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Designing of Optimization Techniques based PID controller for Self Balancing Bicycle

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Abstract: *The objective of this paper is to design the controller for balancing a bicycle. As bicycle is highly nonlinear system it is very much difficult to design the controller. The Proportional Integral Derivative (PID) controller based on intelligent controllers like Bacterial Foraging Optimization (BFO), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) are designed and comparison is made between them to find which will give the better result for the bicycle. Anova test is taken to compare the error values and it is found that ACO based PID gives better result.*

Keyword: *Nonlinear system, Bacterial Foraging Optimization (BFO), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO).*

1. INTRODUCTION

The control of bicycle dynamics is an attractive area of research in recent days. This dynamics of Bicycle has been attracted the attention of various research communities because of its non-intuitive nature, the fact which mainly based on the speed. It is an unstable system like an inverted pendulum, but under few conditions, it is stable in the forward motion. In certain conditions, cycle exhibits both open-loop right-half plane poles and zeros, making a design of the feedback controller for balancing bicycle in a position that is upright or moving in a predefined path is really a challenging problem.

As cycle plays important role this type of research area is an interesting one for more people. These cycles can also be used for various defense purposes to avoid human loss. We can fit a camera on it and can be sent to any places by fitting some obstacle sensors [1]. This type cycle can also be further developed with water and fire resistant body and used in natural calamities like forest fires also. We can also use IoT, Bluetooth devices to get the information and also to control the cycle. This type of device can be used in future for more application.

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Based on the design given by Y. Lam and T. K. Sin [2] the bicycle transfer function is found with some modification in the parameter.

Here in this work, Optimization techniques are used to tune the controller which in turn helps to balance the bicycle. Three types of tuning methods are used such as Bacterial Foraging Optimization (BFO), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO). These three algorithms are very important. The error indices are compared using the Anova test (Analysis of variance) which clearly shows the maximum error values in the graph. With the help of this graph we can decide which algorithm can be suitable for controlling bicycle. The controller used here is Proportional Integral Derivative (PID) controller. PID is the most important controller used in many systems. But tuning of PID controller is not easy. Tuning has been carried out using MATLAB software.

The rest of the paper explores the modeling of bicycle, about the algorithms used, results and discussion followed by conclusion.

2. MODELING OF BICYCLE

When the bicycle is inclined at angle θ_{roll}, inertia measurement unit (IMU) sensor detects this roll angle. Now this data is sent to an controller that in turn sends command to the gimbals motor so that it will be made to rotate. Now the precession torque is produced to balance the bicycle back to its normal position. This

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system uses single gimbals which generates only one axis torque. The gimbals motion decides the direction of output the torque change. The bicycle is balanced based on the torque.

TABLE I PARAMETERS OF SELF-BALANCING CYCLE

Parameters	Value	Unit	Description
m_f	2.04	Kg	Mass of flywheel
m_b	21	Kg	Mass of bicycle
h_f	0.6	M	Flywheel COG upright height
h_b	0.6	M	Bicycle COG upright height
I_b	2.0	kg.m2	Bicycle moment of inertia around ground contact line
I_p	0.009	kg.m2	Flywheel polar moment of inertia around COG
I_r	0.0023	kg.m2	Flywheel radial moment of inertia around COG
ω	500	rad/s	Flywheel angular velocity
L	0.000112	H	Motor Inductance
R	0.7	Ω	Motor Resistance
B_m	0.003	kg.m2/s	Motor viscosity coefficient
K_m	0.03	Nm/A	Motor torque constant
K_e	0.003	V.s	Motor back emf constant
g	9.81	m/s2	Gravitational acceleration

Angular momentum of the flywheel is reason for the amount of toque produced. Therefore, in order to generate the maximum possible torque; the flywheel motor has to run at its maximum speed of about 4480 rpm and so ω is 500 rad/s. the flywheel designed polar moment of inertia (Ip) is 0.009 $kg.m^2$
Angular momentum of rotor is given in Equation (1)

$$Z = Ip \times \omega fly \quad (1)$$

$$= 0.009 \times 500$$

$$= 4.5 \text{ kg-m2/s}$$

If a rotational precession rate of ω_D, is applied to the flywheel around its gimbals axis, precession output torque T, that is perpendicular to the direction of ω_{fly}, and ω_D will be generated. If the angular velocity is high then the maximum torque will be generated. Let consider an example, if an angular velocity of 5 rad/s, is set so that the gimbals precession output torque generated is given in Equation (2).

$$Tp = Z \times \omega D \quad (2)$$

$$= 4.5 \times 5$$

$$= 22.5 \text{ Nm}$$

For the dynamic model of a bicycle, the equilibrium of gravity and centrifugal force is very important. A model for balancing a bicycle is derived based on P. Y. Lam and T. K. Sin. In Figure 1, the system, consists of two rigid body links and has as its first link a bicycle frame which has 1 degree-of-freedom (DOF) rotation around Z axis. The second link is flywheel that is assumed to be having a constant speed ω. The flywheel centre of gravity (COG) is fixed, that is relative to the bicycle frame.

