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Controller tuning and evaluation of PID controllers with non-traditional tuning technique for Ball and Hoop system

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Abstract

The ball and hoop system is the dynamics of a steel ball that is free to roll on the inside of a rotating circular hoop. It is for teaching advanced concepts in control especially to the topics of root locus design, pole placement, and in the way which zeros and poles influences the system dynamics. The system is an example of a non-minimum phase system in which both feed forward and feedback can be used for pole placement and zero placement. PID controllers are simple versatile feedback compensator. PID controllers are often the solution of choice when the controller is needed to close the loop. Particle Swarm Optimization (PSO) is a relatively new technique, for optimization of continuous non-linear functions. It was first presented in 1995 by James Kennedy and Eberhart. Higher order system usually refers to a process that involves more than 2nd order differential equation. This paper clearly converses the comparison of traditional tuning techniques with Particle Swarm Optimization and Ant Colony Optimization. Performance index (ISE, ITAE, IAE, and MSE) and time domain analysis are calculated to prove that PSO is the best method comparing to other methods.

Keywords: Particle swarm optimization (PSO), Ant colony optimization, ZN (Ziegler-Nichols), TL (Tyreus-Luyben).

1. Introduction

The Ball and Hoop apparatus is physical system made by TecQuipment Ltd. It is a product designed for the theoretical study and practical investigation of basic and advanced control engineering principles.

This system is used for the application of basic control (for example by PID controller) of hoop velocity ϖ or control of hoop angular position ϕ or of hoop angular position with damping ball oscillation in the hoop by input voltage u or even for advanced control.

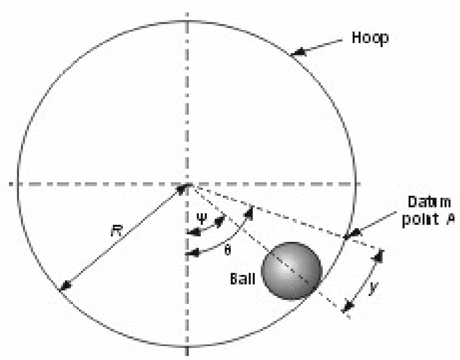

Figure 1: shows the Ball and Hoop schematic, from which the key system variables are:

The hoop radius: R

The hoop angle: ɵ

The ball angle with the vertical, (slop/slash angle): Ψ

The ball position on the hoop: y

PID controllers are widely used in industries. An ideal PID controller is described by the control law

$$c(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{d}{dt} e(t)$$

Kp = Proportional gain

Ki = Integral gain (Kp /τi)

Kd = Derivative gain (Kp *τd)

C(t) = Controlling signal.

e(t) = error signal with respect to time

PID controller is the work horse of the control industry. Tuning is non-trivial. PID structure often has sufficient flexibility to yield excellent results in many applications. Despite the abundance of the sophisticated tool, including advanced controllers, the proportional, integral, derivative (PID controller) is still the most widely used modern industry, controlling more that 95% of closed loop industrial processes. Thegenerally employed performance indices are

Integral Absolute Error (IAE), Integral Squared Error (ISE)and Integral of time multiplied by absolute value of error (ITAE) and Mean Square Error (MSE).

- PSO(Particle Swarm Optimization)is a robust stochastic optimization technique and non-deterministic.
- PSO applies the concept of social interaction to problem solving.
- PSO learned from the scenario and used it to solve optimization problems.

Section 1 describes the introduction, Section 2 describes the controller tuning techniques, Section 3 explains the simulation results and discussion, Section 4 explains the conclusion, Section 5 inclines the references.

The manipulated input-output process transfer function for the system is:

$$G_p(s) = \frac{1}{s^4+6s^3+11s^2+6s+0}$$

2. Comparison of tuning techniques

A PID controller handles step changes to the set point especially well: Fast time rises, little or no overshoot, Fast settling time, Zero steady state error. Thereis plenty of motivation, then, to develop an algorithmic approach to controller tuning. The controllers used are: Ziegler Nichols, Tyreus-Luyben. The non -traditional techniques used are ACO and PSO algorithm.

