain	K_D
4	Particle	P_i
5	Error	e

CHAPTER 1: INTRODUCTION

1.1. INTRODUCTION

The Ball Balancer Arrangement is a non-linear system with complex plant transfer function. The Ball Balancer Arrangement in a 2-dimensional configuration has been a topic of research for a long time. The Ball Balancer Arrangement has found application in real world from being used as benchmark control lab equipment for research [1].

1.2. BALL BALANCER SYSTEM

The 2-dimensional Ball Balancer Arrangement consists of a plate mounted upon perpendicular shafts which can be moved using geared servo motors. These motors are actuated by applying appropriate voltage to keep the platform horizontally stable. The system in real world takes feedback from a digital camera sensor mounted above the plate to track motion of ball using image processing techniques. The modelling of Ball Balancer Arrangement is done using equations and model [2]. The Ball Balancer Arrangement diagram is shown in Fig. 1.

1.3. BALL BALANCER ARRANGEMENT DIAGRAM

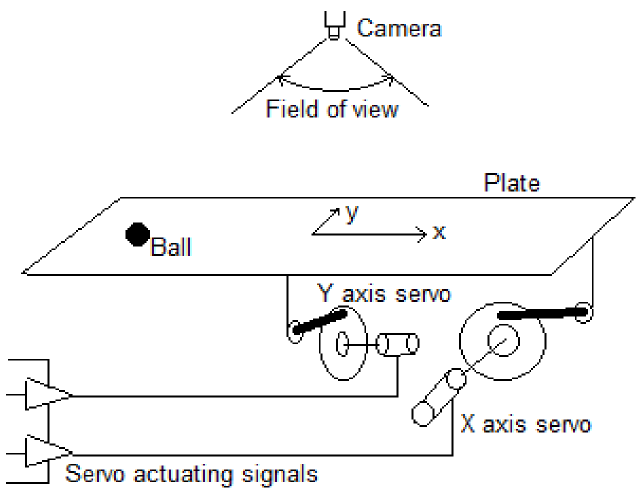

Fig. 1. Ball balancer arrangement diagram.

1.4. CONTROLLER CONFIGURATIONS

Various control techniques have been applied on Ball Balancer Arrangement in the past but there is still room for improvement. Fuzzy logic controller has been applied to the system in the past with improved results compared to Classical PID control [3]. Classical PID control has also been compared with NiF Control [4] and NiF-P Control [5]. Performance of all these techniques is dependent on the implementation and tuning expertise of designer. Application of heuristic tuning methods for PID controller for control of Ball Balancer Arrangement is a research gap. In this project, PSO, SA and GA tuned PID controller [6-8] has been applied and results are compared with Classical PID controller and FLC [9].

Most of the real-world systems are highly non-linear in nature and designing of a control mathematically for such systems prove to be difficult. Heuristically tuned PID controller solves this problem by finding an optimal solution or tuning parameter based on self-experience rather than relying on human expertise. PSO optimization algorithm is a heuristic solver which is based on evolution and it can solve complex problems with simple iterations taking inspiration from nature of birds flocking and fish schooling [10]. Simulated annealing is another heuristic algorithm which is inspired by the heating and cooling behavior of a metal to find optimal solution [11]. Genetic algorithm is one such algorithm which mimics the evolution process of living organism. It starts with a set of population and evolves them upon certain operations after which selection for best member is done and this process is repeated until the best evolved solution is found. The evolution process is random within the population to ensure equal opportunity amongst the population [12]. Heuristic tuning methods require defining a cost function which in case of a controller is error. Interpretation of error for PSO, SA and GA tuned PID controller can be done using various methods. There are four key parameters to choose as cost from error. These parameters are ISE, IAE, ITSE, ITAE [13-16].

1.5. OBJECTIVES OF THE PROJECT

The objective of the project is to design controller configuration for Ball Balancer Arrangement which offers following features:

a) Fast response time corresponding to change in set point for position of ball or its any other free to move entity.
b) Easy adaptability according to design specifications of system such as servo motor torque, ball weight, plate dimensions etc.
c) No oscillations in the trajectory induced due to control action.
d) Efficient trajectory selection so that desired position can be achieved using minimum actuation voltage.

This is achieved by using heuristic algorithms which can learn from the changes in system and adapt accordingly to find optimal control parameters for controller.

1.6. OUTLINE OF THE THESIS

The thesis is presented into chapters as follows.

Chapter 1 introduces the Ball Balancer Arrangement and controller designs previously applied on the system. Chapter 2 elaborates the design and modelling of Ball Balancer Arrangement in detail. Chapter 3 describes the Classical PID controller, FLC and PSO, SA and GA tuned PID controller for Ball Balancer Arrangement. Chapter 4 presents simulation Results and Discussion. The Conclusion is presented in Section 5 followed by references.

CHAPTER 2: BALL BALANCER CONFIGURATION

2.1. INTRODUCTION

The modelling of Ball Balancer Arrangement is required to simulate and analyze the performance of system with PID controller tuned using various algorithm. The modelling of Ball Balancer Arrangement has been done with the equations obtained from [2]. This model accurately represents the system with its nonlinearities. The designing of the model is explained in the below mentioned sections.

2.2. BALL BALANCER ARRANGEMENT PLANT TRANSFER FUNCTION

As the 2D model is decoupled, the X axis and Y axis plant dynamics can be modelled independently. Thus, the system can be represented precisely by only 1D plant dynamics with accuracy. Fig. 2 represents the free body diagram of 1D Ball Balancer Arrangement with the used notation and all the forces acting upon the ball.

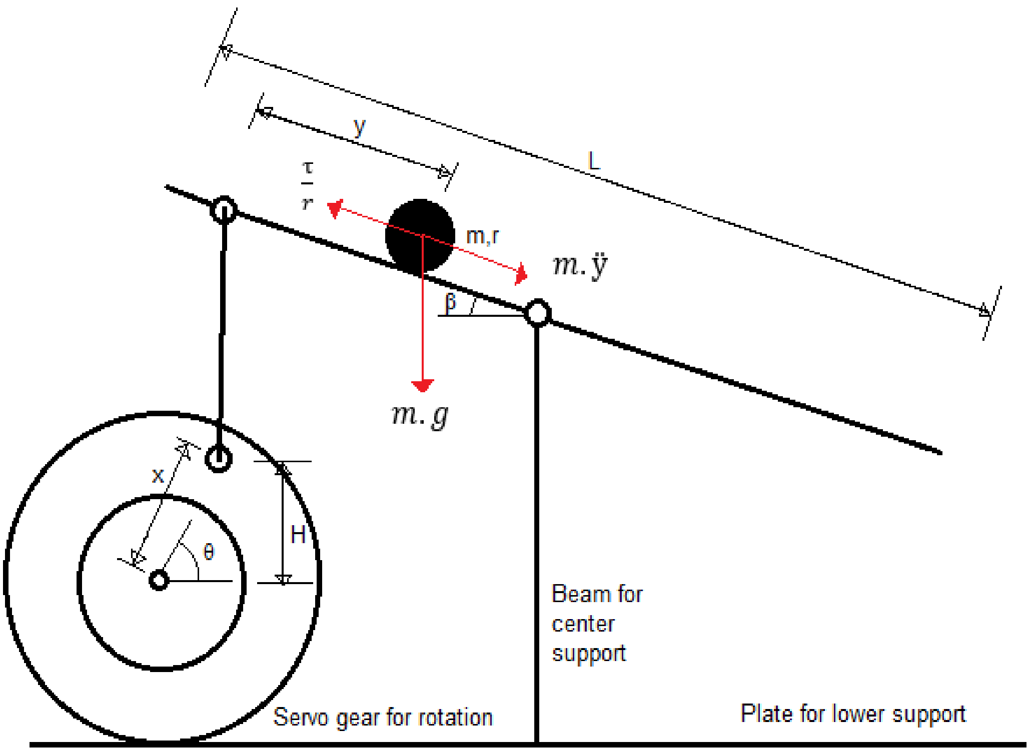

Fig. 2. Ball Balancer arrangement free body diagram.

Fig. 3 represents the 1D plant transfer function and servo closed loop control block which is same for both X and Y axis due to similar dynamics.

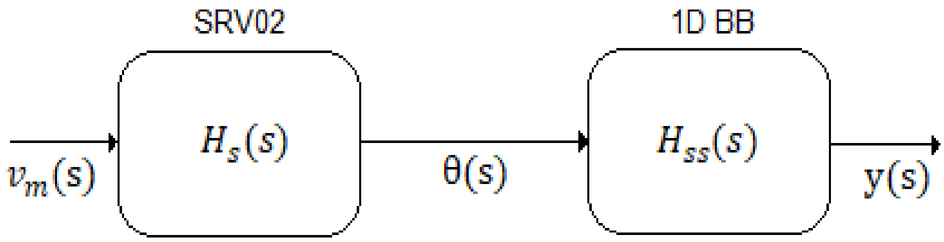

Fig. 3. Ball Balancer Arrangement 1D transfer function diagram.

