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A Novel Clonal Selection Algorithm for Multivariable Optimal Control of Activated Sludge Process

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A novel clonal selection algorithm (NSCA) was proposed in this work and we introduced the novel clonal selection algorithm into the wastewater treatment activated sludge process for multivariable optimal control with the lowest operational costs by limiting total substrate discharge mass. A simulation results shows that the new method is efficient and also provides a new approach for other optimal control problem.

Key Words: Clonal selection algorithm, Multivariable optimal control, Activated sludge process.

INTRODUCTION

Many advanced processes have been developed to improve the efficiency of the removal of organic matter and nutrients by wastewater treatment plants (WWTPs). These proved processes are usually based on complex biological treatment configurations that include combinations of aerobic, anoxic and anaerobic reactors and internal recycling between the different unit-processes.

Actually, cost minimization has become increasingly important in the control and operation of wastewater treatment plants in recent years. In order to run a plant economically efficient, operational costs such as pumping energy, aeration energy and dosage of different chemicals should be minimized. At the same time, total substrate (biological oxygen demand) discharge mass should be limited at a certain level. Of course, minimizing the operational costs and treat the wastewater properly at the same time may lead to a conflict. The main problem is how to keep the effluent discharges below a certain pre-specified limit to the lowest possible cost[1]. Part of the answer is to design the control algorithms in such a way that the overall operational costs are minimized. This goal can be attained in different ways. As an example, the controller setpoints could be separately optimized or the cost could be minimized online by some optimal control strategy, for instance model predictive control (MPC) and gradient method and so on.

Several control strategies for nitrogen removal are proposed and evaluated[2] in a benchmark simulation model of an activated sludge process to test which control strategy delivers better performance with respect to plant operating costs. Optimal periodic control with the lowest operational cost by limiting total substrate discharge mass was studied[3]. Through adding new state variable, using supplement functions and the dynamic searching method of optimal step coefficient was developed to modify the conventional gradient method, consequently the calculation problem of the multivariable optimal periodic control was able to be resolved better. There are still many literatures introduced other control strategies for multivariable optimal control of activated sludge process[4-9]. A novel immune selection operator combining the antibody concentration and the sufficiency vector distance is proposed and a scale variable hybrid mutation operator is designed to improve the search efficiency[10].

In this work, a novel clonal selection algorithm for multivariable optimal control of activated sludge process with the lowest operational costs by limiting total substrate discharge mass is proposed.

EXPERIMENTAL

Multivariable optimal control model of activated sludge process: Currently, the effluent substrate concentration is high or volatile and the higher operating costs are two common problems of wastewater treatment plant. Squaring up the relation of these two problems, we combine the control variables of the waste sludge flow rate (Q_W) and the dissolved oxygen concentration (DO) in the aeration tank for optimal control studies. The performance indicators include the running costs, which has the vast majority of activated sludge operating costs, of remaining sludge treatment, sludge return and air supply with the constraint condition of water quality. Reducing the operating costs is the most important goal to the premise of good effluent quality. The parameters appeared in this paper are shown in Table-1.

TABLE-1
PARAMETERS AND THEIR VALUES IN THIS PAPER

Parameters	Description	Units
Q_0	The wastewater flow rate	m^3/d
Q_r	The sludge return flow rate	m^3/d
Q_w	The wastage discharging flow rate	m^3/d
S_0	The influent substrate mass BOD	mg/L
S	The effluent substrate mass BOD	mg/L
X	The microorganisms (MLSS) concentration of effluent	mg/L
X_0	The microorganisms (MLSS) concentration of influent	mg/L
X_r	The microorganisms (MLSS) concentration of return sludge	mg/L
DO	The dissolved oxygen concentration	mg/L
R	The reflux ratio for the sludge	–
k	The maximum specific substrate utilization rate constant	d^{-1}
V	The volume of aeration tank	m^3
K_s	The substrate saturation coefficient	mg/L
K_o	The oxygen saturation constant	mg/L
K_d	The microbial decay rate	d^{-1}
Y	The yield coefficient	–

Model description: Fig. 1 shows the schematic diagram of activated sludge process. In order to facilitate the quantitative control of the wastage discharging, we make the assumption of the wastage discharge directly from the aeration tank[3], no chemical reaction in the secondary settler and no dissolved oxygen in influent water. The state equations model[8] described as eqn. 1.

