Control of Ball Hoop System using Grey Wolf Optimization Algorithm

Mridul Porwal and Girish Parmar
Department of Electronics Engineering,
Rajasthan Technical University, Kota
Rajasthan, India-324 010

Abstract: In this work, Grey Wolf Optimization (GWO) algorithm has been used to tune the parameters of proportional-integral-derivative (PID) controller for control of ball hoop system. The GWO is a newly developed meta-heuristic algorithm which mimics the behavior of grey wolves. The integral of time multiplied absolute error (ITAE) has been taken as an objective function. The results of GWO/PID scheme has also been compared with other existing techniques available in the literature and it has been observed that the proposed GWO/PID scheme with ITAE as an objective function gives less overshoot and settling time.

Keywords: Ball Hoop, PID Controller, GWO, ITAE.

1. INTRODUCTION

Proportional-integral-derivative (PID) controllers are widely used controllers in industries. PID controllers are popular from last several years due to their robust performance and functional simplicity [1-3]. Proportional gain (K_p), integral constant (K_i) and derivative constant (K_d) are three import parameters of PID controller. To achieve the optimal response, these three parameters of PID controller may vary, it is called tuning of the controller. Classical methods of tuning PID controllers like; Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) have limitations and not suitable for solving complex problems to achieve desired response [1-2].

Now a day's several researchers are using meta-heuristic algorithms for optimization of complex problems due to simplicity, flexibility, random search and avoidance of local optima capabilities of these algorithms [13-15].

Several meta-heuristic algorithms such as; Genetic Algorithm (GA) [17], Particle Swarm Optimization (PSO) [18], Chaotic Particle Swarm Optimization (CPSO), Adaptive Hybrid PSO (AHPSO), Artificial Bee Colony Optimization (ABC), Bacterial Foraging Optimization (BFO), Chaos driven Differential Evolution algorithm (DE_{Chaos}) and Self-Organizing Migrating Algorithm ($SOMA_{chaos}$) are available in the literature to tune the parameters of PID controller for control of ball hoop system [7-12].

In present work, GWO algorithm has been used to tune the parameters of PID controller for control of ball hoop system with ITAE as an objective function.

2. BALL HOOP SYSTEM

Ball hoop system (BH) is simple and easy to construct. The BH system is analogous to the liquid 'slosh' problem. It mimics the complex dynamics of the oscillations of a liquid in a container when the container velocity and direction are changed. The movement of large quantities of liquid can strongly influence the movement of the container itself, which is usually dangerous [10, 15].

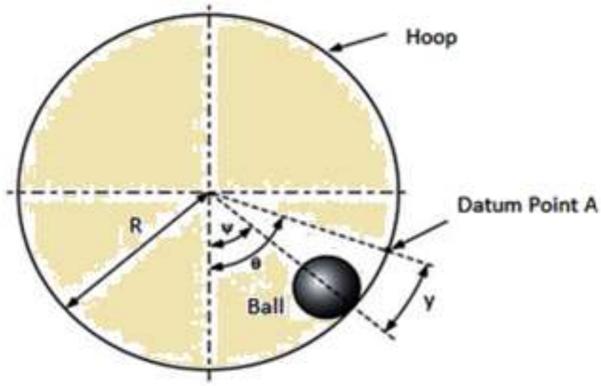

Figure 1: Dynamics of ball hoop system [15]

The model of ball hoop system is shown in Figure 1 [15]. The variables used in BH system are: hoop radius: R, ball radius: r, ball mass: m, hoop angle: θ, ball angles with vertical (slosh angle): ψ, ball position on the hoop: y**,** input torque to the hoop: $T(t)$.

The Ball and Hoop System illustrate the steel ball dynamics that can freely roll on the inner surface of a rotating hoop. Grooves are present on the inside surface of the hoop to rotate steel ball freely inside the hoop. The hoop continuously moves with a motor. The ball will tend to move in the direction of hoop rotation when the hoop is rotated. Gravity will overcome the frictional forces and the ball will fall back at some point. Due to repeat of this process, the ball has oscillatory motion.

