Multivariable PID controller design tuning using bat algorithm for activated sludge process

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Abstract. The designing of a multivariable PID control for multi input multi output is being concerned with this project by applying four multivariable PID control tuning which is Davison, Penttinen-Koivo, Maciejowski and Proposed Combined method. The determination of this study is to investigate the performance of selected optimization technique to tune the parameter of MPID controller. The selected optimization technique is Bat Algorithm (BA). All the MPID-BA tuning result will be compared and analyzed. Later, the best MPID-BA will be chosen in order to determine which techniques are better based on the system performances in terms of transient response.

1. Introduction
Nowadays, the health of natural ecosystems has been giving more attention cause of the effect of the human development in very different ways [1] by increased environmental awareness in terms of water pollution anticipation. The constricted laws and requirements toward quality of water are fortunately acting like a driving force for the development of wastewater treatment plants (WWTPs) [2]. The complex, interrelated and highly nonlinear of its biological, physical and chemical phenomena make the WWTP become more difficult to be controlled while optimizing operating and management costs [3].

Meanwhile, the activated sludge process (ASP), a biological processes are usually popular methods used to remove carbon as well as components of nitrogenous from wastewater beforehand it being released [4]. ASP has been a widely cased study in the automatic control perspective, for example by Yong et al. [5] where the concentration of ammonia in the fluent of the wastewater plant is reducing by the implementation of cascading PI-like controller with feed-forward actions. The model predictive control (MPC) by Holenda et al. [6] proposed that MPC method also can be used for ASP system. There are significant benefits that can be obtained of using the MPC system which is decreasing of more than 25% in power usage and an increase in plant efficiency [7] but it is only determining and controlling the dissolved oxygen concentration.

A previous study was done by Shen et al. where a multiple input approach is implemented, by the recycle flow rates, the oxygen transfer coefficient of three aerated tanks and a complementary carbon source. Fuzzy controller has proved its efficiency to be implemented at WWTPs for improving the denitrification or nitrification process but these method gives a high cost and behaves relatively rough toward its control actions [8].
WWTP also is categorized as a complex system. Therefore, effective control methods need to be implemented for economic and environmental reasons, especially its ASP because it involves a biological process. Unfortunately, an increasing claim for a more stable effluent water quality [1] makes a scalar PID based control systems are become insufficient anymore due to the complexity of the system such as interrelated and highly nonlinear of its biological, physical and chemical phenomena. Besides, when the system becomes more complex, the process of tuning controllers also becomes more difficult [3].

In an attempt to overcome that problem the suitable controller tuning methods and optimization techniques are investigated in this paper in order to obtain an optimal solution to get the best values of the parameter. A type of MPID system where a combination more than one variable at the input or output is being investigated in this paper. Then, MPID methods considered are Davison, Penttinen-Koivo, Maciejowski and Proposed Combined. The optimization approach also being used in this paper for tuning the MPID of ASP where optimization is the process of finding an ideal solution to get the best values of parameters for the problem under stated conditions by executing the procedure in comparing several solutions till an optimum solution is found using an optimization algorithm [9]. The main objectives of this paper are to gain parameter tuning of ASP using optimization technique of BA and comparing the system performances in term of transient response.

This paper is divided into several sections. Section 2, an activated sludge system used is briefly described. Then, a multivariable PID control tuning method is presented in section 3. Section 4 contains a brief explanation on BA. The objective function used is shown in section 5. In section 6, simulation results of MPID-BA are discussed. This paper ends with a conclusion and future works.

2. Activated Sludge Process
Activated sludge process (ASP) is the most widely used for the biological wastewater treatment plant and a type of secondary treatment where a high level of elimination of biodegradable organic pollutants are given to keep receiving water quality that clarification alone cannot provide. The ASP also can speeds up decomposition by adding an activated sludge into the wastewater where the activated sludge particles hold many living organisms that can feed on the incoming wastewater [10].

