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Application of Whale Optimization Algorithm for tuning of a PID controller for a drilling machine

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Abstract – The aim of this work is to implement the recently developed metaheuristic algorithm known as the Whale Optimization Algorithm to tune a PID controller of a high-performance drilling machine. The algorithm is evaluated by setting the Integral Absolute Error as the objective function. The simulation results are then compared with the widely used conventional tuning technique namely Ziegler-Nichols (Z-N) along with another commonly used evolutionary computation technique, the Particle Swarm Optimization (PSO). The results obtained in this work indicates that this novel algorithm can give satisfactory results while tuning the PID controller.

Index Terms – Meta-heuristic algorithm, Whale optimization algorithm, PID controller.

I. INTRODUCTION

Engineers have relied on PID controllers for almost half a century to regulate a wide variety of industrial processes [1]. Throughout the years, the PID controller has proven to be a stable and reliable control system method. It is a relatively simple and robust control technique that has a broad range of application in engineering [2]. It has been reported that about 80% of the control systems particularly in industrial process are using these controllers [3]. Even though a large number of research works are available on the tuning of PID controllers, numerous works are still being developed to enhance the controller performance as improvements in tuning of PID controllers will have a significant practical impact.

Several conventional tuning techniques such as Ziegler-Nichols method [4], Cohen-Coon method [5], IMC method [6] etc exists in the literature to tune a PID controller. In addition to these conventional techniques, numerous optimization algorithms have been applied in the tuning of PID controllers. An optimization algorithm is a numerical method or algorithm for finding the maxima or minima of a function subjected to certain constraints [7]. Majority of the optimization algorithms are classified as computational intelligence algorithms relying mainly on evolutionary computation [8]. These algorithms combine the elements of learning, adaptation and evolution to create programs that are intelligent. One of the most important features of these techniques is that it helps in finding the optima in complicated optimization problems more quickly than the traditional optimization methods [9].

Some of the most widely used evolutionary computation techniques include Genetic Algorithm [10], Particle Swarm Optimization [11], Ant Colony Optimization [12] etc. These algorithms gained importance because of their simplicity, ability to bypass local optima and their potential implementation in a wide range of problems covering different disciplines [13].

Recently, a novel meta-heuristic algorithm known as “Whale Optimization Algorithm (WOA)” mimicking the hunting behaviour of humpback whales was developed by Mirjalili et al [14]. The algorithm is population-based and makes use of exploration and exploitation phases in the search process.

A high-performance drilling process is selected as the case study in improving efficiency in a production environment through a cutting-force control system. The objective of this paper is to implement WOA to tune a PID controller for the above-mentioned system. The simulation results obtained are then compared with the conventional tuning technique (Z-N) and some other evolutionary computation techniques. The optimization results demonstrate that WOA is very competitive compared to the other commonly used optimization methods.

The rest of the paper is organized as follows: We discuss the mathematical model of the high-performance drilling system following which the whale optimization algorithm is explained along with the flowchart of the algorithm. The paper concludes by presenting the tuning results and the comparative studies.

II. DYNAMIC MODEL OF HIGH-PERFORMANCE DRILLING PROCESS

The modeling of a high-performance drilling process [15] includes the modeling of the feed drive system, the spindle system and the cutting process. In this paper, the overall plant model is obtained by experimental identification using different step shaped disturbances in the command feed. The drilling force, F , is proportional to the machining feed, and the corresponding gain varies according to the work piece and drill diameter. The overall system of the feed drive, cutting process and dynamometric platform was modelled as a third-order system, and the experimental identification procedure yielded the transfer function as:

$$G(s) = \frac{F(s)}{f(s)} = \frac{1958}{s^3 + 17.895s^2 + 103.35s + 190.8} \quad (1)$$

Where s is the Laplace operator, f is the command feed, and F is the cutting force. The model does have certain limits in representing the complexity and uncertainty of the drilling process. However, it provides a rough description of the process behavior that is essential for designing a network-based PID control system.

III. PID CONTROLLER

A PID controller is a combination of a proportional, an integral and a derivative controller, integrating the main features of all three. The proportional control action changes the input such that it is directly proportional to the control error. The integral control action changes the input such that it is proportional to the integrated error. The derivative action of the controller changes the input proportional to the derivative of the controlled variable. The overall controller action is the sum of the contributions from these three terms [16].

Fig. 1 demonstrates a simplified block diagram of a plant controlled by a PID. The output of a PID controller, which is the processed error signal, can be presented as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t) \quad (2)$$

Where K_p, K_i and K_d are the proportional, integral and derivative gains respectively.