The transfer function of BH system is represented by [10]:

$$G_{BH}(s) = \frac{y(s)}{\theta(s)} = \frac{1}{s^4+6s^3+11s^2+6s} \tag{1}$$

3. PROBLEM FORMULATION

The PID controller is represented by:

$$G(s) = k_p + \frac{k_i}{s} + k_d \tag{2}$$

In present work, GWO algorithm has been used for the control of Ball and Hoop system with the help of a PID controller. The three parameters of the PID controller; proportional gain (K_p), integral constant (K_i) and derivative constant (K_d) have been tuned by GWO to obtain the minimum value of ITAE objective function.

Integral absolute error (ITAE) performance index is given by Equation (3):

$$ITAE = \int_0^\infty t\left|e(t)\right| dt \tag{3}$$

The Matlab simulink model of ITAE objective function is shown in Figure 2.

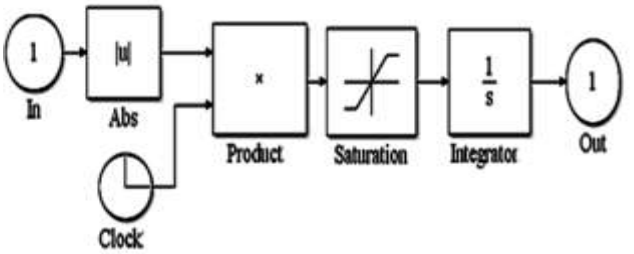

Figure 2: Simulink model of ITAE objective function

4. GREY WOLF OPTIMIZATION

The grey wolf optimization (GWO) technique was proposed by Mirjalili et al. in 2014 [13]. It is a meta-heuristic algorithm inspired by the social hierarchy of wolves as well as their hunting behavior. The GWO algorithm mimics the leadership hierarchy and hunting mechanism of grey wolves in nature. In GWO algorithm, the search starts with population of randomly generated wolves called; solutions. During hunting (optimization) process, these wolves estimate the prey's (optimum) location through an iterative procedure during hunting [15-16].

Four types of grey wolves such as; alpha (α), beta (β), delta (δ), and omega (ω) are employed for simulating the leadership hierarchy. The functions of each group have also been defined in Table 1 [15-16].

Table 1: Types of wolves and functions of each group

Types of Wolves	Function
alpha (α)	Responsible for making decisions about hunting, sleeping place, time to wake, and so on. The alpha's decisions are dictated to the pack.
beta (β)	Subordinate wolves that help the alpha in decision-making or other pack activities.
delta (δ)	Follows alphas and betas but dominate omegas.
omega (ω)	Follow the decision made by other dominate wolves.

The main phases of grey wolf hunting are as follows:

(i) Tracking, chasing, and approaching the prey.

(ii) Pursuing, encircling, and harassing the prey until it stops moving.

(iii) Attack towards the prey.

The functions of each group have also been defined in Figure 3 [13, 14].

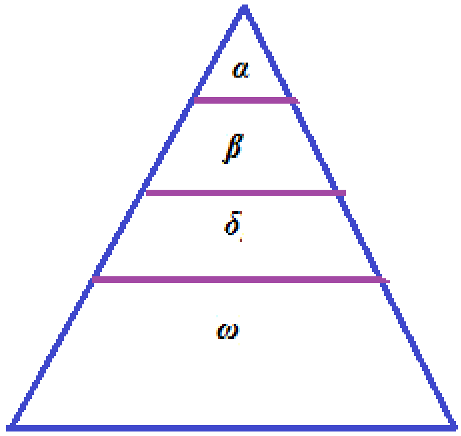

Figure 3: Social hierarchy of GWO [13]

In implementing GWO, first important parameter is the "maximum number of search agents (*SA*)" or "grey wolves". The second parameter is the "number of iterations (*Iter*)". These two parameters may vary according to the application. In present research work, the parameters used for simulation of the GWO algorithm are given in Table 2.

