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An Optimized PID Controller Using Enhanced Bat Algorithm in Drilling Processes

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ABSTRACT

Drilling operation has a direct impact on the quality of the production. Insufficiently controlling the cutting force during the drilling process leads to the risk of early drill failure. Typically, the selection of the drilling parameters is determined based on machining-data handbook where the experience and skill of the operator are required. This paper presents an optimal framework to control the cutting force of the drilling process. A mathematical model that captures complex drilling dynamics between cutting force and feed rate based on system identification is used. Then, a Proportional-Integral-Derivative (PID) controller is proposed to control the cutting force. Taking advantage of up-to-date swam-based optimization technique, an Enhance Bat Algorithm (EBA) approach is used to tune the design variables of the PID controller based on the Integral Absolute Error (IAE) criterion. The results are compared with another two swam optimization, the Particle Swarm Optimization (PSO) and the Whale Optimization Algorithm (WOA). The comparison reveals that EBA can give better results in terms of improving time domain specifications and reducing error performance indices.

1. INTRODUCTION

Drilling operation is one of the common metal-removal processes. It is widely used in manufacturing and has a direct impact on the quality of production [1, 2]. Holes are necessary for the assembly of different items to be combined and finalize the product [3]. Therefore, improving the drilling process leads to significant economic benefits such as improving productivity and reducing costs. The friction and the temperature between the drilling operation and workpiece increase as the depth of the drilling increase. This leads to tool vibration and tool wear [4, 5]. Moreover, sometimes workpiece has a multi-layered (i.e. composite structure) that causes changes in the cutting surface stiffness [6]. Delamination of composite materials during the drilling process often happened due to insufficiently controlling the cutting force [7]. Feed rate of drilling operation is the important variable that needs to be controlled based on the cutting condition to improve the drill operation. Usually, the operator changes the feed rate during the drilling process based on his experience to work on a safe operation condition [8].

In order to control the cutting force, it is important to have an accurate mathematical model of the drilling process. Researchers have been developed a different data-driven mathematical model of the drilling process with different operating conditions. For example, Roukema and Altintas [9] proposed a mathematical model of the drilling process considering cutting speed, type of tool used and workpiece geometries as inputs and cutting forces and vibrations as outputs. The model has been formulated from a linear least squares regression. del Toro et al. [10] established a mathematical model between resultant force and feed rate in the drilling process using conventional identification methods. In the same way, Singh and Sharma [7] developed a mathematical model of a drilling process of a composite material. A transfer function formulation and state-space representation of the process was obtained by converting between thrust force and feed rate. On another side, different controller strategies have been investigated to control the drilling process. The majority of the papers utilized PID controller as the controller strategy [11-16].

Despite the existing extensive research on the tuning the PID controller, there is still a significant gap in understanding the best tuning strategies. In practice, finding optimal tuning for PID controllers is a challenging problem [16]. Nowadays, there is an increasing trend of using optimization in solving industrial problems and engineering research [17-21]. Taking advantage of recent optimization techniques, several tuning methods based on swam based optimization has been proposed for finding the best setting of numerous controllers [22, 23]. In the context of finding the optimal tuning of the PID controller in drilling process, different swarm optimization techniques have been proposed such as Simulated Annealing (SA) [11], PSO [13], WOA [15] and Enhanced Flower Pollination (EFP) [16].

In this paper, an optimal framework to control the cutting force of the drilling process is present. A mathematical model that captures complex drilling dynamics between thrust force and feed rate based on system identification is used. Then, a PID controller is proposed to control the cutting force. An EBA approach is used to tune the design variables of the PID controller based on IAE criterion. The rest of the paper is organized as follows: Section 2 presents the mathematical model of the drilling process. In Section 3 a brief explanation of the PID controller is given. The proposed optimization algorithm is explained in Section 4. Section 5 shows the simulation and comparative study. Section 6 summarizes the conclusion.

2. DRILLING PROCESS MODELLING

Mathematical model of a system provides a way to represent the behavior of that system using mathematical equations. By developing a model of a system, it can be used to gain deep insights into how the system works, predict its behavior under different work conditions, and design control strategies to achieve desired outcomes. Drilling is a machining process that involves complex interactions between the work piece and the cutting tool [12]. The mathematical model that is considered in this work of the drilling process is obtained experimentally using system identification. The specifications of the considered drilling process during the experiments are reported in Table 1 as given in literature [12].