The notation used to further describe the transfer function is as follows:

y = Ball Position (Arm distance from Ball)

θ = Servo gear angle with horizontal plane

v_m = Applied voltage to servo for actuation

The Ball Balancer plant model transfer function is further described in (1) and (2).

$$H_{ss}(s) = \frac{y(s)}{\theta(s)} \tag{1}$$

$$H_s(s) = \frac{\theta(s)}{v_m(s)} \tag{2}$$

Eq. (1) describes relation between ball position and servo gear angle and (2) describes the relation of servo gear angle to the applied actuation voltage.

2.3. NONLINEAR EQUATIONS OF MOTION RELATIVE TO BALL BALANCER ARRANGEMENT

The force balance equation obtained from free body diagram shown in Fig. 1 is as follows:

$$m.\ddot{y} = \sum F = F_{x,t} - F_{x,r} \tag{3}$$

where 'm' is the mass of ball, '$F_{x,t}$' is the force due to gravity and '$F_{x,r}$' is the inertial force of ball. Friction constants and viscosity are neglected. The force experienced by the ball is further described by (4) and (5).

$$F_{x,t} = m.g.\sin\beta \tag{4}$$

$$F_{x,r} = \frac{\tau}{r} \tag{5}$$

where 'g' is gravitational constant, 'β' is the plate angle with horizontal plane, 'τ' is the ball torque and 'r' is radius of the ball. The final equation obtained after substitution (6).

$$\ddot{y} = \frac{g.r^2.sin\beta.m}{J+r^2.m} \tag{6}$$

where 'J' is the moment of inertia of the ball.

2.4. MOTION EQUATION RELATIVE TO SERVO ANGLE

The relation between motion of the ball and servo angle is derived in this section. The servo gear angle and plate angle relation is given by (7).

$$\sin\beta = \frac{2.x.\sin\theta}{L} \tag{7}$$

where 'L' is the length of plate and 'x' is the distance between gear shaft and coupling joint. On further substitution, relation (8) is obtained.

$$\ddot{y} = \frac{2.m.g.\mathrm{x}.r^2\sin\theta}{L(mr^2+J)} \tag{8}$$

The obtained relation can be linearized by approximating $\sin\omega \approx \omega$. Thus, the final linear relation obtained is (9).

$$\ddot{y} = \frac{2.m.g.\theta.\mathrm{x}.r^2}{L(mr^2+J)} \tag{9}$$

2.5. CONCLUSION

The Ball Balancer model is successfully modelled and simulated on MALTAB with all the nonlinear equations representing the system.

CHAPTER 3: INTELLIGENT CONTROLLERS

3.1. INTRODUCTION

The proposed PSO, SA and GA tuned PID controller are compared with Classical PID controller and FLC so that conclusive analysis can be done. The designed controllers are applied on the Ball Balancer Arrangement as shown in the combined block diagram in Fig. 4 to obtain the results for comparison.

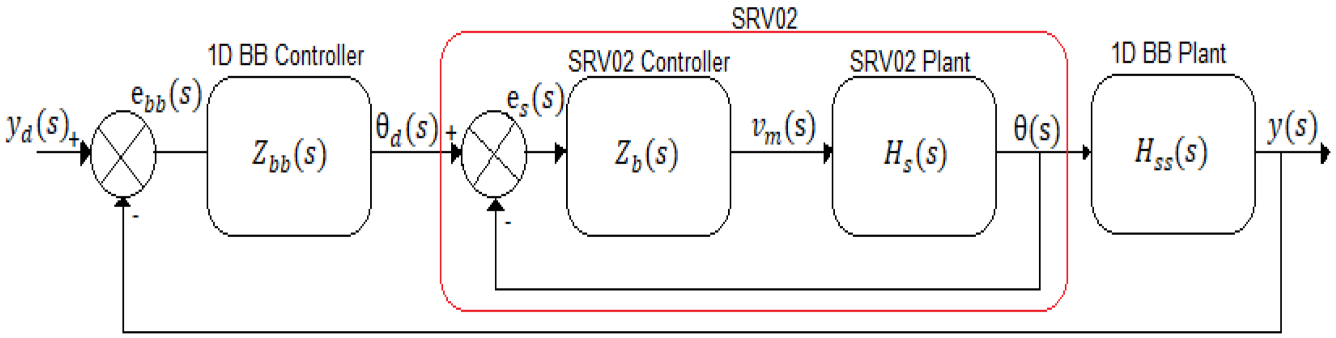

Fig. 4. Combined Block diagram with controller structure.

3.2. CLASSICAL PID CONTROLLER

3.2.1. INTRODUCTION

The Classical PID controller constitutes proportional, integral and derivative interpretation of error which is essential to control the second order plant transfer function in order to minimize error and oscillations in the output. The block diagram of Ball Balancer Arrangement with Classical PID controller is given in Fig. 5.

3.2.2. PROPERTIONAL, INTEGRAL AND DERIVATIVE

The relation between PID controller output and error in position of ball is shown in (10).

$$\theta_d(s) = \left[K_P + \frac{K_I}{s} + K_D . s\right] . (y_d(s) - y(s)) \quad (10)$$

where 'K_P', 'K_I' and 'K_D' are proportional, integral and derivative gain constants [17].

The PID Gain values K_P, K_I and K_D taken for the controller are 5.1, 0.02 and 0.025. The values are chosen after multiple iterations and tuning each parameter for improved characteristics based on transient performance measures [18].

3.2.3. COMBINED SYSTEM BLOCK DIAGRAM

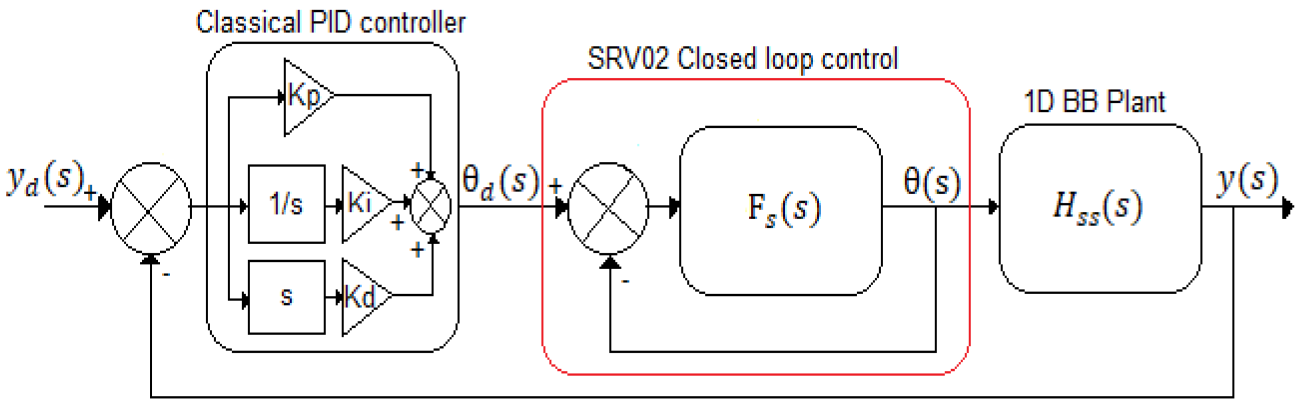

Fig. 5. Combined Ball Balancer Arrangement with Classical PID controller.

3.3. FUZZY LOGIC CONTROLLER

3.3.1. INTRODUCTION

Classical fuzzy logic controller is a heuristic controller which incorporates human like behavior in decision making. Thus, it is easier to implement on nonlinear systems with complex model. Fig. 8 shows the block diagram of Ball Balancer Arrangement combined with Fuzzy logic controller.

3.3.2. FUZZY LOGIC CONTROLLER

Fuzzy logic controller is a controller which incorporated human expertise into the controller logic using linguistic variables and user specified fuzzification methods [19] that are used to establish relation between input and linguistic variables. Certain fuzzy rules [20] are also defined by the user which are used by the controller for decision making to produce a fuzzy output based on user knowledge.

Defuzzifcation methods [21] are then applied to the fuzzy output to get a usable output, which can be used in real world and represents the linguistic instructions defined by user into an output signal which performs similarly. This controller output obtained is crisp value [22] in nature.

