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Design of Optimal Controller for Continuous Time Control Systems using Evolutionary Algorithms

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Abstract—*In this paper, optimal design of PID controllers has been proposed for continuous time systems using various soft computing algorithms. Design of optimal controllers is still an open problem and several methods and theories have been established for the same. In this paper, we consider three different plants, each with complex characteristics for the design of a fixed structure controller using evolutionary algorithms. In this paper, we have considered three examples for the design purposes, namely, motor position control system, first order with time delay (FOTD) plant and a heat exchanger used in soda recovery in sugar industries. Time delay, uncertainties, etc. exist in several real world applications, and the delay is generally caused by the time taken by the sensor to sense the parameter, communication delay etc. Hence such characteristics lead to instabilities and make it difficult to control the system. So, in order to address this problem, in this paper, the design of PID controller has been posed as an optimization problem and solved using genetic algorithm and simulated annealing. As per the obtained results, the designed controllers offer a stable response.*

Keywords*: Controllers, Simulated Annealing, Time Delay Systems, Genetic Algorithm, Control Systems.*

1. INTRODUCTION

Design of optimal control systems is an open problem and has led to the establishment of several control theories. But the classical control theories don't always return an optimal controller, so the use of evolutionary algorithms for controller tuning is beneficial. The use of evolutionary algorithms for finding the optimum controller gains is achieved by minimizing the cost function. In this paper, the optimal design of controller for the time delay systems has been considered. A fixed structure PID controller has been tuned using soft computing algorithms of genetic algorithm (GA) and simulated annealing (SA) implemented for three different plants, namely, motor position control, soda recovery in sugar mills and first order with time delay systems (FOTD). The design problem has been formulated as optimization problem and time domain performance indices have been used to find a stabilizing controller. Soft computing algorithms of GA & SA have been used to minimize the proposed cost functions. From the results obtained in this paper, it can be seen that the obtained controllers offers a stabilizing response, which otherwise is not possible to obtain using conventional classical control theories.Most of the real world systems are time delay systems and the delay is caused mainly due to the delay in receiving the sensor data to the controller, communication delays, etc [1]. Thus the control of such systems with delays becomes challenging. Classical controller design methodologies like Ziegler Nichols, Choen-Coon, CHR, etc. fails to give a stabilizing controller. The real world examples of time delay systems are, combustion systems, CSTR tanks, heat exchanger systems, etc.

2. METHODS AND MATERIAL

In this paper the use of classical PID controller is considered. The time domain performance indices have been used to minimize the cost function using genetic algorithm and simulated annealing. The brief introduction on these is provided in this section:

A. PID Controllers

PID controllers are 3 term controllers and are the most widely used controllers in industry and alone account for the 90% controllers used today [2]. Fig. 1 shows the basic structure of the PID controller [3].

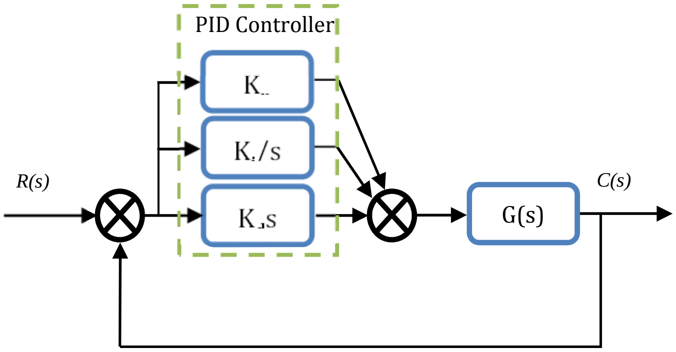


Fig. 1: Structure of PID controllers

The general equation of PID controllers is given as:

$$C(s)=K_P+\frac{K_I}{s}+K_D\cdot s \qquad (1)$$

where, K_P is the proportional gain, is the integral gain and is the derivative gain.