The non-linear Activated Sludge Process that has been selected and used for this research is taken from [11]. Activated sludge processes are biological that removes pollutant from the wastewater. The system comprises of aerator and settler as shown in figure 1. The bioreactor (aerator) includes secondary clarifier to maintain the biomass in the system while producing high-quality effluent. Part of settler output is recycled to allow the right concentration of microorganism the aerated tank.

![Figure 1. Activated sludge reactor.](image)

The model was derived based on component mass balance equation which yields a set of the non-linear differential equation given by equation (1) until (4).
\[
\begin{align*}
\text{Mass balance equation} & \quad = \text{Input - Output} \pm \text{Reaction} \quad \quad \quad (1) \\
\dot{X}(t) & = \mu(t)X(t) - D(t)(1 + r)X(t) + rD(t)X_r(t) \quad \quad \quad (2) \\
\dot{S}(t) & = -\frac{\mu(t)}{Y}X(t) - D(t)(1 + r)S(t) + D(t)S_in \quad \quad \quad (3) \\
\dot{C}(t) & = -\frac{K_a\mu(t)}{Y}X(t) - D(t)(1 + r)C(t) + K_{la}(C_s - C(t) + D(t)C_in) \quad \quad \quad (4) \\
\dot{X}_r(t) & = D(t)(1 + r)X(t) + D(t)(\beta + r)X_r(t) \quad \quad \quad (5) \\
\mu & = \mu_{max}\frac{S}{K_s+S} \times \frac{C}{K_c+C} \quad \quad \quad (6)
\end{align*}
\]

where \((t), S(t), X_r(t)\) and \(C(t)\) are the state variables which represents the concentration, biomass, substrate, dissolved oxygen and recycled biomass respectively. \(S_in\) and \(C_in\) represent concentrations of substrate and dissolved oxygen in the influent stream. The ratio of recycled and waste flow to the influent flow rate are given by \(r\) and \(\beta\). Specific growth rate \(\mu\) produced cell mass \(Y\). \(K_a\) is constant, while \(K_s\) and \(K_{la}\) are maximum dissolved oxygen concentration and oxygen mass transfer coefficient. The relationship between maximum growth rate to substrate and to dissolve oxygen coefficient is given by Monod equation as shown in equation (5). \(\mu_{max}\) is the maximum specific growth rate, \(K_s\) is the affinity constant and \(K_c\) is the saturation constant as shown in equation (6).

The following step is to linearize the nonlinear model. For simplification, the nonlinear is then linearized about its operating point yielding \(A, B, C\) and \(D\) matrices in the form of state space equation as in equation (7).

\[
\begin{bmatrix}
\dot{X} \\
\dot{S} \\
\dot{C} \\
\dot{X}_r
\end{bmatrix} =
\begin{bmatrix}
-0.0990 & 0.1234 & 0.2897 & 0.0495 \\
-0.05077 & -0.3129 & -0.4457 & 0 \\
-0.02538 & -0.0943 & -0.1975 & 0 \\
0 & 0 & 0 & -0.066
\end{bmatrix}
\begin{bmatrix}
X \\
S \\
C \\
X_r
\end{bmatrix}
+ \begin{bmatrix}
-82.17 \\
134 \\
-9.083 \\
8 \times 10^{-5}
\end{bmatrix}
\begin{bmatrix}
D \\
W
\end{bmatrix}
\quad (7)
\]

\[
Y =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
X \\
S \\
C \\
X_r
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
D \\
W
\end{bmatrix}
\]

The state space then manipulated into transfer functions matrix form \(G(s)\) which shown in (8).

\[
G(s) = \begin{bmatrix}
g_{11} & g_{12} \\
g_{21} & g_{22}
\end{bmatrix}
\quad (8)
\]

where,

\[
\begin{align*}
g_{11} & = \frac{134(s + 2.0049)(s + 0.1864)(s + 0.0117)}{(s + 1.9956)(s + 0.2573)(s + 0.2014)(s + 0.0076)} - 0.0312(s + 0.1863)(s + 0.0117) \\
g_{12} & = \frac{9.083(s + 1.4447)(s + 0.1942)(s + 0.0048)}{(s + 1.9956)(s + 0.2573)(s + 0.2014)(s + 0.0076)}\\
g_{21} & = \frac{0.0699(s + 2.802)(s + 0.1993)(s + 0.0074)}{(s + 1.9956)(s + 0.2573)(s + 0.2014)(s + 0.00076)} \\
g_{22} & = \frac{0.05077(s + 0.1234)(s + 0.2897)(s + 0.0495)}{(s + 1.9956)(s + 0.2573)(s + 0.2014)(s + 0.0076)}
\end{align*}
\]