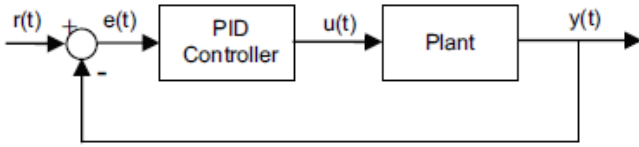


Figure 1: Block diagram of a plant controlled by PID

IV. THE WHALE OPTIMIZATION ALGORITHM

A new metaheuristic algorithm based on the hunting behaviour of humpback whales was proposed by Mirjalili et al. in the year 2016. It is known as The Whale Optimization Algorithm (WOA). The special hunting method employed by the humpback whales is called the bubble-net feeding method. It is a foraging behaviour that is developed by creating distinctive bubbles along a circle or 9-shaped path. The mathematical model of the algorithm is explained in the following sections including the stages of hunting. The WOA algorithm has the following stages:

- Encircling Prey
- Bubble-net attacking method (Exploitation)
- Search for prey (Exploration)

A. Encircling prey

The location of the prey (mainly school of krill or small fishes) can be recognized by the whales following which they encircle them. However, since the position of the optimum solution is not known beforehand, the algorithm uses the equations 2 & 3 to calculate the solution close to the optimum. Once the best search agent is defined, the other agents will try to update their positions towards the best agent as the iterations increases.

$$\vec{D} = |\vec{C} \cdot \vec{X}^*(t) - X(t)| \quad (3)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D} \quad (4)$$

where, t is the current iteration, \vec{X}^* is the position vector of the optimal solution obtained so far and \vec{X} is the position vector, \vec{A} and \vec{C} are coefficient vectors.

The equations to calculate the coefficient vectors are given by

$$\vec{C} = 2 \cdot \vec{r} \quad (5)$$

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \quad (6)$$

where, \vec{a} is a variable linearly decreased from 2 to 0 over the course of iteration and r is a random vector in $[0,1]$.

Different places around the optimum solution can be achieved with respect to the current position by adjusting the value of \vec{C} and \vec{A} vectors. The random vector (\vec{r}) helps in reaching any position in the search space located between the key-points.

B. Bubble-net attacking method (Exploitation phase)

As mentioned earlier, the humpback whales attack the prey using the bubble-net strategy. The model of the attacking method is as follows:

Two approaches are given to model the bubble-net behaviour of humpback whales. They are Shrinking encircling mechanism and Spiral updating position.

B.1. Shrinking encircling mechanism

This mechanism is dependent on the value of \vec{a} . In order to achieve the shrinking behavior, the value of \vec{a} is decreased from 2 to 0 over the course of iterations. From the equation 5, it can be seen that the value of \vec{A} lies in the interval $[-\vec{a}, \vec{a}]$. By setting random values for \vec{A} between $[-1,1]$, the new position of a search agent can be defined between the original position and the position of the current best agent. A simple representation of the mechanism is given in figure 2.

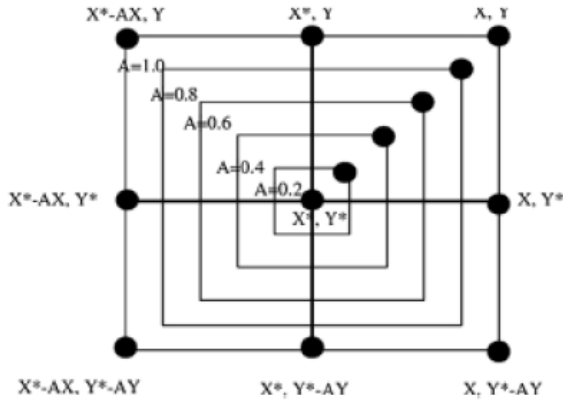


Figure 2: Bubble-net search-Shrinking mechanism

B.2. Spiral updating position

This approach calculates the distance between the whale located at position (X, Y) and the location of the prey at (X^*, Y^*) as shown in figure 3. Following this a spiral equation is then created to represent the helix-shaped movement of the whales. The spiral equation is given by

$$\vec{X}(t+1) = \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t) \quad (7)$$

where, $\vec{D}' = |\vec{X}^*(t) - \vec{X}(t)|$ and indicates the distance of the i^{th} whale to the prey, b is a constant for defining the shape of the logarithmic spiral, l is a random number in $[-1, 1]$.