3.3.3. FUZZY LOGIC CONTROLLER RULE BASE AND SURFACE VIEW

The user defined rule base [23] for Fuzzy logic controller is shown in the Fig. 6. The surface view [24] generated corresponding to the rule base is shown in Fig. 7.

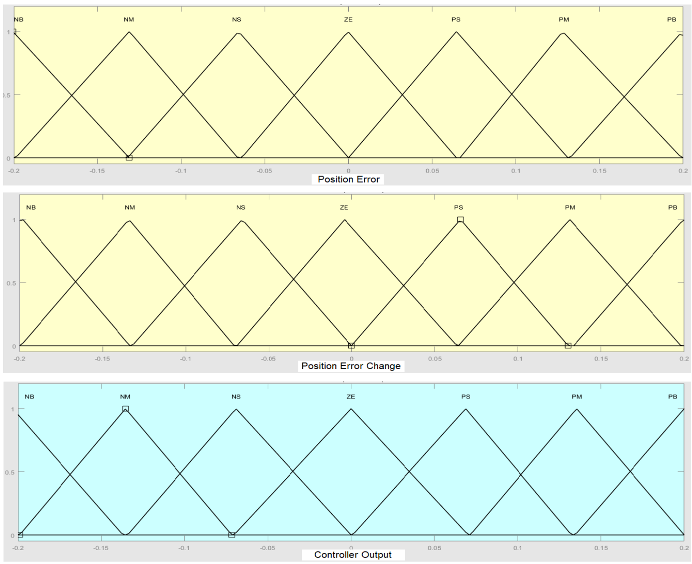

Fig. 6. Fuzzy logic controller rule base.

Table I. Fuzzy logic controller rule base table.

error/change in error	**PB**	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**
PB	PB	PB	PB	PB	PB	PM	ZE
PM	PB	PM	PM	PM	PM	PS	ZE
PS	PB	PS	PM	PS	ZE	ZE	NS
ZE	PM	PM	PS	ZE	NS	NM	NM
NS	PS	ZE	ZE	NS	NM	NS	NB
NM	ZE	NS	NM	NM	NM	NM	NB
NB	ZE	NM	NB	NB	NB	NB	NB

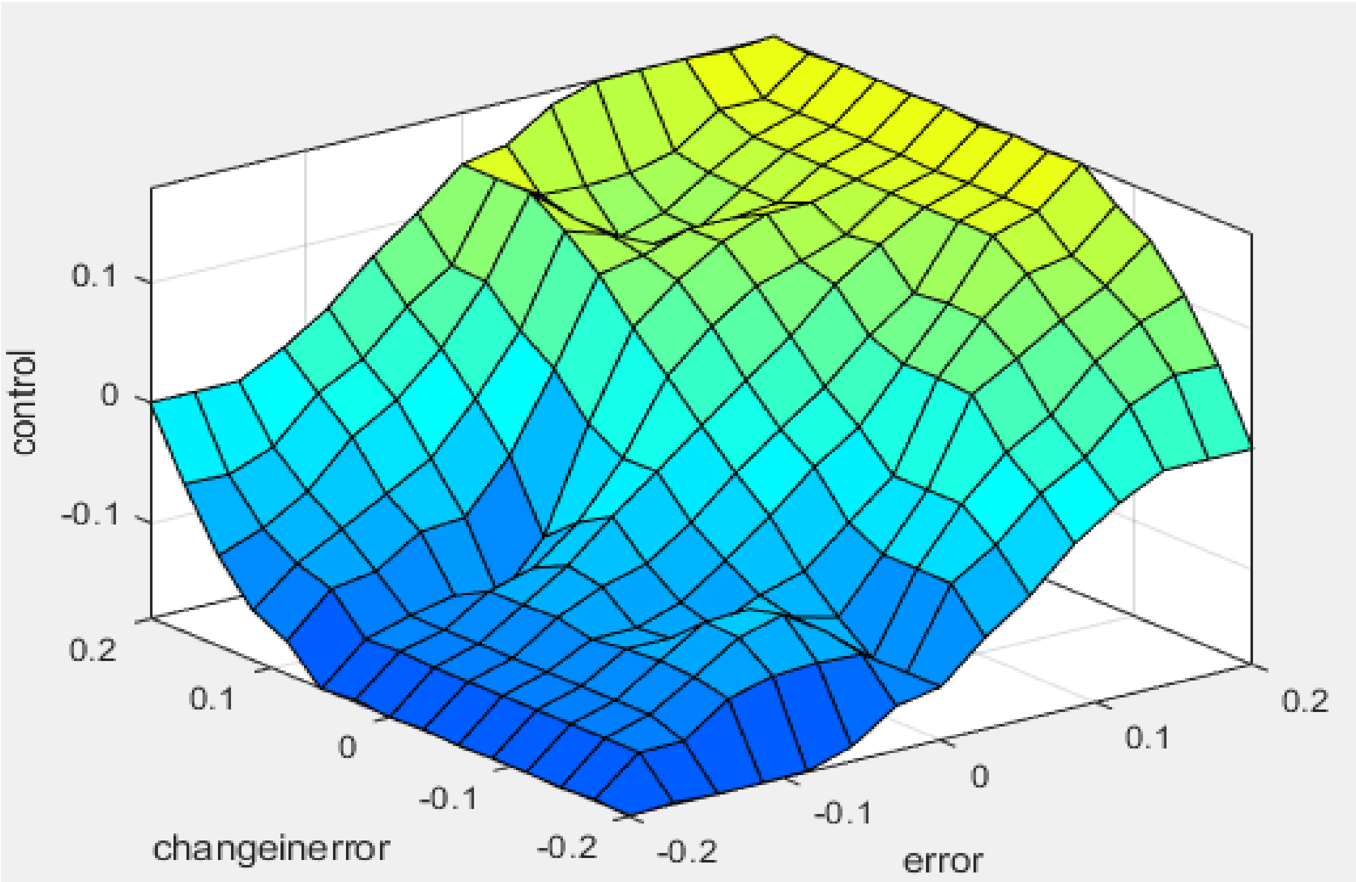

Fig. 7. Fuzzy logic controller surface view.

3.3.4. COMBINED SYSTEM BLOCK DIAGRAM

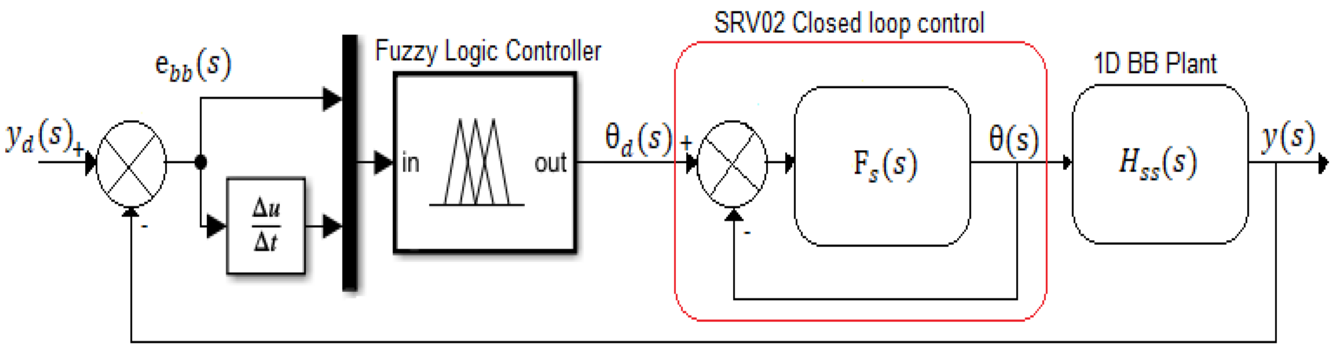

Fig. 8. Combined Ball Balancer Arrangement block diagram with Fuzzy logic controller.

3.4. PSO TUNED PID CONTROLLER

3.4.1. INTRODUCTION

PSO optimization algorithm is a heuristic solver which is based on evolution and it can solve complex problems taking inspiration from nature of birds flocking and fish schooling.

3.4.2. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization algorithm is a heuristic optimization technique which starts with a population of solutions or particles. The particles converge to an optimal solution through a series of iteration based on self-experience and experience of neighboring particles. The equations shown are taken from paper [6]. The PSO algorithm flow chart is shown in Fig. 9.