In the multivariable system, interaction effect is taken into consideration, hence RGA calculation is compulsory to determine which input to use for which controller. RGA is calculated and the result is shown in equation (9). Since the result near to diagonal matrix, hence it can be concluded that manipulated variable 1 (MV1) controlled by the control variable 1 (CV1) and manipulated variable 2 (MV2) controlled by the control variable 2 (CV2).
\[ \Lambda = \begin{bmatrix} 1.05 & -0.05 \\ -0.05 & 1.05 \end{bmatrix} \] (9)

3. Multivariable PID turning method

This section will discuss the method used to tune the parameter of MPID controller. MPID controller is used due to consideration of multivariable system. Then, four types of MPID tuning have been selected which are Davison, Penttinen-Koivo, Maciejowski and Proposed Combined. These methods had been chosen due to its ability in dealing with interaction in simpler ways and it also required only step or frequency test [12]. The aims are to obtain the substrate and dissolved oxygen concentrations at the desired level.

3.1. Davison method

Davison is one of the MPID tuning methods and it is known to diagonalize plant at low frequency. In Davison, only integral is taken into consideration and the expression is given by equation (10).

\[
    u(s) = K_I \frac{1}{s} e(s), \quad K_I = \varepsilon G^{-1}(0) \tag{10}
\]

where \( K_I \) is the integral feedback gain, \( G(s) \) is the open loop transfer function matrix and \( \varepsilon \) as the scalar tuning parameter. Parameter tuning, \( \varepsilon \) Davison is adjusted in order to obtain a better closed loop system performance.

3.2. Penttinen-Koivo method

For the Penttinen-Koivo method, the plant is diagonalized at high frequency. Based on the controller given in equation (11), proportional and integral terms are taken into accounts. It also can be observed that the equation is an extension of Davison method

\[
    u(s) = (K_P + K_I) \frac{1}{s} e(s) \tag{11}
\]

\[
    K_P = \varepsilon G^{-1}(0) \tag{12}
\]

\[
    K_I = (CB)^{-1} \rho \tag{13}
\]

\( K_I \) and \( K_P \) are given by equation (12) and (13). \( C \) and \( B \) value can be obtained from output and input matrices in state space equations. In this method, two scalar parameter can be tune which is \( \varepsilon \) and \( \rho \).

3.3. Maciejowski method

Maciejowski method also uses the proportional and integral term of PID, it differs with Penttinen-Koivo method in the way of Maciejowski try to diagonalize the system near to bandwidth. The expression of the controller can be given by equation (14).

\[
    K = \left[ \left( K_P + K_I \right) \frac{1}{s} \right] \tag{14}
\]

\[
    K_P = \rho G^{-1}(j\omega_b) \tag{15}
\]

\[
    K_I = \varepsilon G^{-1}(j\omega_b) \tag{16}
\]

\[
    J(K, \theta) = \left[ G(j\omega_b) - e^{j\theta} \right] \left[ G(j\omega_b) - e^{j\theta} \right]^T, \quad \theta = \text{diag}(\theta_1, \ldots, \theta_n) \tag{17}
\]

where \( K_P \) is the proportional gain, \( K_I \) is an integral gain, \( \omega_b \) is the bandwidth frequency. The \( G^{-1}(j\omega_b) \) results in a complex number, with that a real approximation given in equation (17) are necessary. In this method, three parameters can be tune which are \( \varepsilon \), \( \rho \), and \( j\omega_b \). But for the purposed of the study, only scalar tuning will be tuned.