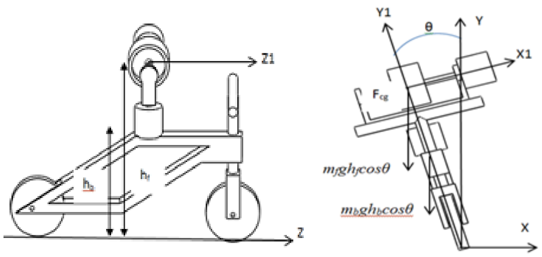

Figure 1 Reference coordinates of bicycle [2]

Y. Lam and T. K. Sin [2] modeled a bicycle and represented it in state-space representation as

$$X = Ax + Bu \quad (3)$$

$$Y = Cx + Du \quad (4)$$

Where,

A=

$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ \dfrac{g(m_b h_b + m_f h_f)}{m_b h_b^2 + m_f h_f^2 + I_b + I_r} & 0 & \dfrac{I_p \omega}{m_b h_b^2 + m_f h_f^2 + I_b + I_r} & 0 \\ 0 & -\dfrac{I_p \omega}{I_r} & -\dfrac{B_m}{I_r} & \dfrac{65K_m}{I_r} \\ 0 & 0 & -\dfrac{K_e}{L} & -\dfrac{R}{L} \end{bmatrix}$$

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$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L} \end{bmatrix}, C = [1\ 0\ 0\ 0] \text{ and } D = [0] \qquad (5)$$

Now substitute the values in Table 1 in Equation (5). Then we get,

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 13.144 & 0 & 0.436 & 0 \\ 0 & -195.65 & -0.130 & 4.78 \\ 0 & 0 & -25 & -5833.3 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 8403 \end{bmatrix}, \quad C = [1\ 0\ 0\ 0] \quad \text{and} \quad D = [0] \qquad (6)$$

Computing the transfer function from the state variables realization (A, B, C, D) yields,

$$\frac{\theta(s)}{U(s)} = \frac{308024.1}{s^4 + 5126.13s^3 + 2470.67s^2 + 428419s + 34040}$$

.

3. BFO ALGORITHM

Bacterial Foraging optimization Algorithm is an important technique used to design the controller. This technique is designed based on the E.coli bacteria [3]. Initially bacterium with help of flagella swims and tumbles in order to reach the food. This process is called as Chemotaxis [4]. Then bacteria with the help of attractive signals will communicate the information to the other and this process is called Swarming. After this stage reproduction stage occurs where the weak bacterium will be removed and good healthy bacterium will increase in population by splitting. The last stage is nothing but Elimination and dispersal stage in which the group of bacterium will be eliminated or scattered [5].

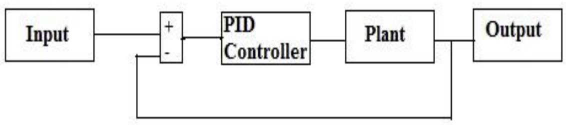

Figure 2 Block diagram of PID controller

With the help of this technique PID controller is tuned and it's Kp, Ki, Kd values are found [6]. Figure 2 represents the block diagram of PID controller. Here the algorithm is made to run for several times and error indices obtained for each PID values are noted down. Minimum 25 iterations have to be taken in consideration. These error values are then compared with other controllers using Anova test.

4. PSO ALGORITHM

Particle Swarm Optimization is another important technique in research area. Here it is based on the techniques that swarm moves in a group and fits in the best place. Here totally 6 steps in which the algorithm works [7]. That is in first step the swarm will be initialized. Then in next step the objective function values are evaluated based on performance criteria. In the third step the initial best values have been set for the swarm. Computation of velocity for each swarm will take place in this step. In the fifth step updating of the swarm takes place. If new value is better when compared to previous best value then new value will be set as best. The last step is stopping criteria in which if the criteria is reached then position of particle will be checked and the value is recorded else if criteria is not reached then repetition from step 4 will takes place until criteria is reached.

Based on this technique the tuning of PID controller is done. Minimum 25 iterations have to be considered and the Error values for each iteration have to be noted.

5. ACO ALGORITHM

Ant Colony Optimization technique is an important technique used to tune the controller. It is based on the interesting idea using which ants search food and reach its home [8]. We have seen ants moving in a straight light in a group. The idea behind this is ant will go in search of food. While moving it deposits pheromone a solution in the path. This solution will evaporates after some time so the solution in longer path will evaporate soon and solution in shorter path remains. So ant finds the shorter path. This technique is used in finding shorter path in salesman problems [9].

Based on this technique PID controller is tuned. Minimum of 25 iterations are made and error values are noted for each iteration. And average of iterations taken is used to check the simulation response.

