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Optimization of PID controller tuning parameters for multivariable system using Duelist algorithm

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Abstract. In this paper, one of the most current new stochastic optimization method is proposed to tune decentralized proportional-integral-derivative (PID) controller for a multi-input-multi-output (MIMO) system. PID controller is still the most used controller in industrial application due to its easy application in control system. However, it still having problem to be tuned correctly especially for MIMO system. The decentralized controllers in this paper will be tuned simultaneously using duelist algorithm (DA) method and optimal value of controller parameters is obtained from a minimum of integral absolute error (IAE) value. The optimization of the objective function is based on the evaluation of IAE when a step change in u1 and u2 is introduced to the system. Form the simulation result, the proposed method is observed to have a better performance than other popular tuning method.

1. Introduction

Multi-input-multi-output (MIMO) system is the most encountered system in real industrial processes. A process in industry is becoming more complex to ensure the quality and quantity of the product is conserved as well as due to energy integration [1-3]. Hence, a more sophisticated way to control the system is needed to meet the requirements. A MIMO system is more complex than a single-input-single-output (SISO) system due to the increase in the number of control loops, thus increase the interactions between the loops [1, 4-5]. A manipulated variable could affect more than one controlled variable due to the loop interactions and increase the complexity of the system. An effective control system should be implemented to such system to ensure the efficiency of the operation and energy of the system [3].

Nowadays, there are many advanced controller has been developed in line with the increase in the complexity of a system. However, proportional-integral-derivative (PID) controller remained the most widely used controller in industrial application [6-7]. Over 90% of controller in industrial control application is using PID algorithm controller [1, 8]. The popularity gained by PID are due to its simple structure, good stability, reliable, robust performance, and wide operating condition and quite easy to be tuned on line [2, 9-14]. Those advantages make a PID controller easy to be operated by an operator or engineer. Despite the advantages, PID controller still having difficulties to be tuned and designed due to the interactions between the loops [7, 15].

There are many methods had been developed to tune a PID controller. One of the method is by optimization method. [8] had listed a few optimization methods had been used to tune a PID controller such as genetic algorithm, particle swarm optimization, tribes algorithm, harmony search, evolution strategy, ant colony and more. [16] had proposed to use multi-objective optimization design procedure in PID controller tuning application. [9-10, 17] had modified the genetic algorithm method to optimize PID parameters to find the suitable controller parameters with minimum integral absolute error (IAE). There is also a hybrid optimization where the author combined the differential evolution algorithm with chaotic Zaslavskii map to optimize PID controller parameters in a multivariable system [8].

In this paper, the most recent new optimization technique, which is duelist algorithm (DA) introduced by [18] is proposed to tune a decentralized PID controller for a multivariable system. Previously, DA has been implemented to simultaneously tune two PID controllers for a cascade control system [19]. It can be observed that DA optimization method did improved the performance of the PID controllers in the cascade control system. Thus, in this study, DA optimization algorithm will be implemented to two decentralized PID controller for a MIMO system of a distillation column to observed whether it can improve the performance of the controller or not.

2. Multivariable System

A multivariable system is a process that has either more than one input variable or output variable. A multivariable system could be difficult to control if there is an existence of cross couplings in the process. The cross coupling should be encountered well to avoid any problems to the control system. There are two main problems could be aroused due to the negligence of the cross couplings.

1. A change in an input could affect more than one output of the process.
2. The tuning of the PID controller will be difficult due to the interaction and the controller will be less stable.

In multivariable system, the system is control to ensure a change in a set point would not or mild affect other control variables.

A matrix of transfer function for a TITO system $G_p(s)$, can be writen as below in equation 1.

$$G_p(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \tag{1}$$

Let a First Order plus Dead Time (FOPDT) model represents the each element of the transfer function matrix $G_{ij}(s)$ in equation above. FOPDT can be written as shown in equation 2 below.

$$G_{ij}(s) = \frac{K_{pij}e^{-\theta_{ij}s}}{(\tau_{ij}s + 1)};\ i = 1, 2\ \ j = 1, 2 \tag{2}$$

PID controller design can be either a centralized or a decentralized controller. In this paper, a decentralized PID controller is designed. The structure for a decentralized controller can be defined as in equation 3 below:

$$G_c(s) = \begin{bmatrix} G_{c11}(s) & 0 \\ 0 & G_{c22}(s) \end{bmatrix} \tag{3}$$

$G_{c,ij}(s)$ is defined based on the mode of PID controller used. PID controller can be in either P mode, PI mode, PD mode or PID mode. PID controller for this paper is assumed to be in parallel form. PI mode of PID controller is used in this paper. The elements of the controller when PI mode is used is described as equation 4.

$$K_c\left(1 + \frac{1}{\tau_I s}\right) \tag{4}$$

Figure 1 illustrates a multivariable system with two decentralized PID controller.