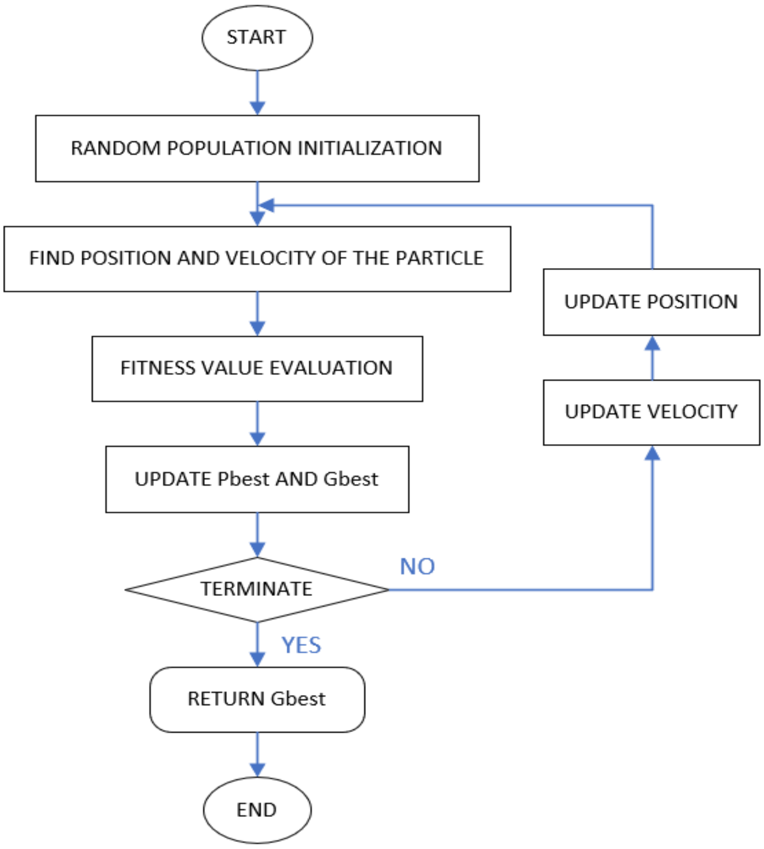

Fig. 9. PSO Algorithm flow chart.

The Velocity vector for each particle is calculated in each iteration using (11).

$$V_i(n+1) = W.V(n) + c_1 r_1 (P_{best\ i} P_i(n))\ (11) \quad + c_2 r_2 (G_{best\ i} - P_i(n)) \tag{11}$$

The range of obtained velocity after each iteration is given by (12) and (13).

$$V_{max} = 0.2(Var_{max} - Var_{min}) \tag{12}$$

$$Var_{max} = -Var_{min} \tag{13}$$

where Var_{max} and Var_{min} is Particle variable range.
The calculated velocity for a particle is then used to calculate new position of that particle (14). The process is repeated for complete population for multiple iterations.

$$P_i(n+1) = P_i(n) + V_i(n+1) \tag{14}$$

3.4.3. PID TUNED USING PSO

Since the PID controller has three varying parameters to achieve the desired control, each particle in swarm contains three variables as shown in (15).

$$P_i = [K_P, K_I, K_D] \tag{15}$$

PSO tuning uses a cost function in order to identify best particles so that the cost can be minimized. Hence, cost must be chosen as error. There are multiple parameters to interpret the error for cost. These parameters are ISE, IAE, ITSE, ITAE and can be obtained from (16)-(19). The detailed results from each parameter as Cost Function are shown in chapter 4 in detail. The block diagram of Ball Balancer Arrangement along with PID controller tuned with PSO is shown in Fig. 10.

$$ISE = \int_0^\infty e^2(t)dt \tag{16}$$

$$IAE = \int_0^\infty |e(t)|dt \tag{17}$$

$$ITSE = \int_0^\infty te^2(t)dt \tag{18}$$

$$ITAE = \int_0^\infty t|e(t)|dt \tag{19}$$

3.4.4. COMBINED SYSTEM BLOCK DIAGRAM

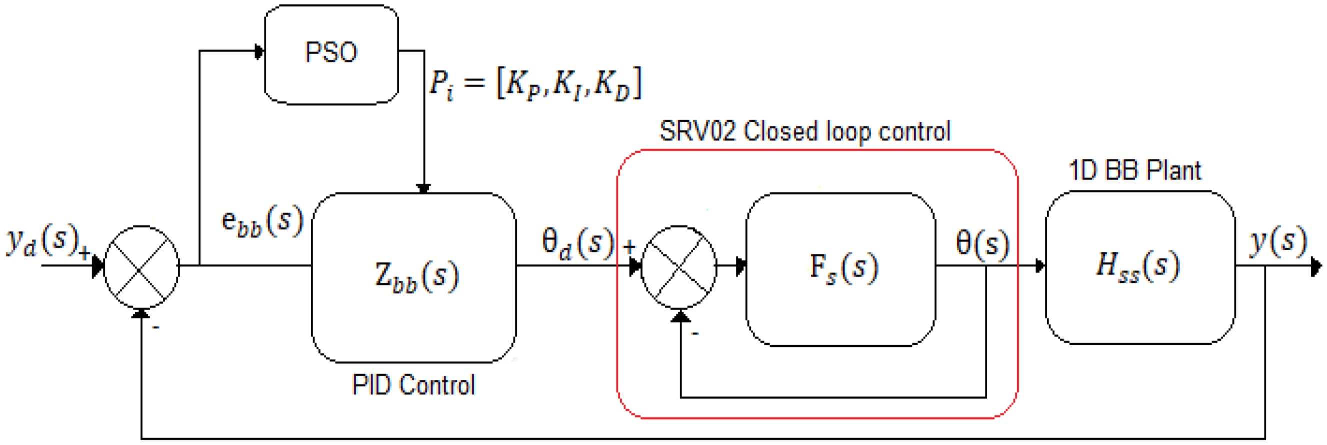

Fig. 10. Combined Ball Balancer Arrangement block diagram with PSO tuned PID controller.

3.5. SA TUNED PID CONTROLLER

3.5.1. INTRODUCTION

Simulated annealing is another heuristic algorithm inspired by the annealing process which is heating and cooling behavior of a metal to a minimum energy state solid, and finds an optimal solution in a user defined search solution space using probabilistic distribution similar to a metal temperature profile.

3.5.2. SIMULATED ANNEALING

Simulated annealing algorithm starts with a population in a user defined space and finds new solution randomly and moves to new point in every iteration. The new point is found using probabilistic distribution similar to a temperature profile of metal.

Simulated annealing algorithm finds new points based on new points that have lower objective function value but some points increase the value of objective function. This ensures that the algorithm is not stuck in a local minima and it is able to find best solution overall. Simulated annealing is an optimization technique which is inspired from crystallization process of metals. SA finds a single point based solution by mimicking the thermodynamic process. Search for SA algorithm starts with an initial temperature T_0 which is chosen randomly. New solutions is generated in the neighborhood by altering the current solution. The new solution replaces the current solution if found better, else probabilistic selection is done.

The probability of acceptance of new solution follows the Metropolis criteria given by (20).

$$P(\Delta E) = \exp(-\frac{\Delta E}{K_B T}) \quad (20)$$

where $P(\Delta E)$ is probability of acceptance, ΔE is the difference between new and old solution, T is the temperature and K_B is Boltzmann's constant.

Acceptance for worse solutions decreases with decrease in temperature and the initial temperature should accept maximum alterations. The acceptance probability drop is controlled by cooling schedule. Boltzmann's logarithmic cooling schedule is among the various cooling schedules proposed over time. The cooling schedule is (21).

$$T_i = {}^{T_0}\!/_{\log i} \quad (21)$$

3.5.3. PID TUNED USING SA

Since the PID controller has three varying parameters to achieve the desired control, each population member contains three variables as shown in (22).

$$P_i = [K_P, K_I, K_D] \quad (22)$$

SA tuning uses a cost function in order to identify best particles so that the cost can be minimized. Hence, cost must be chosen as error.