2.1 Ziegler Nichols Method

It was developed by John G. Ziegler and Nathaniel B. Nichols. The Ziegler-Nichols method is used for both open loop and closed loop systems. This closed loop tuning technique was perhaps the first rigorous method to tune the PID controllers. It is widely used method for PID tuning. The tuning parameters are tabulated, based on the critical gain and period:

Table 1: Ziegler Nichols Formula

Controller type	k_c	k_i	k_d
PID	$0.6k_{cu}$	$P_{u/2}$	$P_{u/8}$

2.2 Tyreus-Luyben Method

Tyreus and Luyben have suggested tuning parameter rules that result in less oscillatory responses and that are less sensitive to changes in the process condition. Their rules are:

Table 2: Tyreus-Luyben Formula

Controller type	k_c	k_i	k_d
PID	$k_{cu/2.2}$	$2.2p_u$	$P_{u/6.3}$

2.3 Ant Colony Optimization

Ant Colony Optimization (ACO) is a metaheuristic approach for solving hard combinatorial optimization problems. The inspiring source of ACO is the foraging behaviour of real ants. While walking from food sources to the nest and vice versa, ants deposit a substance called pheromone on the ground. Paths marked by strong pheromone concentrations are more probable to be chosen when deciding about a direction to go. This basic behaviour is the basis for a cooperative interaction which leads to the emergence of shortest paths, thus minimizing the length of the path between nest and food source. There are two working modes for ants either backwards or forwards.

ACO can be used for both static and dynamic combinatorial optimization problems. It is typically used to solve minimum cost problems. The foremost features of this algorithm are natural metaphor, stochastic nature, adaptivity, inherent parallelism, and positive feedback. It shows boundless performance with the “ill-structured” problems. ACO local search is a key to obtain good results.

STEPS FOR SOLVING A PROBLEM BY ACO:

- Represent the problem in the form of sets of components and transitions, or by set of weighted graphs, on which ants can build solution.
- Define the meaning of the pheromone trails.
- Define the heuristic preference for the ant while constructing a solution.
- If possible implement an efficient local search algorithm for the problem to be solved.
- Choose a specific ACO algorithm and apply to problems being solved.
- Tune the parameter of the ACO algorithm.

Based on the distribution ranges of ACO the PID parameters obtained are:

K_p=5.4900

K_i=0.0018

K_d=8.8442.

2.4 Particle Swarm Optimization

It was developed in 1995 by James Kennedy (social psychologist) and Russell Eberhart (electrical engineer).

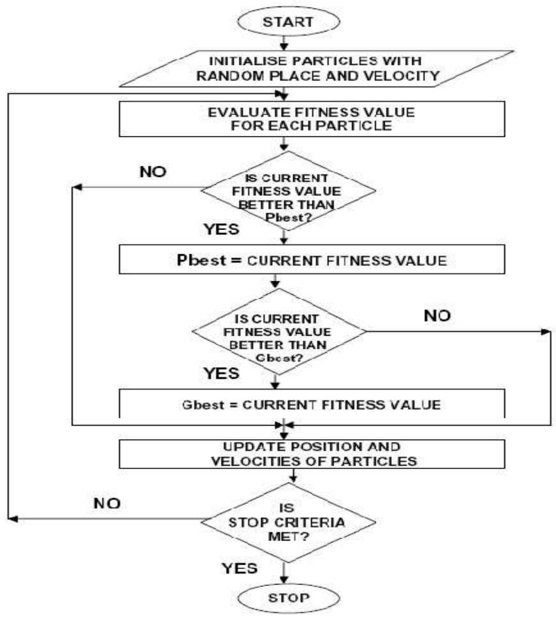

Figure 3: Flowchart of PSO

In PSO algorithm, the system is initialized with a population of random solutions, which are called particles, and each potential solution is also assigned a randomized velocity. PSO relies on the exchange of information between particles of the population called swarm. Each particle adjusts its trajectory towards its best solution (fitness) that is achieved so far. This value is called p_{best}. Each particle also modifies its trajectory towards the best previous position attained by any member of its neighborhood. This value is called *gbest.* Each particle moves in the search space with an adaptive velocity.

The fitness function evaluates the performance of particles to determine whether the best fitting solution is achieved. During the run, the fitness of the best individual improves over time and typically tends to stagnate towards the end of the run. Ideally, the stagnation of the process coincides with the successful discovery of the global optimum.