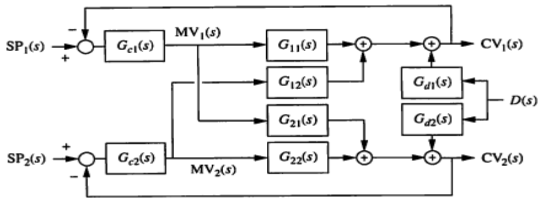


Figure 1. Block diagram of closed 2x2 system with two single control loop.

3. Optimization Using Duelist Algorithm

In this paper, the multivariable system of a distillation column is considered. In the system, the manipulated variables are reflux flow (MV1) and reboiler flow (MV2), meanwhile the controlled variable is the distillate (CV1) and bottom (CV2) product. There are two decentralized PID controller implemented in the system. The optimization of the four controller parameters ($K_{p,1}$, $K_{i,1}$, $K_{p,2}$ and $K_{i,2}$) will be done by simulation in MATLAB. A suitable value of each parameter will be obtained to have an optimal objective function for the system.

3.1. Objective Function Evaluation

In this paper, a simultaneous unit step change in set point value for u1 and u2 are set and allow an evaluation of Integral Absolute Error (IAE), which is defined in equation 5 up to the settling time. The IAE of the system is used as an objective function for the optimization and to be minimized by DA.

$$\mathrm{IAE} = \int_0^\infty |\mathrm{e(t)}|\mathrm{dt} = \int_0^\infty |\mathrm{r(t)} - \mathrm{y(t)}|\,\mathrm{dt} \qquad (5)$$

The performance of the controller will be analysed based on the IAE, steady state error, settling time and maximum overshoot.

3.2. Optimization by Duelist Algorithm

Duelist Algorithm (DA) is a new stochastic optimization algorithm inspired by human fighting and learning capabilities. In DA, the individual of the population is known as duelist. The duelist will be fight to each other in order to determine the winner, loser and champion. The result from the fighting, either win or lose will determine what kind of action will be taken by the duelist. Figure 2 shows the sequence of DA method.

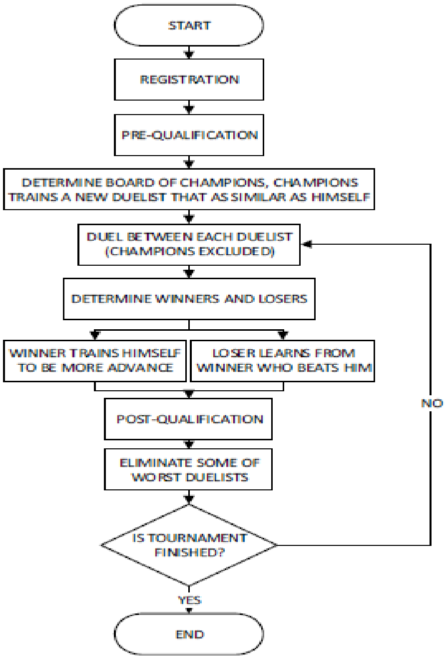


Figure 2. Sequence on how duelist algorithm (DA) is worked.

3.2.1. Registration. Each duelist is registered using a binary array which also known as skillset in DA while in genetic algorithm known as chromosome.

3.2.2. Pre-Qualification. A test taken by each duelist to measure their fighting abilities. Their abilities depend on their skillset.

3.2.3. Determination of Board of Champions. The best duelist for the fighting is kept in the Board of Champions. The champion will train other duelist to be as par as it in its fighting capabilities. The new duelist with the same abilities from previous champion will join the next game.