A. Genetic Algorithm

Genetic algorithms has been introduced by John Holland in 1970's and are one of the most robust optimization algorithms [7]. GA is based upon the natural phenomenon of evolution and survival of the fittest. The working of the genetic algorithm is shown in Fig. 2. The GA parameters used in the optimization are given in Table 1 as:

Table I: Genetic Algorithm Parameters

Parameter	Type/Values
Population Type	Double Vector
Population Size	60
Fitness Scaling	Rank Based
Reproduction Elite Count	2
Population Crossover Function	0.8
Crossover Function Type	Scattered
Mutation Function	Constant Dependent
Migration Direction	Both Sides
Migration Fraction	0.2
User Function Evaluation	Series Type

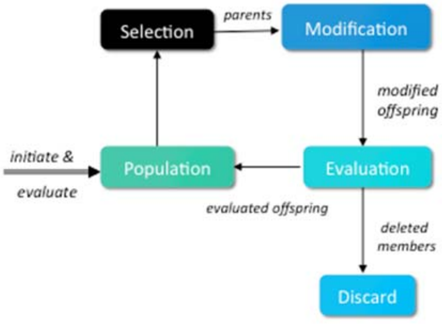


Fig. 2: Flow chart of Genetic Algorithms

B. Simulated Annealing

Simulated annealing is a meta-heuristic optimization technique that is based upon the phenomenon of steel annealing [8]. In the physical process of annealing the temperature of the material is raised initially and is cooled down under controlled environment. Due to which the defects in the crystals are minimized and the over all crystal lattice improves. As the temperature decreases the algorithm limits it search for solutions and converges towards a minima. The SA parameters used in the optimization are given in Table 2 as:

Table II: Simulated Annealing Parameters

Parameter	Type/Values
Annealing Fcuntion	Boltzmann Annealing
Reannealing Interval	100
Temperature Update Function	Exponential Temperature Update
Initial Temperature	100
Acceptance Criteria	Stimulated Annealing Accpeteance

C. Tuning Cost Function

In the paper, for the optimal tuning of the PID controller, time domain performance indices of integral square error (ISE) and integral time square error has been minimised using soft computing algorithms. The minimization of these cost functions assures proper and optimal reference tracking. ISE and ITSE are given by equations as below:

$$ISE=\int\left(e(t)\right)^2dt$$

$$ITSE=\int t\times\left(e(t)\right)^2dt$$

3. RESULTS AND DISCUSSION

A. Motor Position Control

A typical actuator in control frameworks is the DC engine. It specifically gives revolving movement and, combined with wheels or drums and links, can give translational movement. The electric identical circuit of the armature and the free-body chart of the rotor are appeared in the Fig. below as:

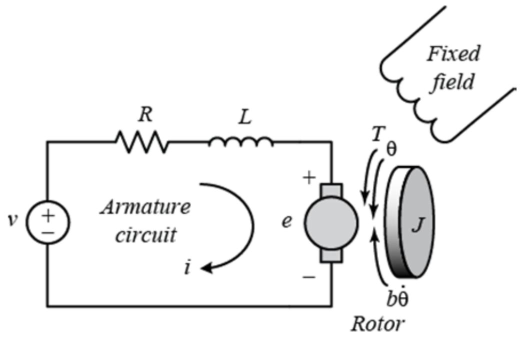


Fig. 3: Free body diagram of DC motor.

The transfer function is given as below:

$$G(s) = \frac{\Theta(s)}{V(s)} = \frac{K}{s\left((Js+b)(Ls+R)+K^2\right)} \qquad (2)$$

Using the values given in [10], the transfer function is obtained as:

$$G(s) = \frac{0.01}{0.005 \times s^2 + 0.06 \times s + 0.1001} \qquad (3)$$

The controller tuning has been carried out using GA & SA by minimizing the ISE & ITSE cost function. The PID gains obtained after optimization are given in Table 3. The results have been compared with classical method of Ziegler Nichols. Fig. 4 shows the compared step response of the designed motor position control system and various time domain performance indices are given in Table 4.

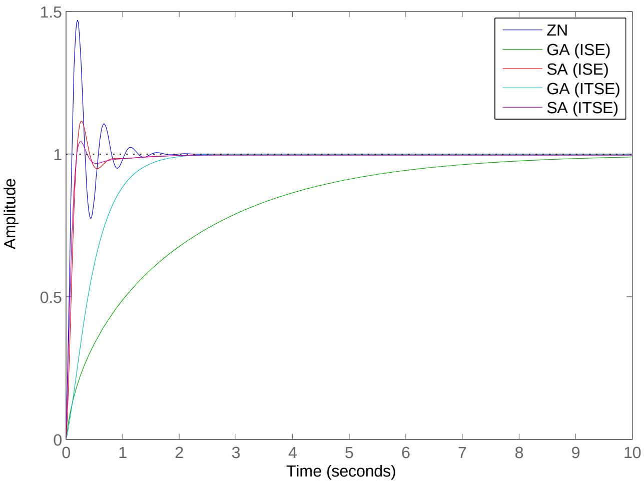


Fig. 4: Closed loop step response of the system with tuned PID controller.