Table 1. Drilling specification [12]

Parameter	Specification
Power	26 KW
Nominal feed rate	100 mm/min
Nominal spindle speed	870 rpm
Tool diameter	10 mm
Maximum hole depth	30 mm
Drilling tool coating	TiN/TiAlN

The modeling of the drilling process consists of modeling the feed drive, the spindle and the cutting process [13]. The input/output data from all the experiments are then processed. An open loop single-input single-output (SISO) mathematical model that best approximates the actual drilling process was obtained as a 3rd order transfer function. The feed rate is used as an input and the cutting force is the output. The 3rd order transfer function between cutting force and feed rate is given by [11, 12]:

$$G(s) = \frac{F(s)}{f(s)} = \frac{1958}{s^3 + 17.89s + 103.3s + 190.8} \tag{1}$$

where,
s: Laplace operator
G: Drilling-process transfer function
F: Cutting force
f: Feed rate

3. PID CONTROLLER

PID controller is used for stabilization and disturbance rejection of dynamical systems. It provides effective solutions to a majority of the control engineering problems [24]. PID consists of three terms of the proportional (P), integral (I) and derivative (D) as shown in Figure 1. The proportional term changes the control signal proportionally to the error. The proportional term makes the system faster and reduces the error steady-state. The integral term changes the control signal proportionally to the integration of the error. The integral term eliminates the error steady-state. The derivative term changes the control signal proportionally to the derivative of the error. This term reduces the settling time of the system [25].

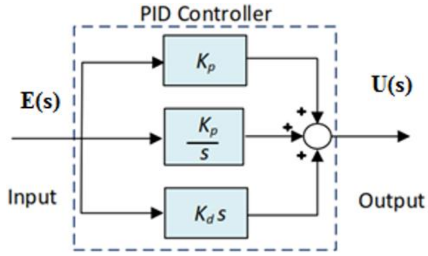

Figure 1. The block diagram of PID controller

The overall action of the controller is the sum of the contributions from these three terms. The final control signal $u(t)$ of the PID controller is the sum of the three terms as given [26, 27]:

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

The overall transfer function of the PID controller can be represented as follows:

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \tag{3}$$

where,
G_{PID}: PID transfer Function
U: Control signal
E: Error
K_p: Proportional gain
K_i: Integral gain
K_d: Derivative gain

4. ENHANCE BAT ALGORITHM

Bat Algorithm (BA) is a population-based swarm optimization algorithm. It was developed by Yang [28]. BA mimics the echolocation behavior of bats. Echolocation is a strategy used by bats to estimate distance and distinguish between prey and obstacles [29]. By using echolocation, the bat sends a series of loud ultra-sound waves and then receives back echoes with various sound levels. This process enables bats to identify between prey and obstacles [30]. Yang [28] assumed three approximations as follows:

The echolocation is used by all bats to discover the distance, and they know the difference between prey and obstacles when an echo is received back with various sound levels [31].

All bats have a velocity v, position x and frequency f. For searching for prey, bats fly randomly with fixed frequency and varying wavelength λ and loudness A [32]. Depending how they far from the target, they repeatedly adjust the wavelength of their emitted pulses and adjust the rate of pulse emission $R \in (1,0]$.

Loudness A reduces from the maximum value A_0 to its minimum value A_{min}.

In the bat algorithm, the frequency f_i, velocity v_i and position x_i are updated for each bat in as follows [28]:

$$f_i = f_{max} \times r_1 s \tag{4}$$

$$v_i(itr+1) = v_i(itr) + (x_i(itr) - x_g) \times f_i \quad (5)$$

$$x_i(itr+1) = x_i(itr) + v_i(itr+1) \quad (6)$$

where,

i: Counter for population (i=1,2,3,…,N)
itr: Counter for iteration (itr=1,2,3,…,T)
f_i: Frequency for bat i
f_{max}: Maximum frequency
r_1: Random value between [0,1]
v_i: Velocity for bat i
x_i: Position for bat i
x_g: Position of the bat that has the best fitness

The next search in bat algorithm is based on two parameters: loudness A and the pulse emission rate R as follows: Select a solution among best solutions. Then, select a round number ($Rand$) if $Rand < R_i$, generate new local solution around the best solution as given in Eq. (7).

$$x_i(itr+1) = x_i(itr) + r_2 A_p(itr) \quad (7)$$

where,

r_2: Random value between [0,1]
$A_p(itr)$: Average loudness value of all bats in the current iteration

Furthermore, a new solution randomly is generated based on Eq. (8).

$$x_i(itr+1) = x_i(itr) + r_2 A_p(itr) \quad (8)$$

If $Rand > A_i$ and the new solution f_{x_1} have better objective value than the best one found by the algorithm f_{x_g}, the algorithm will accept the new solution and loudness and pulse emission rate will be updated based on Eqs. (9) and (10).

$$A_i(itr+1) = \alpha A_i(itr) \quad (9)$$

$$R_i(itr+1) = R_i(1 - e^{-\gamma itr}) \quad (10)$$

where, α and γ are constant and for simplicity could be considered equal.