Let *D* be the dimension of the search space taken into consideration and Xi = [xi1, xi2….x_{iD}]^{T}denote the current position ofi^{th}particle of the swarm, Then: Xi pbest =[x_{i1}^{pbest},x_{i2}^{pbest},….x_{iD}^{pbest}] ^{T} denote the best position ever visited by the particle.Xgbest =[x_{i1}^{gbest},x_{i2}^{gbest},….x_{i2}^{gbest}] ^{T} represents 'gbest',i.e the best position obtained this far by any particle in the population. Vi=[v_{i1},v_{i2},….v_{iD}] ^{T} represents the velocity of i^{th} particle. Vimax = [v_{i1}^{max},v_{i2}^{max} ….v_{iD}^{max}] ^{T} denotes the upper bound on the absolute value of the velocity with which the particle can move at each step.The position and velocity of the particles is adjusted as per the following equation:

$$V_{id} = w*v_{id} + c1.*r1 * (x_{id}^{pbest} - x_{id}) + c2 *r2 *(x^{gbest} - x_{id}) \text{ ----- (1)}$$

$$V_{id} = \begin{cases} v_d^{max}, & v_{id} > v_d^{max} \\ -v_d^{max}, & v_{id} < -v_d^{max} \text{ ---- (2)} \end{cases}$$

$$x_{id} = x_{id} + v_{id} \text{ -----(3)}$$

where c1 and c2 are positive constants, represent the cognitive and social parameter respectively; r1 and r2 are random numbers uniformly distributed in the range [0,1]; w is inertia weight to balance the global and local search ability.

Table 3: PSO Selection Parameters

Population size	100
Number of iterations	100
Velocity constant,c1	2
Velocity constant,c2	2

3. Simulation Results and Discussion

Table 4: Controller Parameters for ZN and TL

Controllers	k_p	k_i	k_d
ZN	5.904	1.8614	4.680
TL	3.075	0.22035	3.0959

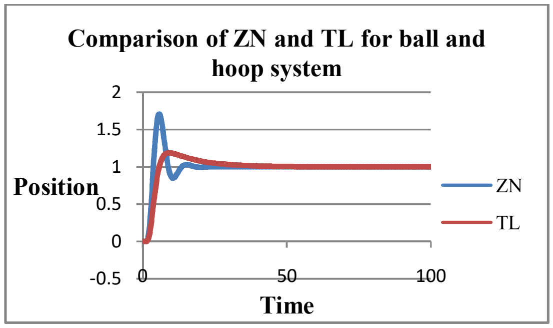

Figure 4:Graph labelling ZN nd TL for Ball and Hoop system

Comparing the parameters of the controllers ZN and TL, ZN is the best method.Overshoot and settling time are small compared to Tl method.Furthermore,ZN is compared with ACO and PSO and it is proved that PSO is the method for optimization.

Table 5: Controller Parameters for ZN,ACO and PSO

Controllers	K_p	K_i	k_d
ZN	5.904	1.8614	4.680
ACO	5.490	0.0018	8.8442
PSO	5.8631	0.0018	9.2495

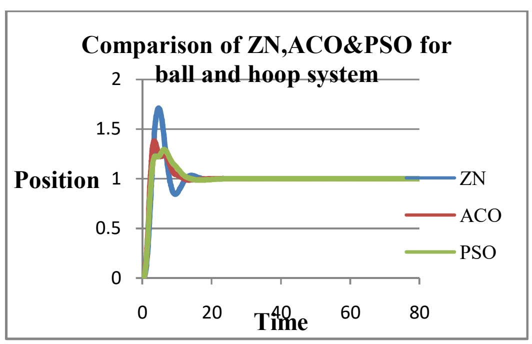

Figure 5:Graph labelling ZN,ACO and PSO for Ball and Hoop system

3.1 Time Domain Specifications

3.1.1 SETTLING TIME: Time required for the response curve to reach and stay with a certain % of the final value.

3.1.2 RISE TIME: Time taken by the signal to change from specified low value to specified high value.

3.1.3 PEAK TIME: Time taken by the system to have maximum value of the curve.

3.1.4 OVERSHOOT: Maximum peak value of the response curve. It occurs when the transitory value exceeds its final value.

Table 6: Time domain specifications

Controllers	Settling Time	Rise Time	Peak Time	Overshoot
ZN	26	1.6	5.6	70.6
TL	60	7.8	18.8	3.38
ACO	14	1.04	3.5	0.37
PSO	22	0	0	0

3.2 Performance Index

Performance measures which utilize the entire transient response usually assume the form of a time integral of the actuating error function.

3.2.1 ISE ((Integral Square Error):

The ISE is a better criterion for suppressing large errors because a squared error greater than unity contributes more to the integral than does an absolute error.