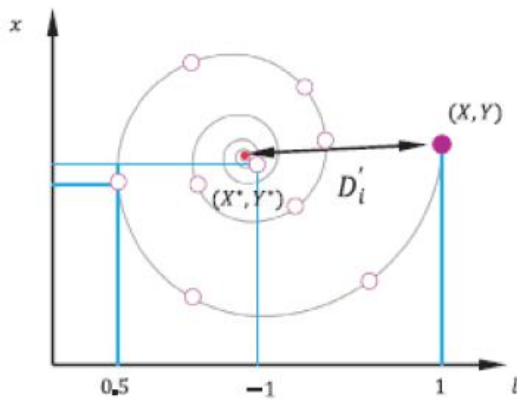


Figure 3: Bubble-net search – Spiral updating position

The humpback whales use both the mechanisms given above while hunting i.e., they swim around the prey within a shrinking circle and also along a spiral-shaped path simultaneously. In order to take this behaviour into account, it is assumed that there is a probability of 50% to choose between either one of the mechanisms. The mathematical model for the above said assumption is given by

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A} \cdot \vec{D} & \text{if } p < 0.5 \\ \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t) & \text{if } p \geq 0.5 \end{cases} \quad (8)$$

C. Search for prey (Exploration phase)

In this phase, it is considered that the humpback whales search randomly for prey according to the position of each other. The model for this approach is given by

$$\vec{D} = |\vec{C} \cdot \vec{X}_{rand} - \vec{X}| \quad (9)$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A} \cdot \vec{D} \quad (10)$$

D. Implementation of WOA

The detailed algorithm is given as follows:

- 1) Start with a set of random solutions
- 2) At each iteration update the position of the search agents with respect to either the randomly chosen search agent or the best solution obtained so far.
- 3) The parameter \vec{a} is decreased from 2 to 0 to provide the exploration and exploitation phase.
- 4) Check for the value of p and switch between the shrinking mechanism or the spiral mechanism.
- 5) When $A \geq 1$, choose a random search agent and when $A < 1$, choose the best solution for updating the position of search agents.
- 6) Terminate the algorithm when the satisfactory termination criterion is reached.

The flow chart of the algorithm is given in figure 4.

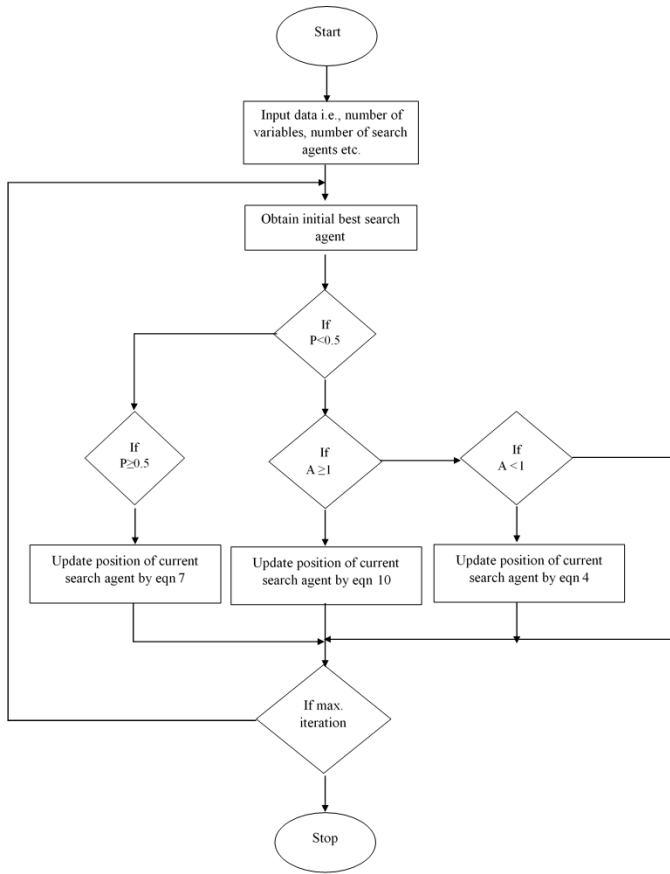


Figure 4: Flow chart of the Whale Optimization Algorithm

V. PERFORMANCE INDICES

The objective functions considered are based on the error criterion. A number of such criteria are available and in this work controller's performance is evaluated in terms of Integral of Absolute Error (ITAE) criterion [17].

The error criterion is given as a measure of performance index given by equation:

$$I_{IAE} = \int_0^T |e(t)| dt \quad (11)$$

The IAE weighs the error with time and hence emphasizes the error values over a range from 0 to T, where T is the expected settling time.