It can be notice that BA compromise between PSO and SA. However, in this work the BA enhanced by improving the update processes of velocity. The improvement is made by adding a new term to the Eq. (5) to let the bat guided by its best location found x_{ip} in addition to the global guidance x_g. This is similar to the PSO. The Eq. (5) after the modification becomes [33]:

$$v_i(itr+1) = v_i(itr) + \left(x_i(itr) - x_{ip}\right) \times f_i + (x_i(itr) - x_g) \times f_i \quad (11)$$

The pseudo code of EBA is illustrated in Algorithm 1.

Algorithm 1. Pseudo code of EBA

1. Input
•Objective function, Population size (N), Maximum frequency (f_{max}), Coefficient value (α), Number of iteration (T)
2. Initialization
•Initialize velocity v, position x, loudness A and the pulse emission rate R of the population
•Evaluate objective function and assign x_{pi} and x_g
3. Loop:
•while ($itr < T$)
‣**For** each bat in the population (N)
√Update population based on Eq. (4), Eq. (11) and Eq. (6)
‣**End for**
√Select a random number (Rand)
∗If $rand < R_i$
Select a solution randomly
Generate new local solution based on Eq. (7)
∗If rand > A_i
Generate new solution randomly based on Eq. (8)
Update loudness based on Eq. (9)
Update pulse emission rate based on Eq. (10)
√Update x_{pi}
‣**End for**
‣Update x_g
‣$itr = itr + 1$
•End while
4. Print the Optimal Solution

5. SIMULATION STUDY

In this section, the simulation results of controlling the cutting force of the drilling process that is given by the transfer function in Eq. (1) using the PID controller as given in Eq. (3) are reported. EBA is employed to find the optimal value of the gain parameters of the PID controller. IAE index as given in Eq. (12) [34] is used as a cost function of the optimization.

$$IAE = \int_{t=0}^{t=T} |e(t)| dt \quad (12)$$

The parameters of the EBA are listed in Table 2.

Table 2. EBA algorithm parameters

Parameters	Value
Population size (N)	50
Number of iterations (T)	100
Maximum Frequency (f_{max})	0.8
Loudness	0.9
Pulse emission rate	0.5

A step change in the input force is considered and the goal of the PID controller is to follow set-point changes. The simulation was executed in MATLAB and the values of the parameters of the PID controller are found as given:

$$K_p = 0.8828, K_i = 1.8188, K_d = 0.2227$$

Figure 2 shows the response of the system to unit step input. Comparatives analysis was performed with another two swam optimizations, PSO and WOA. The value of the designed gains K_p, K_i and K_d of the PID controller that were obtained by the proposed EAB, PSO and WOA is given in Table 3.

For evaluation the proposed EBA, time domain specifications comparison as given in Table 3 is made with the results obtain by PSO and WOA.

It can be noticed form Figure 2 and also form the results that reported in Table 4 that the proposed EBA-PID controller is a compromise solution between the PSO-PID and WOA-PID. For instance, EBA-PID has less overshoot than WOA-PID but need longer time to reach steady state. In the same way, EBA-PID has less settling time than PSO-PID but it has more overshoot.

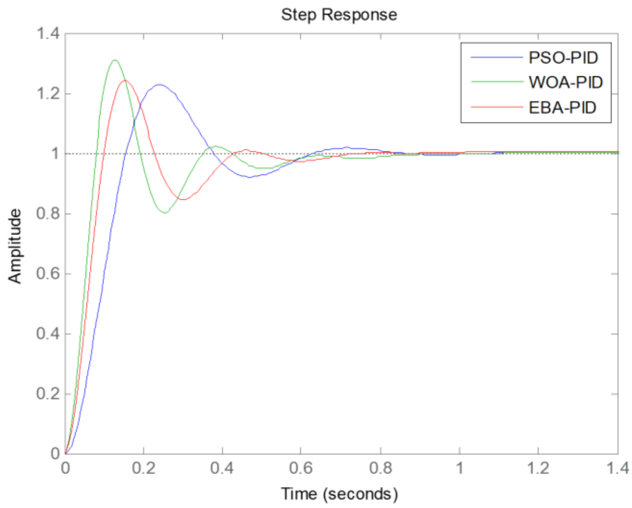

Figure 2. Unit step response of the PSO, WAO and EBA based PID controller

Table 3. PID controller values using PSO, WAO and EBA based PID controller

Tuning Algorithm	k_p	k_i	k_d
PSO-PID [13]	0.7164	1.4665	0.0984
WAO-PID [15]	1.13	2	0.31488
EBA-PID (Proposed)	0.8828	1.8188	0.2227

Table 4. Time domain specifications of the PSO, WAO and EBA based PID controller

Time Domain Specifications	PSO-PID	WAO-PID	EBA-PID
Overshoot (%)	18	31	24
Peak time (s)	0.2	0.13	0.15
Rising time (s)	0.17	0.054	0.067
Settling time (s)	1.4	0.588	0.64