There are multiple parameters to interpret the error for cost. These parameters are ISE, IAE, ITSE, ITAE and can be obtained from (23)-(26). The detailed results from each parameter as Cost Function are shown in chapter 4 in detail. The block diagram of Ball Balancer Arrangement along with PID controller tuned with SA is shown in Fig. 11.

$$ISE = \int_0^\infty e^2(t)dt \tag{23}$$

$$IAE = \int_0^\infty |e(t)|dt \tag{24}$$

$$ITSE = \int_0^\infty te^2(t)dt \tag{25}$$

$$ITAE = \int_0^\infty t|e(t)|dt \tag{26}$$

3.5.4. COMBINED SYSTEM BLOCK DIAGRAM

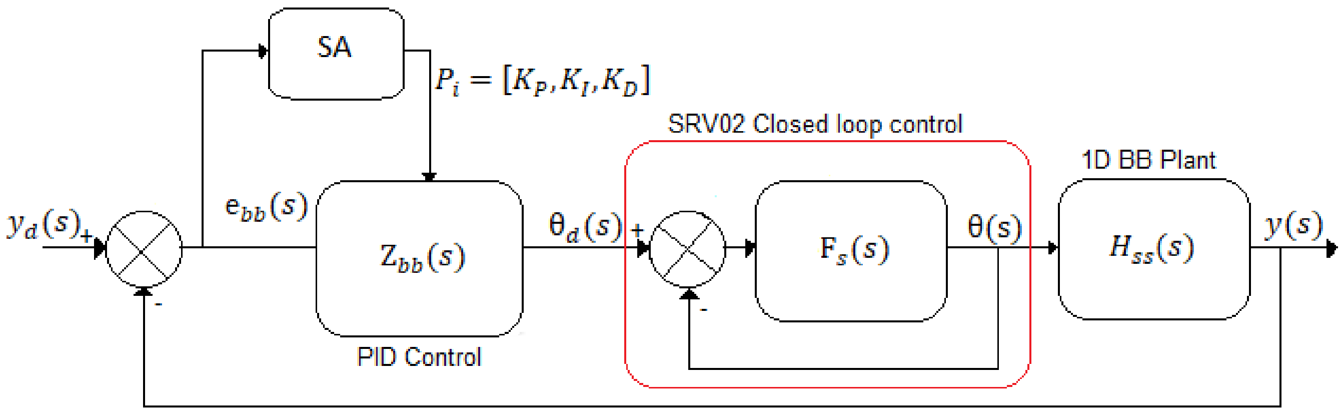

Fig. 11. Combined Ball Balancer Arrangement block diagram with SA tuned PID controller.

3.6. GA TUNED PID CONTROLLER

3.6.1. INTRODUCTION

Genetic algorithm is one such algorithm which mimics the evolution process of living organism. It starts with a set of population and evolves them upon certain operations after which selection for best member is done and this process is repeated until the best evolved solution is found.

3.6.2. GENETIC ALGORITHM

GA is a stochastic search algorithm that mimics the evolution process of natural living organisms. The algorithm starts with an initial population and calculation of fitness value is done using cost function. Evolution of the initial population is performed upon selection, crossover and mutation operations after which, offspring are obtained. The process of evolution is repeated until convergence is obtained among majority of offspring and the fitness value is acceptable.

Many parameters affect the performance of algorithm such as probability of crossover, mutation and size of population. All of these parameter are user defined and depends on the complexity of objective function, small size of population always leads to poor evolution and results while a large size of population takes toll on computation power. Thus, an optimal population size needs to be chosen depending on the complexity of the function to be optimized.

3.6.3. PID TUNED USING GA

Since the PID controller has three varying parameters to achieve the desired control, each population member contains three variables as shown in (27).

$$P_i = [K_P, K_I, K_D] \tag{27}$$

GA tuning uses a cost function in order to identify best particles so that the cost can be minimized. Hence, cost must be chosen as error.

There are multiple parameters to interpret the error for cost. These parameters are ISE, IAE, ITSE, ITAE and can be obtained from (28)-(31). The detailed results from each parameter as Cost Function are shown in chapter 4 in detail. The block diagram of Ball Balancer Arrangement along with PID controller tuned with GA is shown in Fig. 12.

$$ISE = \int_0^\infty e^2(t)dt \tag{28}$$

$$IAE = \int_0^\infty |e(t)|dt \tag{29}$$

$$ITSE = \int_0^\infty te^2(t)dt \tag{30}$$

$$ITAE = \int_0^\infty t|e(t)|dt \tag{31}$$

3.6.4. COMBINED SYSTEM BLOCK DIAGRAM

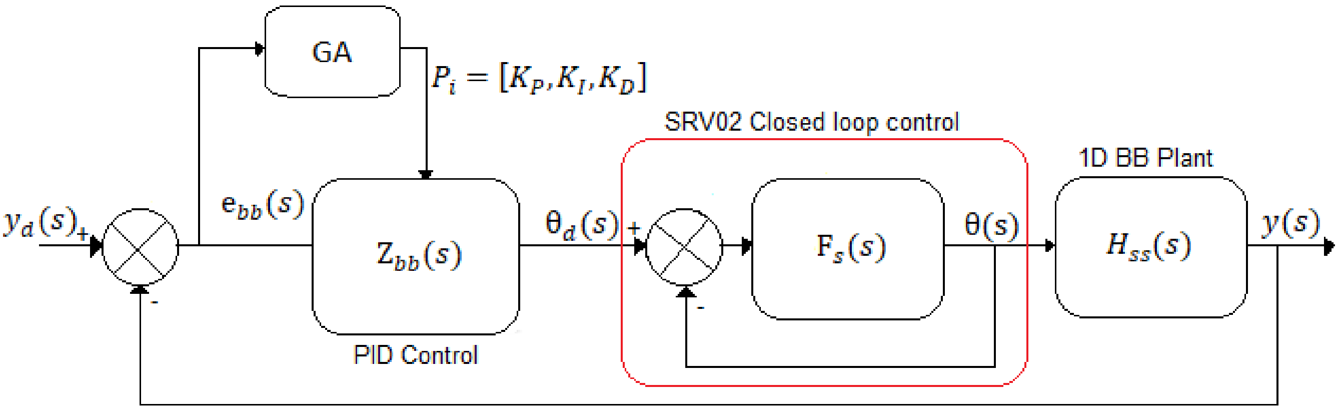

Fig. 12. Combined Ball Balancer Arrangement block diagram with GA tuned PID controller.

3.7. CONCLUSION

The Ball Balancer controllers are successfully modelled using heuristic algorithms and optimized to the purpose.

CHAPTER 4: RESULTS & DISCUSSION

4.1. PSO, SA AND GA TUNED PID CONTROLLER RESULTS

4.1.1. PSO TUNED PID CONTROLLER RESULTS

The PSO algorithm is run for multiple iterations with ISE, IAE, ITSE, ITAE as cost functions and the optimized PID controller gains are shown in Table II. These controller gains values are used with PID controller individually and comparison is made.

Table II. PID Gain Values from PSO for IAE, ITSE, ITSE, ITAE.

Cost Function	**K_P**	**K_I**	**K_D**
ISE	7.8889	24.3045	0.0032
IAE	2.4062	0.1719	0.0086
ITSE	0.0003	1.7010	36.9494
ITAE	0.0121	27.4363	27.8200

The error parameters ISE, IAE, ITSE, ITAE obtained during each optimization with one of them being cost function is shown in Table III.

Table III. ISE, IAE, ITSE, ITAE values obtained for different cost functions in PSO optimization.

Cost Function	**ISE**	**IAE**	**ITSE**	**ITAE**
ISE	0.0017	0.0600	0.1397	0.0636
IAE	0.0024	0.05961	0.1481	0.0470
ITSE	0.0485	0.9061	-129.2	-7.3310
ITAE	0.1480	1.4120	-99.85	-5.0280

The ITSE and ITAE values being negative for ITSE, ITAE cost functions indicate divergence from optimal solution which signifies that ITSE and ITAE parameters as cost function is not fit for optimization of Ball Balancer Arrangement.

This result is also reflected in simulation results in Fig. 13 when Ball Balancer Arrangement is simulated using PID gain values shown in Table II.