6. RESULTS AND DISCUSSION

Simulation is carried work in MATLAB. The simulation graph of the controller is obtained by taking the average value of various iterations. Set point is given as 1. The servo and regulatory response of the controller is shown in Figure 3 and 4 respectively. Error values like integral of time-weighted absolute error [ITAE], Integral Squared Error (ISE) and Integral Absolute Error (IAE) that have been noted for each iteration are used to compare using Anova test [10]. The result of Anova test and Multi-comparison method are shown in Figure 5,6,7,8.

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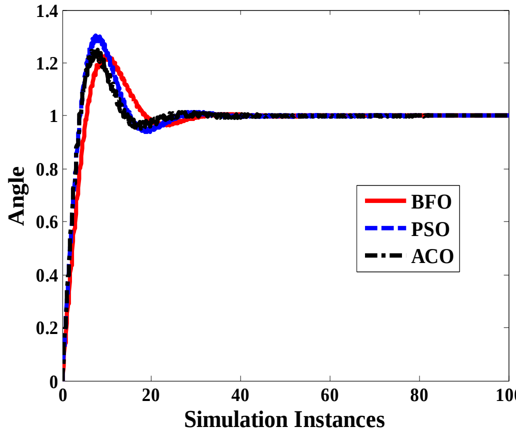

Figure 3 Servo Response of the Bicycle

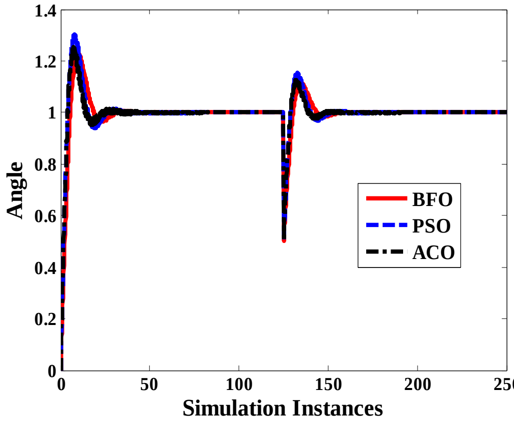

Figure 4 Regulatory Response of the Bicycle

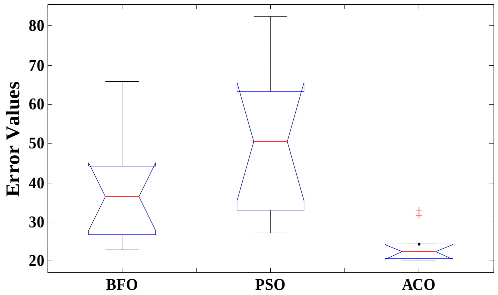

Figure 5 Anova test for ITAE

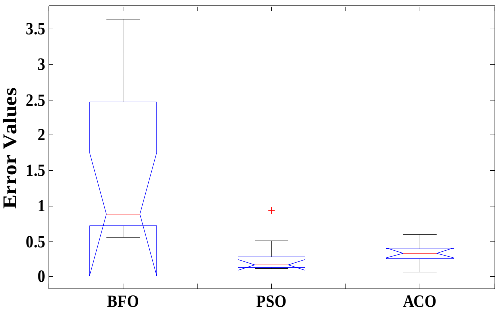

Figure 6 Anova test for IAE

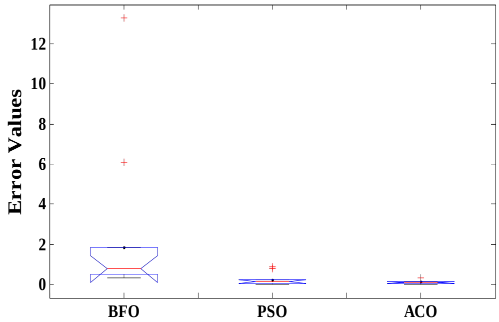

Figure 7 Anova test for ISE

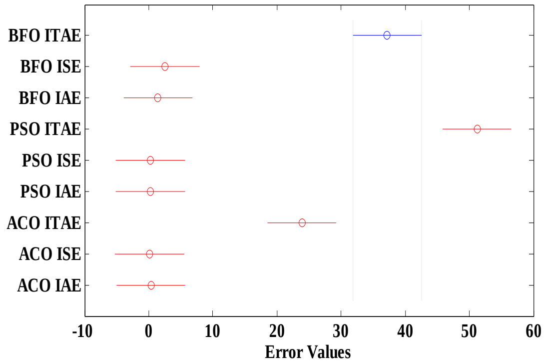

Figure 8 Multi-comparisons of Error Indices

7. CONCLUSION

PID controller for Self Balancing bicycle is designed based on optimization techniques like BFO, PSO and ACO Algorithms. Their error values are compared using Anova test. It is found that ITAE error of PSO is higher than other two algorithms. From the Multi-comparison graph it is clearly found that ACO Algorithm has less error value when compared to other algorithms. Further improvement can be made by connecting with Bluetooth microcontroller to control the cycle [11].

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