The other performances indices are

Integral Square of Errors (ISE) criteria given by

$$I_{ISE} = \int_0^T e^2(t) dt \quad (12)$$

Integral of Time multiplied by Absolute Errors (ITAE) given by

$$I_{ITAE} = \int_0^T t|e(t)| dt \quad (13)$$

The time is considered as $t=0$ to $t=T_s$, where T_s is the settling time of the system to reach steady state condition for a unit step input.

Mean Square Error (MSE) given by

$$I_{MSE} = \frac{1}{t} \int_0^T (e(t))^2 dt \quad (14)$$

For the transient domain of response, maximum overshoot, settling time and rise time are normally considered significant where the benefit of faster system, necessitates minimum possible values for them.

A. Termination criterion

The termination of the algorithm considered can be done either when the maximum number of iterations is reached or a satisfactory fitness value is attained. In the proposed work, the algorithm is terminated on reaching the maximum number of iterations.

VI. SIMULATION RESULTS

To implement the WOA, certain parameters need to be defined which decides the ability of the algorithm to converge at global minimum or maximum. The WOA uses the number of search agents, number of iterations and the number of variables as the input parameters.

The initial parameters used for the algorithm is given below:

Number of search agents: 100

Number of iterations: 100

Number of variables: 3

The algorithm was implemented in MATLAB and the calculated values of the PID controller are:

$$K_p = 1.13, K_i = 2, K_d = 0.31488$$

Comparison with other tuning techniques

The algorithms selected for the comparative study are Z-N (Conventional tuning technique) and Particle Swarm Optimization (PSO) [18]. The values obtained through the traditional as well as the proposed technique are presented in table 1. A tabulation of the time domain specifications comparison for the selected model with the designed controller is presented in table 2.

Table 1 : Table indicating the PID controller values using different tuning algorithms

Tuning algorithm	K_p	K_i	K_d
Z-N	0.5128	1.6649	0.0395
PSO	0.7164	1.4665	0.0984
WOA	1.13	2	0.31488

Table 2: Table giving the time domain specifications obtained using the PID controllers tuned by different algorithms

Time domain specifications	Z-N	PSO	WOA
Overshoot (%)	43	18	31
Rise time (s)	0.223	0.17	0.0541
Peak time (s)	0.4	0.2	0.13
Settling time (s)	2.7	1.4	0.588

The response of the system along with the controller is analysed with respect to a unit step input. The comparative plot of the system response is given in figure 5. It is clear from the figure and tables given above that WOA based controller has a better time domain performance when compared to all the other tuning techniques considered in this work.

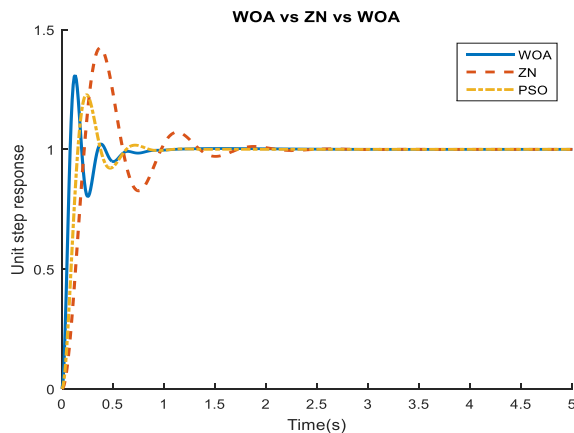


Figure 5: Comparison between WOA, ZN and PSO algorithms for a unit step response.

In addition to the time domain specifications, the four major error criteria used by most of the researchers namely Integral Time of Absolute Error (ITAE), Integral of Absolute Error (IAE), Integral Square of Error (ISE) and, Mean Square Error (MSE) has been used to compare the performance of the proposed algorithm as shown in table 3.

Table 3: Table showing the different performance indices values obtained using the PID controllers tuned by different algorithms

Performance indices	Z-N	PSO	WOA
IAE	3.4496	1.9047	1.5195
ITAE	1.1824	0.2157	0.1954
MSE	0.0369	0.0241	0.0210
ISE	1.8844	1.2291	1.0626

It is clear from table 3 that the proposed algorithm has better performance when compared to the other tuning techniques considered for the study.

VII. CONCLUSION

In the proposed work, a novel meta-heuristic optimization algorithm is implemented for tuning of a PID controller for a high-performance drilling system. It is shown analytically and graphically that there is considerable improvement in the time domain specification in terms of lesser rise-time, better settling time and lesser peak time. It is also shown that the performance index for various error criterion for the proposed controller using WOA is better than the other algorithms considered in this work. Future work includes the tuning of Fractional Order PID controller (FOPID) and its comparison with PID controller applied to various systems with varying complexity.

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