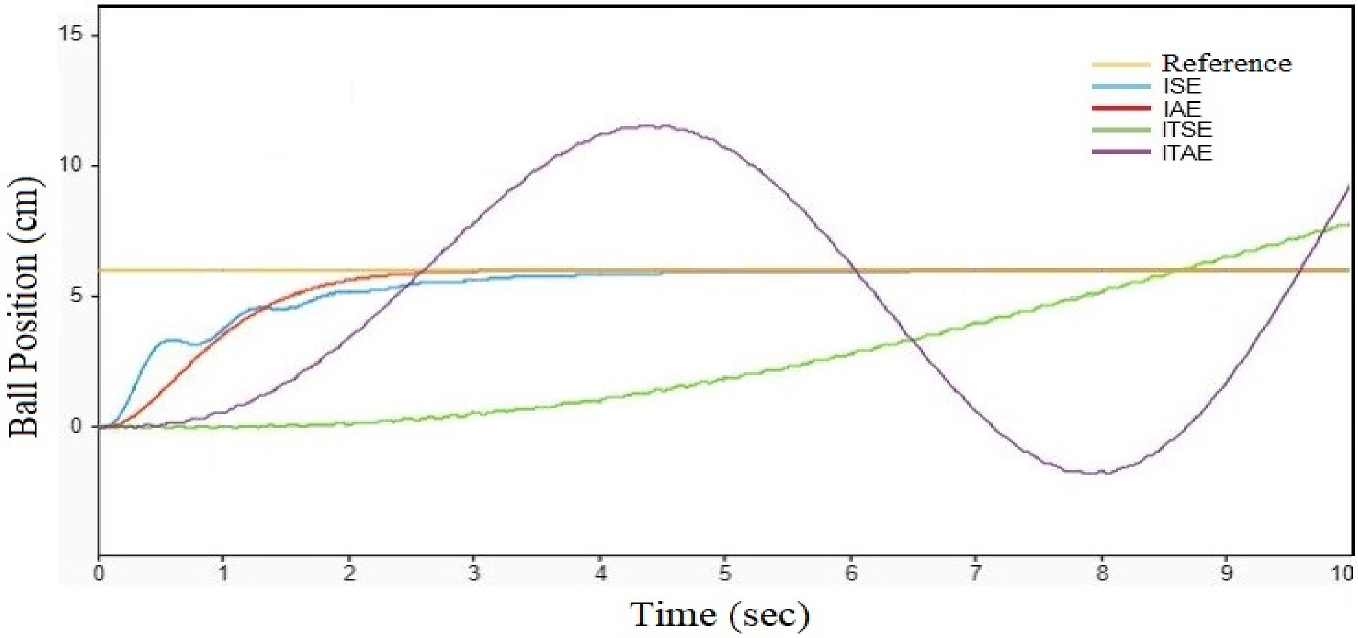

Fig. 13. Ball position output for PID controlled Ball Balancer Arrangement with PSO tuned gains with cost functions ISE, IAE, ITSE, ITAE.

The optimization results obtained from IAE parameter as cost function gives best ball trajectory as evident from the Ball position graph above. So, tuning parameters from IAE based optimization is selected and results are compared with Classical controlling methods in next section.

4.1.2. SA TUNED PID CONTROLLER RESULTS

The SA algorithm is run for multiple iterations with ISE, IAE, ITSE, ITAE as cost functions and the optimized PID controller gains are shown in Table IV. These controller gains values are used with PID controller individually and comparison is made.

Table IV. PID Gain Values from SA for IAE, ITSE, ITSE, ITAE.

Cost Function	K_P	K_I	K_D
ISE	4.0014	0.9847	0.0070
IAE	16.4154	0.5470	6.5440
ITSE	0.0050	14.4777	40.3894
ITAE	0.2140	0.5416	14.1178

The error parameters ISE, IAE, ITSE, ITAE obtained during each optimization with one of them being cost function is shown in Table V.

Table V. ISE, IAE, ITSE, ITAE values obtained for different cost functions in SA optimization.

Cost Function	ISE	IAE	ITSE	ITAE
ISE	0.0011	0.0462	0.3268	0.1665
IAE	0.0021	0.4562	0.1659	0.4665
ITSE	2.4998	0.9691	-19.446	-95.650
ITAE	0.6594	1.3266	-45.55	-45.669

The ITSE and ITAE values being negative for ITSE, ITAE cost functions indicate divergence from optimal solution which signifies that ITSE and ITAE parameters as cost function is not fit for optimization of Ball Balancer Arrangement.

This result is also reflected in simulation results in Fig. 14 when Ball Balancer Arrangement is simulated using PID gain values shown in Table IV.

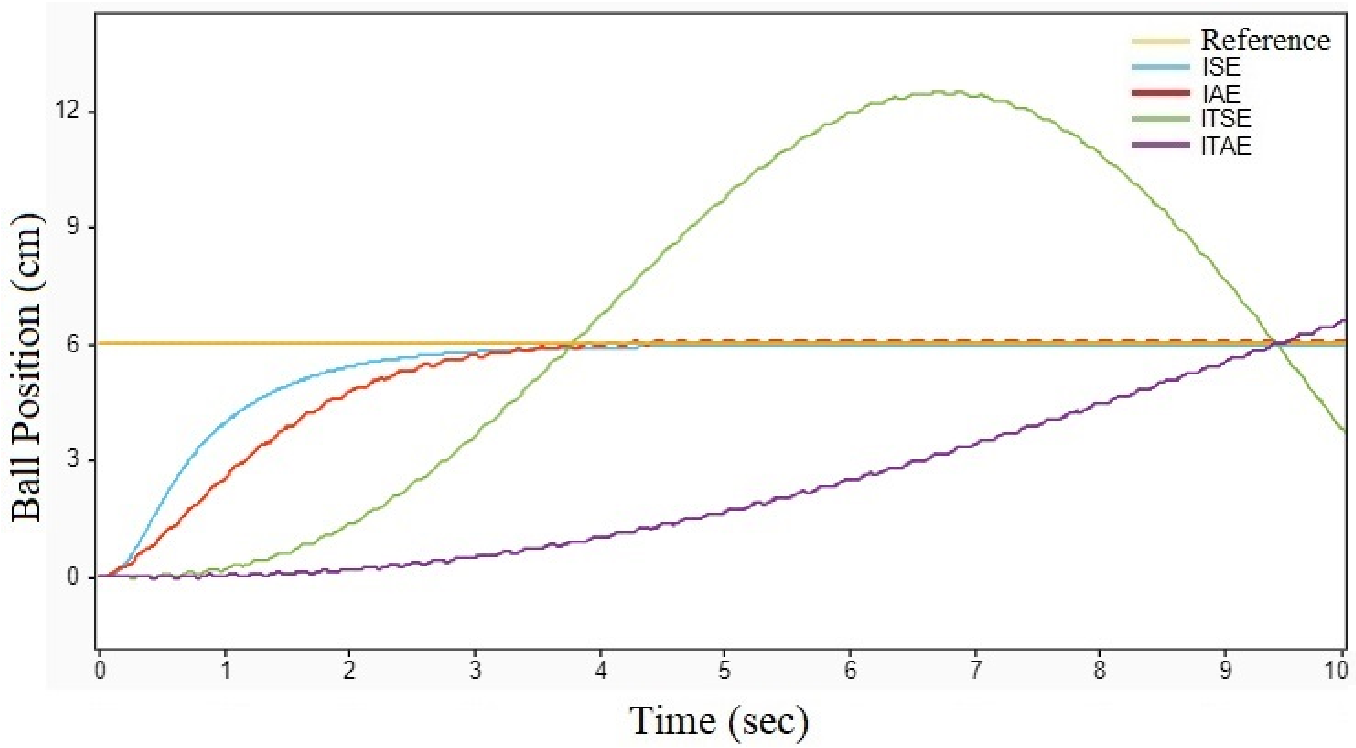

Fig. 14. Ball position output for PID controlled Ball Balancer Arrangement with SA tuned gains with cost functions ISE, IAE, ITSE, ITAE.

The optimization results obtained from ISE parameter as cost function gives best ball trajectory as evident from the Ball position graph above. So, tuning parameters from IAE based optimization is selected and results are compared with Classical controlling methods in next section.

4.1.3. GA TUNED PID CONTROLLER RESULTS

The GA algorithm is run for multiple iterations with ISE, IAE, ITSE, ITAE as cost functions and the optimized PID controller gains are shown in Table VI. These controller gains values are used with PID controller individually and comparison is made.

Table VI. PID Gain Values from GA for IAE, ITSE, ITSE, ITAE.

Cost Function	**K_P**	**K_I**	**K_D**
ISE	2.1229	0.0026	2.8754
IAE	0.1265	16.5877	0.0216
ITSE	0.1254	13.2459	5.5987
ITAE	2.9822	24.5567	0.6547

The error parameters ISE, IAE, ITSE, ITAE obtained during each optimization with one of them being cost function is shown in Table VII.

Table VII. ISE, IAE, ITSE, ITAE values obtained for different cost functions in GA optimization.

Cost Function	**ISE**	**IAE**	**ITSE**	**ITAE**
ISE	0.0065	0.0546	0.9876	0.1645
IAE	0.6595	0.4958	0.2364	0.4952
ITSE	0.0698	0.4589	-22.569	-4.982
ITAE	0.4589	1.5159	-44.37	-69.36

The ITSE and ITAE values being negative for ITSE, ITAE cost functions indicate divergence from optimal solution which signifies that ITSE and ITAE parameters as cost function is not fit for optimization of Ball Balancer Arrangement.

This result is also reflected in simulation results in Fig. 15 when Ball Balancer Arrangement is simulated using PID gain values shown in Table VI.