3.2.4. Duel between each Duelist. The fighting game is set randomly for each duelist. The winner and loser for very match is determined from the duelist's capabilities and luck. The duelist's luck is purely determined by a random function. This is to avoid local optimum. Algorithm shown below is the pseudocode used to determine the loser and the winner.

```
Required: Duelist A and B; Luck_Coefficient
A(Luck) = A(Fighting_Capabilities) * (Luck_Coefficient + (rand(0-1) * Luck_Coefficient));
B(Luck) = B(Fighting_Capabilities) * (Luck_Coefficient + (rand(0-1) * Luck_Coefficient));
If ((A(Fighting_Capabilities) + A(Luck)) <= (B(Fighting_Capabilities) + B(Luck)))
A(Winner) = 1;
B(Winner) = 0;
Else
A(Winner) = 0;
B(Winner) = 1;
End
```

3.2.5. Improvement by Duelist. The duelists will try to improve themselves after the match. There are three types of action or treatment taken by a duelist. For a loser, it will learn from the winner by copying the binary array of a winner. For a winner, it will try on something new by randomly manipulate its own array and for a champion, it will train other new duelist.

3.2.6. Elimination. Elimination is done based on the fighting capabilities. The worst duelist in the duel will be eliminated. Below are the details on DA optimization parameters*:*
Population = 20
MaxGeneration = 100
FightCapabilities = 20
Champion = 0.1
ProbLearning = 0.8
ProbInnovate = 0.1
Luckcoeff = 0.01
Dimension = 6

4. Results and Discussion

The plant used for the simulation is taken from Marlin (2000). Equation 6 and 7 show the transfer function of the plant for manipulated variable and disturbance respectively;

$$G_p = \begin{bmatrix} x_D(s) \\ x_B(s) \end{bmatrix} = \begin{bmatrix} \frac{0.0747e^{-3s}}{12s+1} & \frac{-0.0667e^{-2s}}{15s+1} \\ \frac{0.1173e^{-2.2s}}{11.7s+1} & \frac{-0.1253e^{-2s}}{10.2s+1} \end{bmatrix} \begin{bmatrix} F_R(s) \\ F_V(s) \end{bmatrix} \tag{6}$$

$$G_d = \begin{bmatrix} \frac{0.70e^{-5s}}{14.4s+1} \\ \frac{1.3e^{-3s}}{12s+1} \end{bmatrix} [x_F(s)] \tag{7}$$

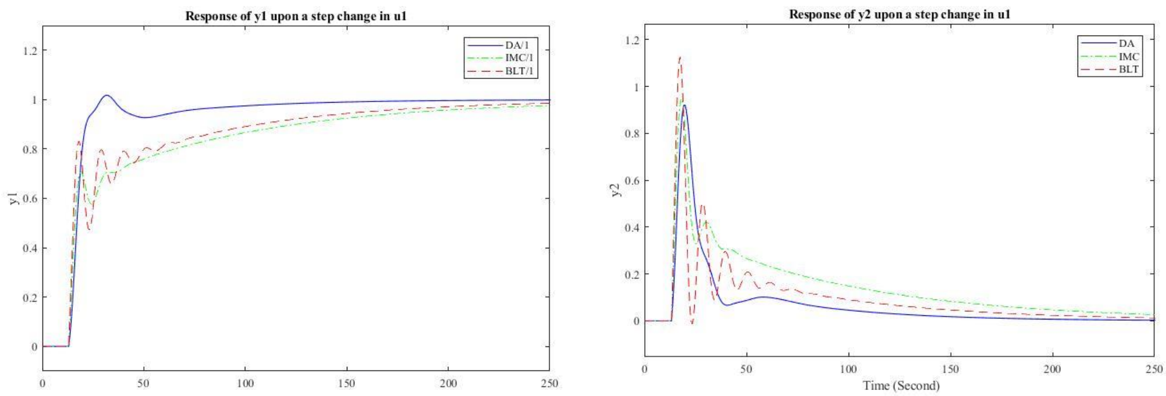
The simulation is done for a few step change; set point change of x_D (u1), set point change of x_B (u2), simultaneous set point change of x_D (u1) and of x_B (u2) and step change of disturbance. The performance of the controller using DA method is being compared with other methods, which are conventional Internal Model Control (IMC) and biggest-log modulus tuning (BLT) method. Table 1 shows the controller parameters when being tuned using three different tuning methods. From the simulation, the steady state error for all response using those three different methods are observed to be zero.