Table 2: Parameters used for the GWO algorithm with ITAE objective function

Parameter	Value
Number of Search Agents (SA)	30
Dimension (D)	3
Maximum Iterations ($Iter_{max}$)	40
Lower Bounds (LB)	[0.0001 0.0001 0.0001]
Upper Bounds (UB)	[20 20 20]

5. IMPLEMENTATION OF GWO/PID APPROACH

The complete Simulink model of the BH system with ITAE objective function is shown in Figure 4. The GWO algorithm has been run 5 times for the simulink model shown in Figure 4 and obtained PID parameters are given in equation (4).

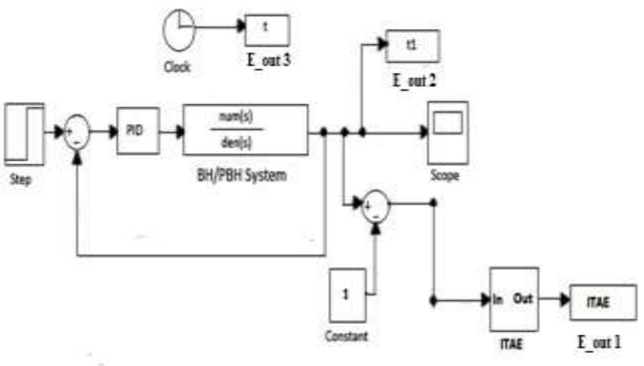

Figure 4: Simulink model of BH system with PID controller and ITAE objective function

$$K_P = 3.9920; \quad K_I = 0.0010; \quad K_D = 4.4359 \tag{4}$$

Therefore, the PID controller is given by:

$$G_C = 3.9920 + \frac{0.0010}{s} + 4.4359s \tag{5}$$

By multiplying the transfer function of PID controller (Eq. 5) and the transfer function of BH system (Eq. 1)

$$G_F = PID\ Controller\,(G_C) \times Ball\ Hoop\,(G_{BH}) \tag{6}$$

The closed loop transfer function of the BH system with a PID controller and unity feedback can be obtained from:

$$G_{CL} = \frac{G_F}{1 + H(s)\, G_F} \tag{7}$$

where $H(s) = 1$. The closed loop transfer function of the BH system with a PID controller and unity feedback is given by:

$$G_{CL}(ITAE) = \frac{4.4359s^2 + 3.9920s + 0.0010}{s^5 + 6s^4 + 11s^3 + 10.4359s^2 + 3.9920s + 0.0010} \tag{8}$$

Table 3: Parameters of PID controller for BH system obtained by DE_{chaos}, $SOMA_{chaos}$, and GWO

Algorithm	ITAE		
	K_P	K_I	K_D
$SOMA_{chaos}$ [11]	4.8436	0.00025	7.0235
DE_{chaos} [11]	4.963	0.0003	7.3089
GWO (Proposed)	**3.9920**	**0.0010**	**4.4359**

In Table 3, the parameters of PID controller obtained by other existing techniques in literature for the same BH system have also been given.

6. COMPARATIVE ANALYSIS

In Table 4, different closed loop transfer functions of the BH system for the proposed and other existing techniques have been calculated, as per the parameters of PID controller given in Table 3. Based on these closed loop transfer functions, the responses of the GWO/PID approach for the BH system with other existing techniques have been compared in Figure 5.