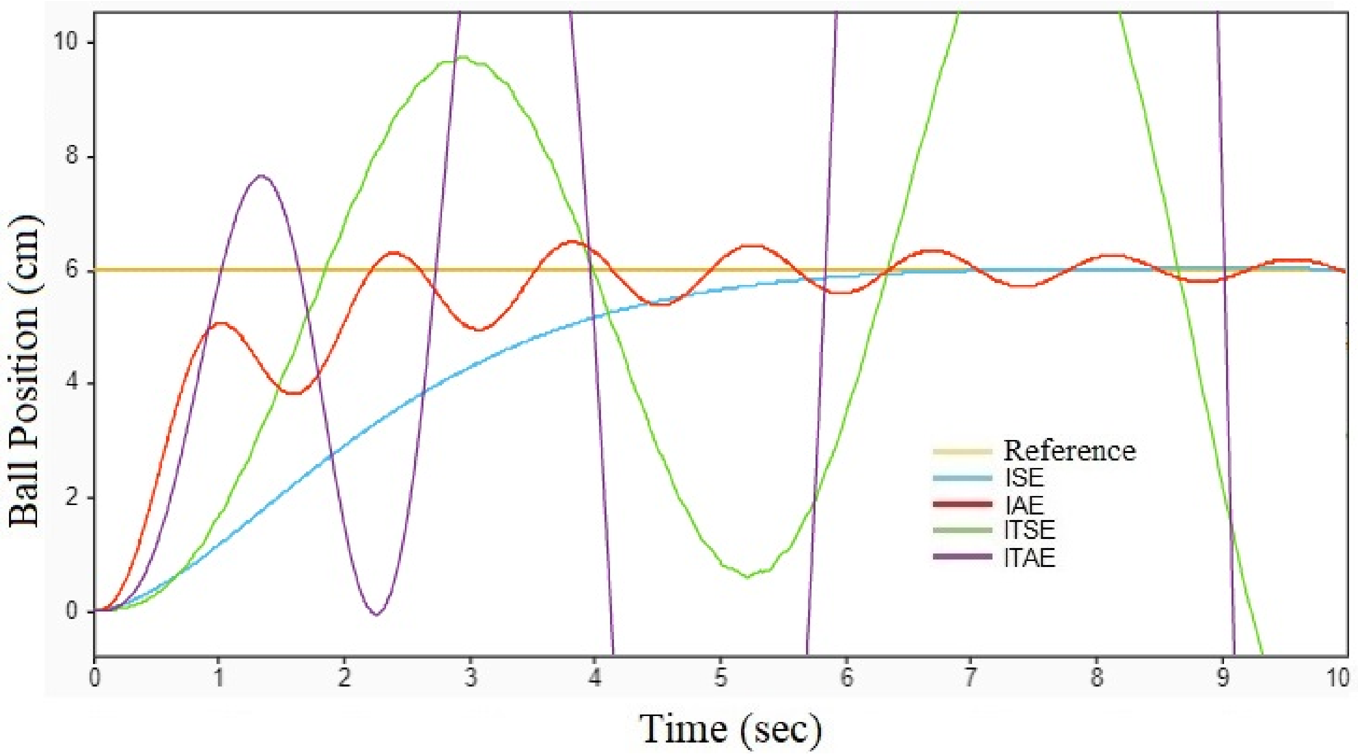

Fig. 15. Ball position output for PID controlled Ball Balancer Arrangement with GA tuned gains with cost functions ISE, IAE, ITSE, ITAE.

The optimization results obtained from ISE parameter as cost function gives best ball trajectory as evident from the Ball position graph above. So, tuning parameters from IAE based optimization is selected and results are compared with Classical controlling methods in next section.

4.2. PSO, SA AND GA TUNED PID CONTROLLER COMPARISON WITH CLASSICAL PID CONTROLLER AND FLC

The Ball position characteristics of Ball Balancer Arrangement is shown in Fig. 16. The reference position for ball is set to 6 cm. All controllers successfully reach set target but the trajectory is solely dependent on type of controller.

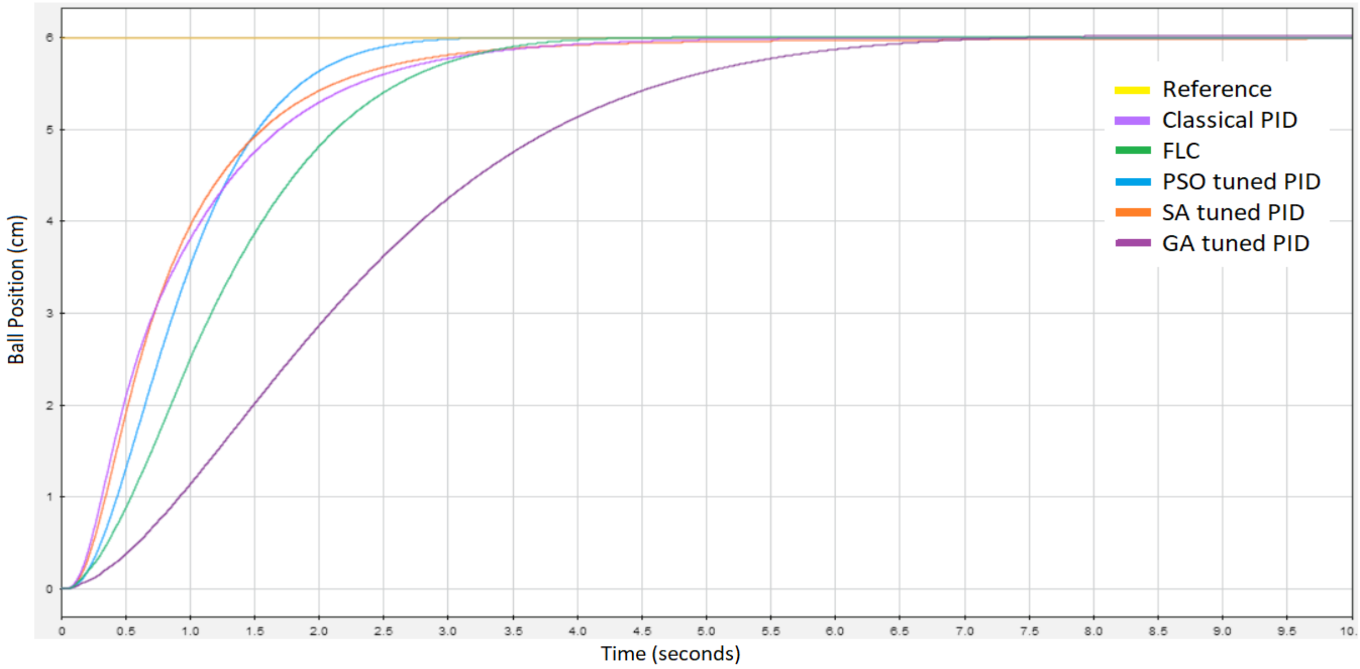

Fig. 16. Ball position characteristics of Ball Balancer Arrangement for PSO, SA, and GA tuned PID controller compared with Classical PID controller and FLC.

Table VIII. Time domain specifications of Ball position characteristics for Classical PID, FLC, PSO, SA and GA tuned PID controller.

Controller/ Specification	Delay Time	Rise Time	Settling Time
Classical PID	0.71 sec	5.45 sec	3.55 sec
FLC	1.17 sec	4.41 sec	3.42 sec
PSO tuned PID	0.87 sec	3.36 sec	2.43 sec
SA tuned PID	0.70 sec	7.65 sec	3.50 sec
GA tuned PID	2.06 sec	7.01 sec	5.95 sec

Time domain specifications are essential to understand the performance of controller based on ball position characteristics. Hence, the delay time, rise time and settling time of the obtained characteristics for Ball Position is shown in Table VIII.

The comparative study shows that PSO tuned PID controller performance is much better compared to Classical PID controller, FLC, SA and GA tuned PID controller in terms of ball position trajectory. While the delay time for PSO tuned PID controller is not the least, it has the least rise time and settling time which results in fastest overall response. GA tuned PID controller performs the worst amongst all the controllers with highest settling time. SA tuned PID controller and Classical PID controller are comparable in performance followed by FLC.

The Ball plate angle characteristics for Classical PID controller and FLC is compared with PSO, SA and GA tuned PID controller with Ball Balancer Arrangement is shown in Fig. 17. The GA tuned PID controller and FLC response contains oscillations in Ball plate angle characteristics which is unwanted as it represents oscillations in mechanical structure. Classical PID controller show most peaky angle response followed by SA tuned PID controller which corresponds to high settling time as observed in Table VII. PSO tuned PID controller response for Ball plate angle has no oscillations and peak angle is nearly half compared to Classical PID controller which translates to fastest rise time and settling time.