Table 1. PID controller parameters of three different tuning methods.

Method	$K_{p,1}$	$K_{p,2}$	$K_{i,1}$	$K_{i,2}$
DA	10.210	-31.644	6.855	-4.394
IMC	26.774	-20.351	2.231	-1.995
BLT	35.789	-27.207	2.659	-3.034

4.1. A step change in first input, u1 (set point of x_D) at time, t=10s

Figures 3(a) and 3(b) show the responses given by y1 and y2, respectively, when a step change in u1 is set, while table 2 shows the performance analysis of the controller for different methods. From figures 3(a) and 3(b), the response shown by DA method is the best among the other two methods. When a step change of u1 is introduced to the system, PID controller optimized by DA shows the faster response to the desired value for y1 and y2, which is 1 and 0 respectively. Besides, both y1 and y2 responses when using DA optimization method illustrates a minimum oscillation, which leads to a more stable system towards the step change in u1. BLT method shows the highest oscillation among the three methods. IMC is seen to have a very minimum overshoot, however, the response is too sluggish for both output. The response obtained using DA is hence the best and DA method is observed to have the minimum value of IAE for both output, y1 and y2 compared to other methods.



(a) (b)

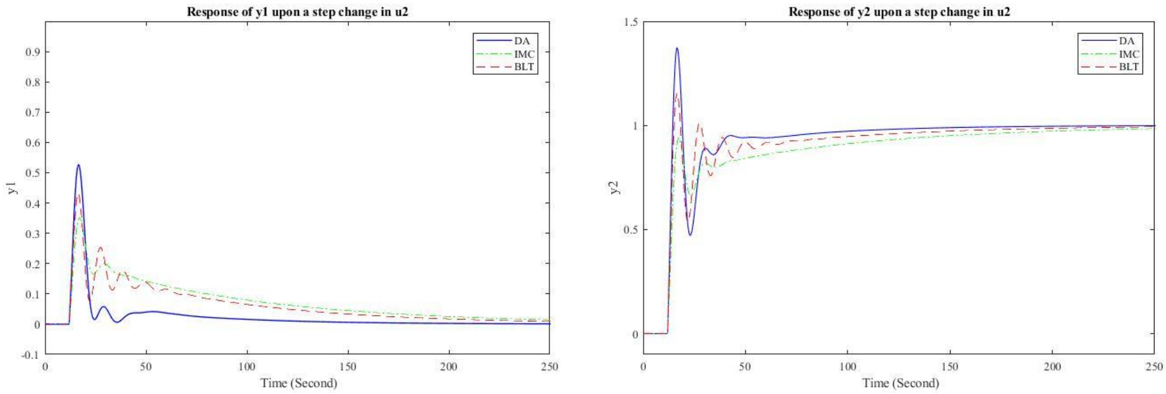
Figure 3. Response of (a) first output, y1 and (b) second output, y2 when a step change of first input, u1 is introduced.

Table 2. Performance analysis of y1 and y2 for three different tuning methods.

	y1				y2		
	Maximum peak	Overshoot (%)	Settling Time (s)	IAE	Maximum peak	Settling Time (s)	IAE
DA	1.0177	1.7736	225.7905	12.03	0.9217	295.8903	17.38
IMC	0.9987	0	520.1091	36.53	0.9471	545.5867	38.23
BLT	0.9995	0	451.2056	30.63	1.1255	405.6164	25.16

4.2. A step change in second input, u2 (set point of x_B) at time, t=10s

Figures 4(a) and 4(b) show the responses of y1 and y2 accordingly when a step change in u2 is introduced to the system. Meanwhile, table 3 lists the performance analysis for all different methods. From the analysis, PID controller parameters optimized using DA method shows the fastest response to the set point value compared to BLT and IMC method for both output responses. DA method gives the shortest setting time. Minimum overshoot or peak is given by IMC method for both output responses but the system is very sluggish. IMC method has the longest settling time compared to other two methods. As can be observed from figures 4(a) and 4(b), DA method has a very minimum oscillation and the system can be seen to be very stable. However, in y2 response, DA method is observed to show a quite aggressive response towards the bottom composition tracking (y2) where there is a significant overshoot can be seen. DA method still shows the best performance among the three methods as the IAE value is very minimum and gives faster response.