Table 4: Comparison of the GWO/PID (ITAE) approach with other existing techniques

Algorithm	Closed loop transfer function (G_{CL})
$SOMA_{chaos}$ [11]	$\frac{7.3089s^2 + 4.963s + 0.0003}{s^5 + 6s^4 + 11s^3 + 13.3089s^2 + 4.963s + 0.0003}$
DE_{Chaos} [11]	$\frac{7.0235s^2 + 4.8436s + 0.00025}{s^5 + 6s^4 + 11s^3 + 13.0235s^2 + 4.8436s + 0.00025}$
GWO (Proposed)	$\frac{4.4359s^2 + 3.9920s + 0.0010}{s^5 + 6s^4 + 11s^3 + 10.4359s^2 + 3.9920s + 0.0010}$

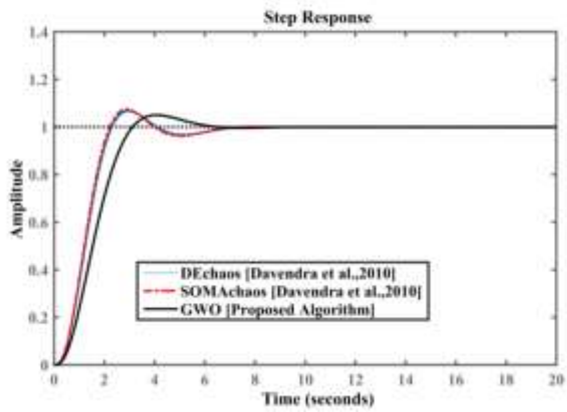

Figure 5: Comparison of GWO/PID (ITAE) approach with existing techniques for BH system

It can be seen in Figure 5 that, GWO/PID approach with ITAE gives less overshoot and settling time in comparison to existing approaches in the literature.

In Table 5, proposed GWO/PID scheme has been compared with other existing approaches in terms of settling time. It is observed in Table 5 that, the proposed GWO/PID approach gives less settling time in comparison to existing techniques. In Figure 6, the settling time comparison has also been shown in bar graph form.

Table 5: Settling time comparison with the existing techniques of the GWO/PID (ITAE) approach for the BH System

Algorithm	Settling Time (Sec)
DE_{chaos} [11]	6.095
$SOMA_{chaos}$ [11]	6.095
GWO (Proposed)	**5.41**

Figure 6: Bar chart comparison of settling time for BH system with ITAE objective function

In Table 6, comparative analysis of proposed GWO/PID has also been shown with other existing approaches in terms of overshoot. It can be observed in Table 6, that the proposed GWO/PID approach gives less overshoot in comparison to existing techniques. In Figure 7, the overshoot comparison has also been shown in bar graph form.

Table 6: Overshoot comparison with the existing techniques of the GWO/PID (ITAE) approach for the BH System

Algorithm	Overshoot (%)
DE_{chaos} [11]	6.715
$SOMA_{chaos}$ [11]	6.715
GWO (Proposed)	**5**

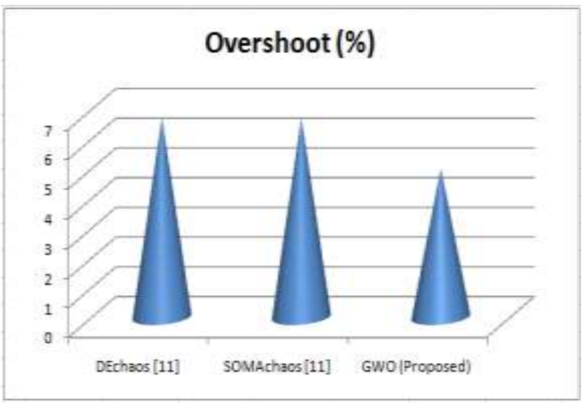

Figure 7: Bar chart comparison of overshoot for BH system with ITAE objective function

7 CONCLUSIONS

The application of GWO algorithm in control of ball hoop system has been shown. The ITAE has been taken as an objective function. Comparison of proposed GWO/PID scheme with ITAE has also been shown with other existing techniques; such as DE_{chaos} [11] and $SOMA_{chaos}$ [11], etc. The simulation results shows that GWO/PID scheme with ITAE as an objective function gives less value of overshoot and settling time in comparison to other existing approaches.

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