3.4. Proposed Combined method

The Proposed Combined method is introduced by [11]. In this method, it uses the criteria of Maciejowski in diagonalizing system near bandwidth frequency. The proposed combined method is being developed to reduce the difficulties in finding the suitable bandwidth frequency. Nevertheless, it shows similar behavior with Maciejowski. The expression of the proposed combined controller is shown in (18).
\[ u(s) = e(s)(\rho K + \varepsilon K)^{\frac{1}{s}} \]

\[ K = [\alpha G(0) + (1 - \alpha) CB]^{-1} \]

where \( K \) is given in equation \( 19 \) and \( \alpha \) is a constant value between \([0, 1]\). By that, three scalar tuning will be tuned in this method which is \( \alpha, \varepsilon, \) and \( \rho \).

4. Bat algorithm

Bat algorithm is a type of meta-heuristic swarm algorithm intelligent optimization algorithms. It was introduced by Yang in 2010 [13] and was inspired by the behavior of microbats which use echolocation pulses with different emission and sound. Besides, it is based on the echolocation capability of microbats guiding them on their foraging actions [14].

The approximate rules of BA can be categorized into three [13,14]. First, all the bats use echolocation to sense distance, and they also know the difference between food or prey and background barrier in some unknown way. Second, bats fly randomly with velocity at the position with a fixed frequency, varying wavelength, and the loudness to search for prey by automatically adjust the wavelength of their emitted pulses and also adjust the rate of pulse emission depending on the proximity of their target. Lastly, although the loudness can vary in many ways, assumed that the loudness varies from a large to a minimum constant value. Figure 2 shows the BA flowchart.

The step of BA is given as follows [14]:

1) Initialize the initial population of bats.
2) Setting the parameters: pulse frequency, pulse rate, loudness.
3) Generate the position and velocity for initial bats.
4) If the result of rand>\( pulse \) rate is yes, select the solution among best solution.
5) If the result of rand>loudness and Fnew<=fmin is yes, accept the new solution.
6) Rank the bats and determine the best one.
7) Go back to step 3 and repeat all the step until stopping criteria is met.

The velocity and position equation is given by equation \( 20 \) and \( 21 \) respectively. All the parameter value are given in table 1.

\[ Q_{new} = Q_{min} + (Q_{min} - Q_{max}) \times \text{random no.} \] (20)
\[ V_{i,k+1} = V_{i,k} + (P_{i,k} - X_{i,k}) \times Q_{new} \] (21)
\[ X_{i,k+1} = P_{i,k} + V_{i,k+1} \] (22)

where \( Q_{new}, V^k_i, X^k_i \) and \( P_{i,k} \) are the new frequency of bats, the velocity of the \( i^{th} \) individual at iteration \( k \), best position of the \( i^{th} \) individual at iteration \( k \) and position of the \( i^{th} \) individual at iteration \( k \) respectively.

| Table 1. Parameter initialization in BA. |
|----------------------------------------|
| **Initialization**                     |
| Population size                       | 50 |
| No. of iteration                      | 100|
| Search range                          | 0-10|
| **BA initialization**                 |
| Loudness                              | 0.95| Max. frequency | 2 |
| Pulse rate                            | 0.9 | Min. frequency | 0 |
BA is a stochastic algorithm, where different results obtained for every time the algorithm is executed, even though the same initial point is used. Hence, each optimization technique was executed for 20 times to make a fair observation for further analysis and the result was selected based on the execution that gives the best performances index. The repeated process done in BA to obtain optimum result caused the stopping criteria to be introduced. For this study, the stopping criteria used is when the maximum number of iteration is reached. The repetition of the algorithm will stop when the maximum number of iteration is achieved.

5. Objective function
The objective function is to evaluate the performance index of the system where it can be found in various forms such as time-domain specifications, frequency domain specifications and time-integral performance [15]. It is also representing system criteria that desired by the user. In this study, no specific criteria of the system as long as it gives the optimum value of the objective function. Thus, the smaller the error or the objective function, the better the system or performance index.