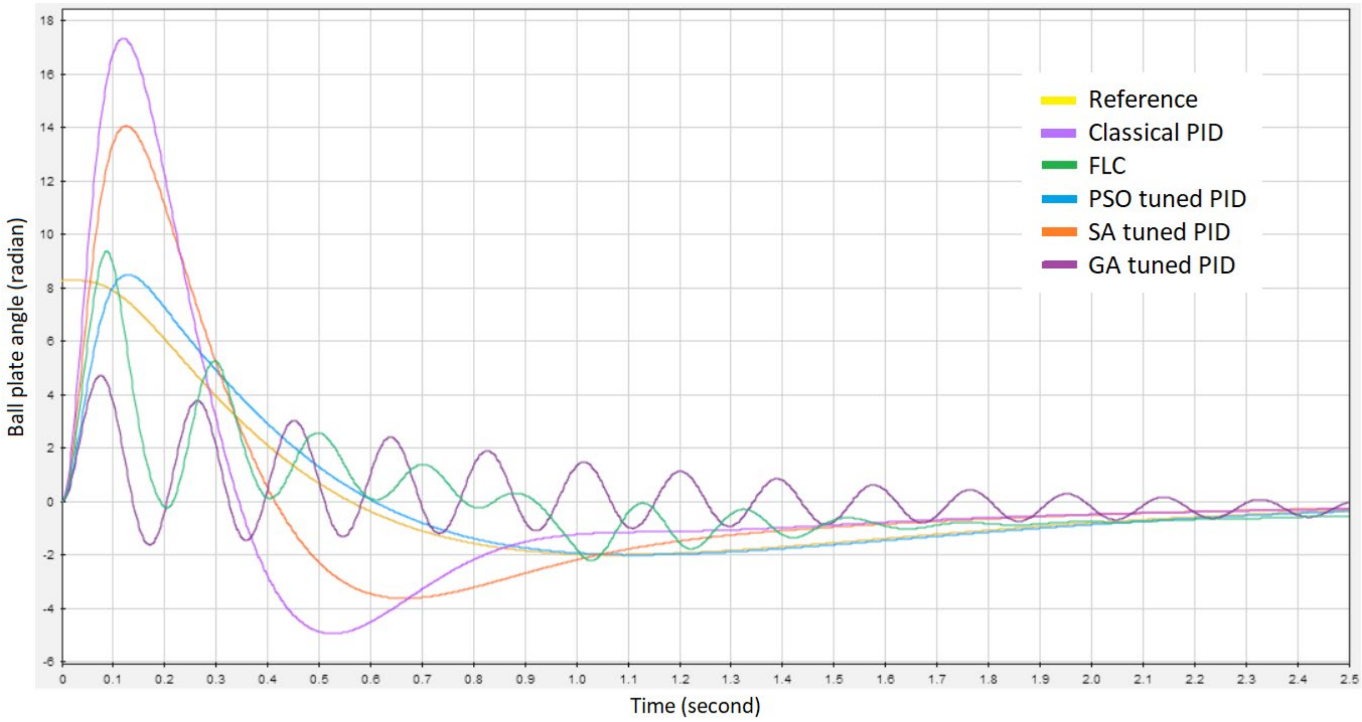

Fig. 17. Ball plate angle characteristics of Ball Balancer Arrangement for PSO, SA, and GA tuned PID controller compared with Classical PID controller and FLC.

The actuation voltage characteristics of Ball Balancer Arrangement for Classical PID and FLC controller compared with PSO, SA and GA tuned PID with Ball Balancer Arrangement are shown in Fig. 18. GA tuned PID controller and FLC actuation voltage response contains large oscillations which is unwanted and inefficient as it creates electrical stress on actuating device and oscillations in plate angle as seen in Fig 17.

Classical PID controller response has a peaky actuation voltage response but it is acceptable as there are no oscillations present. SA tuned PID controller actuation voltage characteristics are better than Classical PID controller but PSO tuned PID controller actuation voltage response show much smoother characteristics when compared to all the other controllers as it has least peak voltage and it does not contain any oscillations.

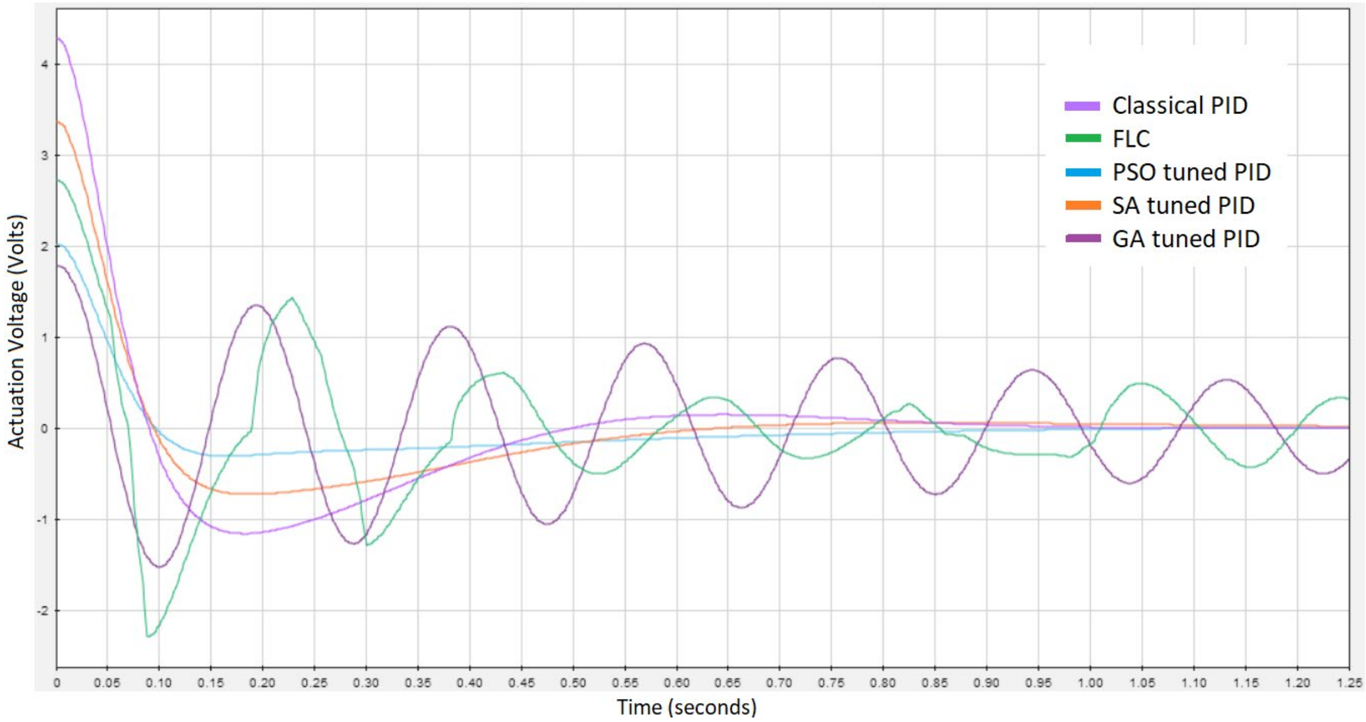

Fig. 18. Actuation Voltage characteristics of Ball Balancer Arrangement for PSO, SA, and GA tuned PID controller compared with Classical PID controller and FLC.

CHAPTER 5: CONCLUSION AND FUTURE SCOPE OF WORK

5.1. CONCLUSION

The Ball Balancer Arrangement is modelled and control is achieved with Classical PID controller, FLC, PSO, SA and GA tuned controller successfully. The PSO, SA and GA tuned PID controllers are tuned with ISE, IAE, ITSE and ITAE as cost functions in order to determine the best suitable error parameter for cost calculation. The analysis results show IAE as best suited tuning parameter for Ball Balancer Arrangement if tuning is done using PSO algorithm while SA and GA tuning algorithms tuned best using ISE as tuning parameter. Further, PSO, SA and GA tuned PID controller responses are compared with Classical PID controller using time domain specifications. The comparative study shows that PSO tuned PID controller performance is better compared to Classical PID controller, FLC, SA and GA tuned PID controller in terms of ball position trajectory, ball plate angle characteristics and actuation voltage characteristics. GA tuned PID controller and FLC response has unwanted oscillations both in ball plate angle characteristics as well as actuation voltage characteristics. Although Classical PID controller and SA tuned PID controller response is free from oscillations, the peaky response in ball plate angle and actuation voltage characteristics leads to inefficiency in use of energy and high rise time and settling time. PSO tuned PID controller shows no such abnormality or oscillation and it is able to control Ball Balancer Arrangement efficiently.

5.2. FUTURE SCOPE OF WORK

Scope of future work for development of Ball Balancer Arrangement controllers include implementation of new algorithms for tuning such as Firefly algorithm, Ant colony optimization and compare their results.

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