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

3.2.2 IAE (Integral Absolute Error):

IAE leads to controller which better suppress small errors.

IAE $=\int_0^\infty |e(t)|dt$

3.2.3 ITAE (Integral Time Weighted Absolute Error):

ITAE index is generally preferred because it places greater penalty on small errors occurring at large time. ITAE is the most popular among the four criteria, probably because its use results in the most conservative controller design.

ITAE= $\int_0^\infty t|e(t)|dt$

3.2.4 MSE (Mean Square Error):

This method is best of all since it measures the average of the squares of the error.

Table 7: Performance Index

Controllers	ISE	IAE	ITAE	MSE
ZN	18.81	36.01	138.21	0.0623
TL	16.21	38.73	309.12	0.0270
ACO	10.30	18.76	38.10	0.0342
PSO	8.953	13.74	17.035	0.0297

From the above criteria's (time domain, performance index) it is proved that PSO is the best method comparing to traditional tuning techniques.

3.3 Servo Regulatory

If the process of the control system is to make the process follow changes in set point then it is called servo operation. Reference value changes than disturbance. Regulatory operation serves the purpose of control system to keep the controlled variable constant in spite of changes in load. Disturbance occurrence is more than reference value changes. System that serves good for servo operation will generally not be best for regulation operation.

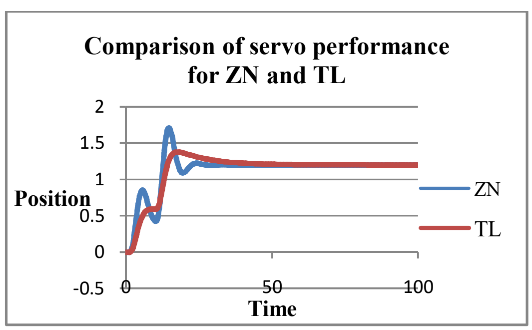

Figure 6: Servo performance of ZN and TL

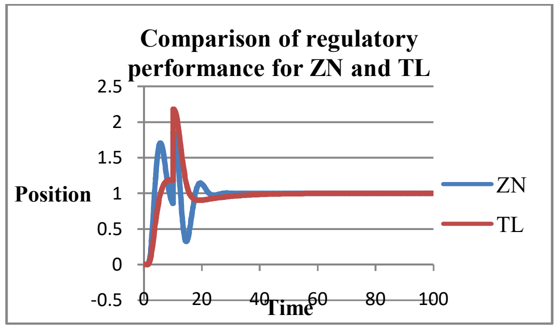

Figure 7: Regulatory performance of ZN and TL

From the above figure ZN and TL controller performs well for both servo and regulatory performance. From this response it proves that ZN is functioning well than TL controller in terms of settling time. Furthermore, ZN is compared with ACO and PSO servo regulatory performance and it is proved that PSO works well comparing to other traditional tuning techniques.