In addition, a number of error performance indices namely IAE as given in Eq. (12) [34], Integral Time of Absolute Error (ITAE) as given in Eq. (13) [35], Integral Square of Error (ISE) as given in Eq. (14) [36] has been employed to compare the performance of the proposed EBA algorithm as revealed in Table 5.

$$ITAE = \int_{t=0}^{t=t_{sim}} t|e(t)|dt \quad (13)$$

$$ISE = \int_{t=0}^{t=t_{sim}} e^2(t)dt \quad (14)$$

Table 5. Error performance indices of the PSO, WAO and EBA based PID controller

Performance Indices	PSO-PID	WAO-PID	EBA-PID
IAE	1.9047	1.5195	1.3933
ITAE	0.2157	0.1954	0.1848
ISE	1.2291	1.0626	1.0406

It can be clearly seen from Table 5 that the PID controller designed by EBA reduces error performance indices in comparison with the PID controller designed by PSO and WOA. For example, EBA-PID reduces the IAE of the system by 26.85% and 8.3% in comparison with PSO-PID and WOA-PID respectively. Besides, the ITAE of the system with EBA-PID is reduced by 14.3% and 5.4% in comparison with PSO-PID and WOA-PID respectively. In the same way, the ISE is reduced by 15.3% and 2% in comparison with PSO-PID and WOA-PID respectively. These results show superiority of EBA over other two methods to tuning the designed gains k_p, k_i and k_d of the PID controller.

The implication of the current study is to improve the control algorithm of the drilling process using the compensation of the PID controller with the swarm optimization techniques. The economic advantages from this improvement of the closed-loop drilling control by keeping the value of the feed rate close to the set point without overshoot prevents damage to the workpiece surface and drilling tool.

6. CONCLUSIONS

Drilling process is the most commonly manufacturing operation in today's industries. Feed rate of drilling process is the important variable that needs to be controlled based on the cutting condition to improve the drill operation. Due to the simplicity and the low cost compared to other controllers, PID controller has been implemented in this paper to control the cutting force during the drilling process. To find the optimal value of the designed gains k_p , k_i and k_d of the PID controller, an Enhance Bat Algorithm (EBA) approach is used based on the Integral Absolute Error (IAE) criterion. A step change in the input force is considered and the goal of the PID controller is to follow set-point changes. To evaluate the proposed tuning method, the results is compared with two swam optimization, the Particle Swarm Optimization (PSO) and the Whale Optimization Algorithm (WOA). In terms of time domain specification, it is revealed that there is an improvement such as reducing settling time and reduce overshoot. In terms of the performance induces that are based on error, the proposed tuning algorithm achieved better results than the other swam optimization that are considered in this paper. The results show that the EBA-PID reduces the IAE of the system by 26.85% and 8.3% in comparison with PSO-PID and WOA-PID respectively. Moreover, the ITAE of the system with EBA-PID is reduced by 14.3% and 5.4% in comparison with PSO-PID and WOA-PID respectively. Besides, the ISE is reduced by 15.3% and 2% in comparison with PSO-PID and WOA-PID respectively.

Future research for further improving in the system performance can be performed in different directions. One possible improvement is by investigation a new novel optimization technique to tune the design parameters of the PID controller. Other direction for future work, the proposed tuning method for the PID can be used in other applications beyond the context of drilling process.

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NOMENCLATURE

$A_p(itr)$	Average loudness value of all bats in the current iteration
E	Error
F	Cutting force
f	Feed rate
f_i	Frequency for bat i
f_{max}	Maximum frequency
$G(s)$	Drilling-process transfer function
$G_{PID}(s)$	PID transfer Function
i	Counter for population ($\mathrm{i} = 1,2,3,..\mathrm{N}$)
itr	Counter for iteration ($\mathrm{itr} = 1,2,3,..\mathrm{T}$)
K_d	Derivative gain
K_i	Integral gain
K_p	Proportional gain
r_1	Random value between [0,1]
r_2	Random value between [0,1]
s	Laplace operator
U	Control signal
v_i	Velocity for bat i
x_i	Position for bat i
x_g	Position of the bat that has the best fitness

Greek symbols

α	Coefficient in EBA
γ	Coefficient in EBA

Acronym

BA	Bat Algorithm
EBA	Enhance Bat Algorithm
IAE	Integral Absolute Error
ITAE	Integral Time of Absolute Error
ISE	Integral Square of Error
PSO	Particle Swarm Optimization
PID	Proportional-Integral-Derivative
SA	Simulated Annealing
SISO	Single-Input Single-Output
WOA	Whale Optimization Algorithm