Table III: PID Controller Parameters Obtained

Method	Kp	Ki	Kd
ZN	123.815	1157.813	3.3101
GA (ISE)	5.392	5.462	0.775
GA (ITSE)	10.495	19.968	0.321
SA (ISE)	78.94	93.281	1.039
SA (ITSE)	90.352	99.204	3.216

Table IV: Time Domain Performance Indices

Method	Overshoot %age	Rise Time	Settling Time
ZN	46.96 %	0.0804 sec.	1.183 sec.
GA (ISE)	0 %	4.63 sec.	8.44 sec.
GA (ITSE)	0 %	0.965 sec.	1.697 sec.
SA (ISE)	11.51 %	0.134 sec.	0.763 sec.
SA (ITSE)	4.39 %	0.134 sec.	0.816 sec.

4. HEAT EXCHANGER FOR SODA RECOVERY IN SUGAR INDUSTRY

In this subsection, the optimal design of controller temperature control system used in heat exchanger meant for soda recovery in sugar industry has been considered. The dynamic equation of the system at Star Paper Mills Ltd., Saharanpur (U.P.) has been derived in [11] and in this paper have considered for the controller design purposes. The closed loop system considered for design purpose is given by Fig. 5 as:

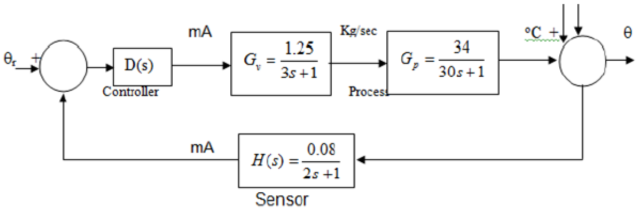


Fig. 5: Closed loop setup of the control system.

The controller tuning has been carried out using GA & SA by minimizing the ISE & ITSE cost function. The PID gains obtained after optimization are given in Table 5. The results have been compared with classical method of Ziegler Nichols. Fig. 6 shows the compared step response of the designed motor position control system and various time domain performance indices are given in Table 6.

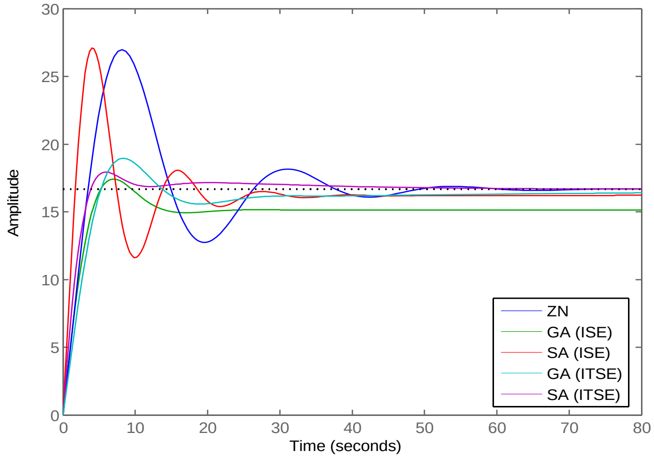


Fig. 6: Closed loop step response of the system with tuned PID controller.

Table IV: PID Controller Parameters Obtained

Method	Kp	Ki	Kd
ZN	5.177	0.7266	9.219
GA (ISE)	3.872	0.00011	10.594
GA (ITSE)	3.934	0.06	7.84
SA (ISE)	11.95	0.019	20
SA (ITSE)	3.843	0.169	15.04

Table VI: Time Domain Performance Indices

Method	Overshoot %age	Rise Time	Settling Time
ZN	61.88 %	2.75 sec.	46.013 sec.
GA (ISE)	4.49 %	3.965 sec.	14.94 sec.
GA (ITSE)	13.69 %	3.963 sec.	64.37 sec.
SA (ISE)	62.65 %	1.36 sec.	27.11 sec.
SA (ITSE)	7.6 %	2.79 sec.	31.5 sec.