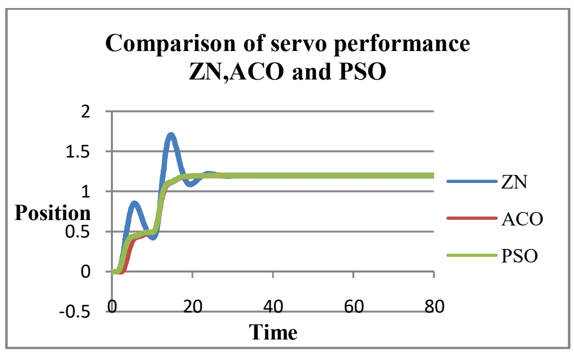

Figure 8: Servo performance of ZN, ACO and PSO

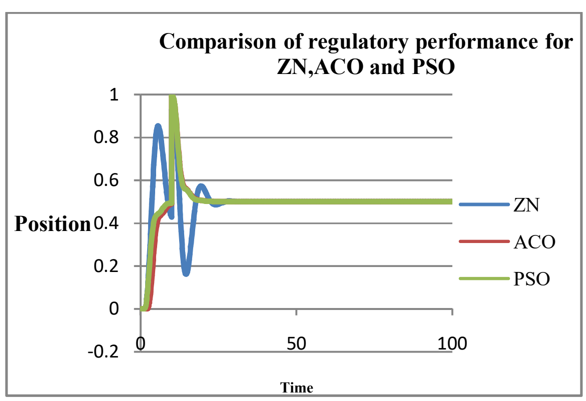

Figure 9: Regulatory performance of ZN,ACO and PSO

3.4 Distribution Ranges of PSO

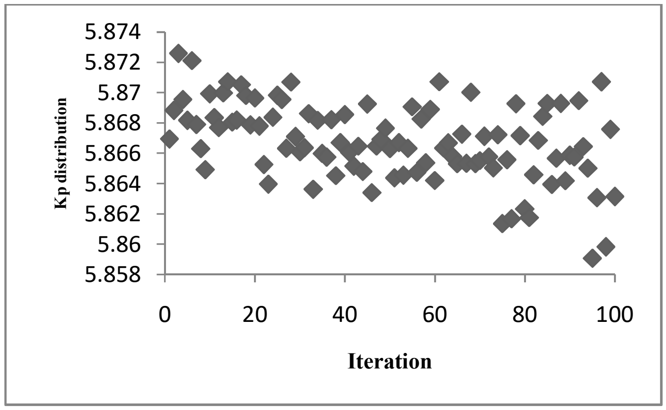

Figure 10: Distribution of K_p for 100th iteration

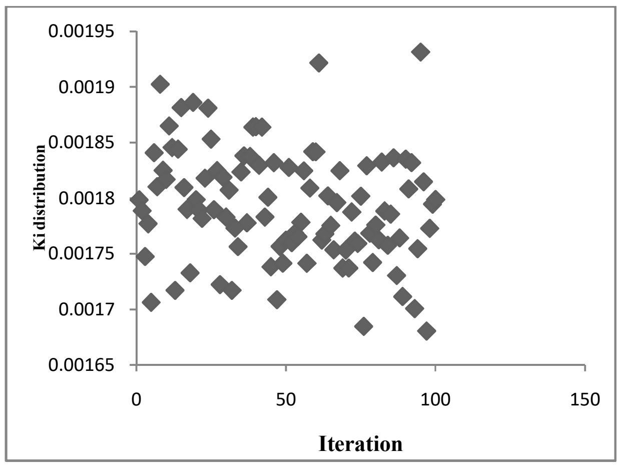

Figure 11: Distribution of K_i for 100th iteration

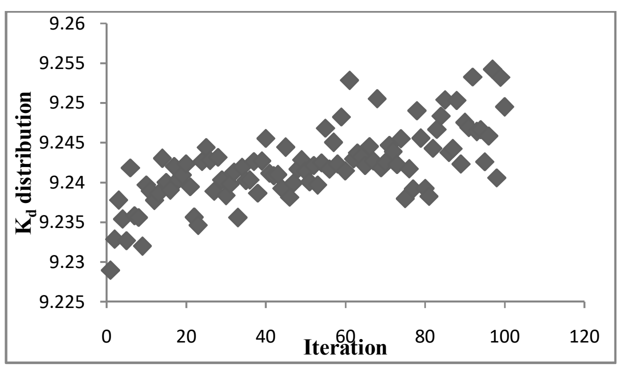

Figure 12: Distribution of K_d for 100th iteration

The PID controller was formed based upon the respective parameters was selected for the 100 iterations and the gbest solution is selected for the set of parameters, which had the minimum error. The PID tuning parameters for this model is

$$K_p=5.8631$$

$$K_i=0.0018$$

$$K_d=9.2495$$

3.5. Robustness Investigation

The robustness investigation was done to the considered model by applying a step input and thereby calculating the performance index based on the error criterion. The uncertainties to the model are included by varying the gain constant by +20%. The altered model is given by,

$$G(s)=\frac{1.2}{s^4+6s^3+11s^2+6s+0}$$

The performance index calculated based on the error criterion for the model with uncertainties is given in the Table 8:

Table 8: Performance Index

Controllers	ISE	IAE	ITAE	MSE
ZN	18.81	36.015	139.51	0.0625
ACO	9.102	13.708	15.8915	0.0453
PSO	6.354	10.67	14.523	0.0352

Conclusion

It can be concluded that PSO is an efficient optimization algorithm.Since PSO is based on the intelligence it can be used for both scientific and engineering use. The calculation in PSO is very simple. Compared with the other calculations, it occupies the bigger optimization stability and it can be completed easily. PSO can serve as a solution for most of the complicated engineering applications. PSO is more efficient in maintaining the diversity in swarm. The development of PSO is still ongoing.This paper clearly proves that PSO serves well for Ball and Hoop system. PSO gets better results in a faster, cheaper way compared with other methods.

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