(a) (b)

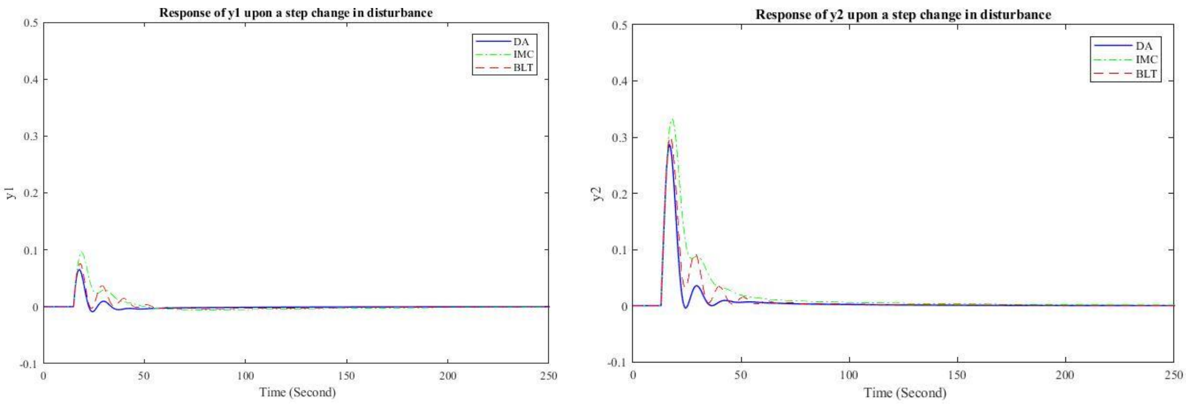
Figure 4. Response of (a) y1 and (b) y2 when a step change of second input, u2 is introduced.

Table 3. Performance analysis of y1 and y2 for three different tuning methods.

	y1			y2			
	Maximum peak	Settling Time (s)	IAE	Maximum peak	Overshoot (%)	Settling Time (s)	IAE
DA	0.5272	242.6308	6.334	1.3736	37.3588	237.4746	13.3
IMC	0.3498	604.9694	19.44	0.9991	0	451.3486	24.35
BLT	0.4315	497.8624	16.31	1.1554	15.5375	346.6113	16.66

4.3. A step change in disturbance input at time, t=10s

Figures 5(a) and 5(b) show the responses of y1 and y2, respectively, using three different methods when a step change in disturbance is introduced to the system. Table 4 above shows the performance analyses for the method. DA is observed to give the fastest time to remain to its desired steady state value for both y1 and y2 when a disturbance change is set to the system. For y1 response, there is very insignificant oscillation observed when the disturbance is set to the system. The peak for all method is below 0.1 and 0.4 for y1 and y2 response accordingly. However, even though the overshoot is not very significant, the response obtained when DA is used is observed to remain as the best response. From table 4, it clearly states that the minimum IAE and peak belongs to DA method. Moreover, DA method has the fastest response to return to the desired steady state value.



(a) (b)

Figure 5. Response of (a) first output, y1 and (b) second output, y2 when a step change of disturbance is introduced.

Table 4. Performance analysis of y1 and y2 for four different tuning methods.

	y1			y2		
	Maximum peak	Settling Time (s)	IAE	Maximum peak	Settling Time (s)	IAE
DA	0.0652	186.9565	0.5774	0.2868	118.1192	2.231
IMC	0.0962	372.2831	1.667	0.332	182.2883	4.889
BLT	0.0758	325.4664	1.059	0.3002	130.5139	3.218

5. Conclusion

In this paper, DA optimization method is being used to find the optimal PID controller parameters for a minimum IAE value. A MIMO system of a distillation column is considered for the simulation. From the result obtained, DA has proved that it could improve the performance of the PID controller. The system is less oscillated when a step change in either set point or disturbance is introduced to the system. It has a low overshoot and peak. Moreover, in all step changes, DA gives the shortest settling time for both y1 and y2 as well as the most minimum value of IAE. Thus, DA is seen to be one of a stochastic optimization method that could be used to tune and optimize a decentralized PID controller parameters for a MIMO system. DA method has a high potential to improve the performance of the controller towards the system when either there is a step changes in set point or disturbance is introduced to the system. Further improvement to the DA algorithm could be done to improve its ability in optimizing the controller parameters by reducing the overshoot.

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