B. First Order with Time Delay (FOTD)

In this paper, the controller tuning for a time delay system has been considered using soft computing. The considered here in this word is a first order with time-delay plant given by equation 4 as:

$$G(s)=\frac{1}{11s+1}e^{-3.5s} \tag{4}$$

Initially, for tuning the controller, the use of classical method of Ziegler Nichols has been chosen and from the step response of the closed loop system with ZN tuned controller, an unstable response has been generated.

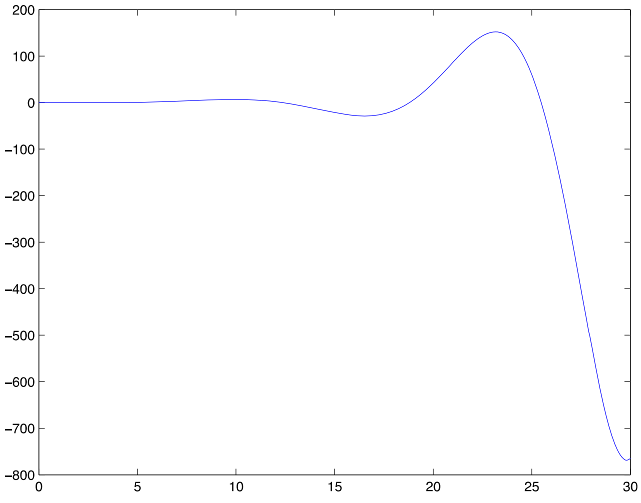


Fig. 7: Closed loop step response of the system with ZN-PID controller.

So, classical tuning methods fail for these time delay systems, so in this work, GA & SA has been applied to optimally tune the controller. Two time domain performance of ISE and ITSE indices have been considered.

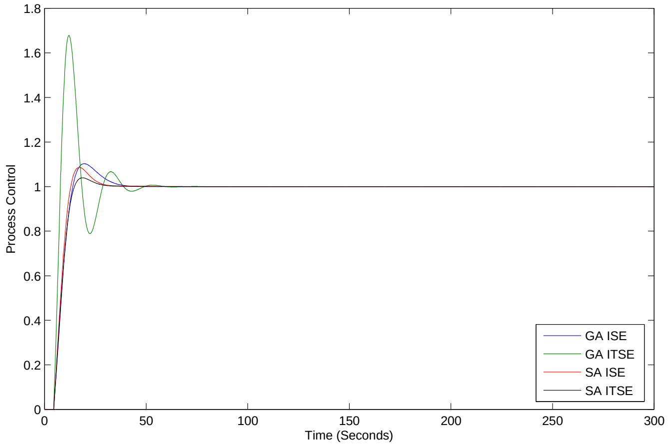
These have been used to form the cost function and their minimization assures proper tracking of the reference signal. The GA & SA parameters considered in the optimization are given in Table 1 & 2 respectively. The obtained controller parameters are given in Table 7. The compared closed loop step response of the system with GA & SA tuned PID controller with ISE and ITSE performance indices are shown in Fig. 8 and their respective time domain performance indices are given in Table 8.

Table VII: PID Controller Parameters Obtained

Method	Kp	Ki	Kd
ZN	15.778	27.709	-0.328
GA (ISE)	1.396	0.1612	0.0013
GA (ITSE)	2.884	0.552	2.0833
SA (ISE)	1.6	0.161	0
SA (ITSE)	1.5	0.141	0

Table VIII: Time Domain Performance Indices

Method	Overshoot %age	Rise Time	Settling Time
ZN	NaN	NaN	NaN
GA (ISE)	10.3 %	6.91 sec.	32 sec.
GA (ITSE)	58.8 %	2.51 sec.	35.5 sec.
SA (ISE)	8.62 %	6.13 sec.	25.2 sec.
SA (ITSE)	3.94 %	7.05 sec.	23.2 sec.



ig. 8: Compared closed loop step response of the system with all obtained PID controllers.

. CONCLUSION

Most of the real systems are complex systems and classical control theory does not offer an optimal controller for such systems. In this paper, the optimal designing of PID controllers has been considered for three different control systems using soft computing algorithms of genetic algorithm and simulated annealing using time domain performance indices. As per the results obtained in this paper, the designed controllers offer a stabilizing response.

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