Figure 2. Flowchart of Bat Algorithm.
Time-integral performance or more specifically Integral Time Square Error (ITSE) has been chosen as the objective function. ITSE expression is given by equation (23) and from the equation, ITSE only required system error and the answer represents the area of the output and desired output. This selection is due to ITSE behavior that provides a better dynamic performance with good settling time.

\[ ITSE = \int_0^t (e(t))^2 \, dt \]  
\[ e(t) = y(t) - r(t) \]  

where \( e(t) \) is an error in equation (24), \( y(t) \) is output of system and \( r(t) \) is desired output.

6. Simulation result

The simulation of BA to tune the MPID controller for ASP was carried out by using MATLAB/SIMULINK software and the MPID control methods as previously mentioned was implemented to ASP transfer function. This method is called offline tuning method because the scalar tuning parameter is obtained first using the simulation of MPID-BA tuning using MATLAB. Then, the simulation results obtained are used to run closed loop nonlinear ASP model in SIMULINK.

The best parameter tuning is selected based data execution that gives the smallest fitness function (ITSE value). The smaller the ITSE value, the better the system performance. The simulation result obtained is shown in figure 3 and the data of closed loop performance are given in table 2. Each MPID control methods are being compared by the transient response in terms of rise time, settling time and percentage of overshoot to make an analysis on which methods will the best performances for the ASP system.

| Controller Tuning | Davison | Penttinen-Koivo | Maciejowski | Proposed |
|-------------------|---------|-----------------|-------------|----------|
| Fitness Function  | 132.6092| 0.0075          | 1.5119      | 9.8716   |
| Epsilon, \( \varepsilon \) | 10.2245 | 10.0027         | 7.9816      | 9.9900   |
| Rho, \( \rho \) | -       | 4.1857          | 9.9988      | 6.0562   |
| Alpha, \( \alpha \) | -       | -               | -           | 0        |
| Output            | S       | DO              | S           | DO       |
| Rise Time, \( T_R \) | 0.814  | 0.274           | 0.476       | 0.285    |
| Settling Time, \( T_S \) | 28.1   | 3.75            | 2.10        | 1.15     |
| Overshoot, OS%    | 73.0    | 48.4            | 2.4         | 10.6     |

*S: Substrate; DO: Dissolved Oxygen

Based on the time response data, it can be seen clearly that Davison on BA algorithm also give the worst response with the longer settling time and rise time. The reason for it is due to the missing proportional term in its equation where it only used the integral term. The advantages of having the proportional term in a system are where it can help to reduce the rise time and settling time. The Davison also give the worst result in terms of overshoot and fitness function compared to the others.

While, the other three methods control tuning of BA algorithm, Penttinen-Koivo, Maciejowski and Proposed Combined method shows the similar results. The similarity of the result is because of the same property of equation that they are used, which is the proportional and integral term. However, the Proposed Combined method gives the better performance compared to Maciejowski even though they are having similarities in the expression. This is because the complexity of finding suitable bandwidth in Maciejowski method has been reducing by the Proposed Combined method.
7. Conclusion and future works

This project shows that Davison method gives the worst performance. However, Penttinen-Koivo, Maciejowski and Proposed Combined method produce quite similar results. This is because Davison’s method involves integral term only while the other methods consider the part of the proportional and integral terms. The importance of having proportional term in MPID is where the rise time and settle time can be reduced.

This study also proves that by using the optimization technique, a system can be tuned to obtain better performance responses. The result also concludes that the BA optimization with the Proposed Combined method is the best way to tune multivariable PID of activated sludge process. It is because the BA has the advantage with its ability to further find a solution with a lower fitness function. Thus, the ASP performance can be improved in order to have a great wastewater treatment plant.

For this study, the BA optimization has only covered the velocity at position solution of the system with a fixed frequency. It can be improved by continuing the simulation using the others criteria of BA which are by varies the loudness, pulse rate and wavelength for the bat to search a better solution.

Besides, this study can be better if the ASP system with MPID-BA is further testing by including a disturbance in the system. This testing process can determine whether the MPID controller can resist the disturbances or not. It also can prove that whether the system can fix the corner caused by the disturbances.

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