$$\begin{cases} \dfrac{dX}{dt} = X\left(\dfrac{kYS}{K_S + S} - K_d\right)\dfrac{DO}{K_0 + DO} - \dfrac{Q_W X}{V} \\ \dfrac{dS}{dt} = \dfrac{Q_0(S_0 - S)}{V} - \dfrac{kXS}{K_S + SK_0}\dfrac{DO}{K_0 + DO} \end{cases} \quad (1)$$

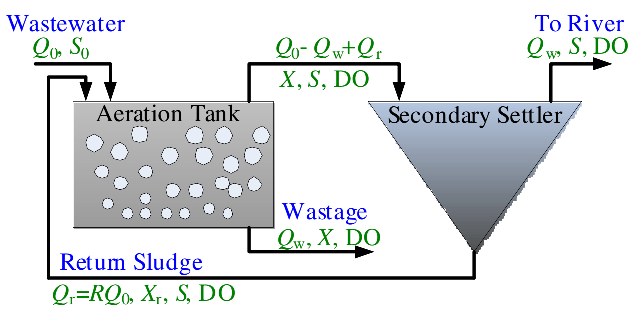


Fig. 1. Schematic diagram of activated sludge process

Performance indicators: As mentioned above, the performance indicators[3] with the constraint condition of water quality include the operating costs of the remaining sludge treatment (J_1), sludge return (J_2) and air supply (J_3).

$$J = J_1 + J_2 + J_3$$

$$= \int_0^{1\,day}\left(AQ_W X + \frac{BX(Q_0 - Q_W)}{X_r - X} + \frac{C(D_S - DO_1)}{D_S - DO}\left(\frac{VXDO}{K_0 + DO}\right)\left(\frac{\alpha kS}{K_s + S} + 1.42K_d + Q_0 DO\right)\right)dt \quad (2)$$

where, J is the total operating costs in 1 day; A, B, C are the expense constants; α is the aerobic substrate utilization factor unit; D_S is the saturation concentration of dissolved oxygen; DO_1 is the set point of dissolved oxygen.

$$Z(t) = \int_0^{1\,day} Q_0 S dt \quad (3)$$

Eqn. 3 is the restrictions for the optimizing problem in this paper. Where, Z(t) is the added state variable to describe the limitation of total substrate discharge mass, so Z(0) = 0 and Z(1) is the limit value of daily amount of total substrate discharge mass. Z(1) should be no more than Z_S, the daily permitted amount of total substrate discharge, Z_S = 150 kg (BOD)/d. There are also two restrictions, one is Q_w must be a positive value, another one is DO's value must be between 0 and D_S.

$$\begin{cases} Z_S - Z(1) \geq 0 \\ Q_w > 0 \\ 0 < DO < D_S \end{cases} \quad (4)$$

Novel clonal selection algorithm: Recently, clonal selection theory in the immune system has received the attention of researchers and given them inspiration to create algorithms that evolve candidate solutions by means of selection, cloning and mutation procedures. The clonal selection algorithm (CSA) in its canonical form and its various versions are used to solve different types of problems and are reported to perform better compared with other heuristics (*i.e.*, genetic algorithms, neural networks, *etc.*) in some cases, such as function optimization and pattern recognition[11].

In this paper, we proved the clonal selection algorithm with a special Gaussian mutation to collect more priori information was coded in the clonal selection algorithm. And the size of the search space is decreased and the convergence speed of the algorithm is increased at the same time. We called it novel clonal selection algorithm (NCSA).

The steps of novel clonal selection algorithm are defined as follows:

Step 1: Initialization: Randomly initialize an antibodies population (Abi) with p antibodies and determine its affinity with each element of the population and then define an empty antibodies memory library (Abm). All individuals in the algorithm are used in real-coded.

Step 2: Selection: Select a number (s) of the best highest affinity elements to compose a selected antibodies population (Abs) from initialize antibodies population and update the Abm with the best highest affinity antibodies at the same time.

Step 3: Cloning: Individuals in Abs generate the clonal expansion to a number of c to compose a new antibodies population (C);

Step 4: Gaussian mutation: Mutate all the individuals in C with the randomly selected number of genetic locus of genes to compose a new antibodies population (C*).

The achieved method is shown in the following eqn. 5,

$$L_i' = L_i + r(y_i^{max} - y_i^{min})N(0,1) \quad (5)$$

where, L'_i and L_i are the genetic locus values of before and after mutation; y_i^{max} and y_i^{min} are the maximum and minimum values of the independent variable of the genetic locus. They are derived from prior experience; N(0, 1) is a random number subject to the standard normal distribution; r is the expansion radius of mutation operation.

Step 5: Repeat step 2 to step 4 until a termination criterion is met.

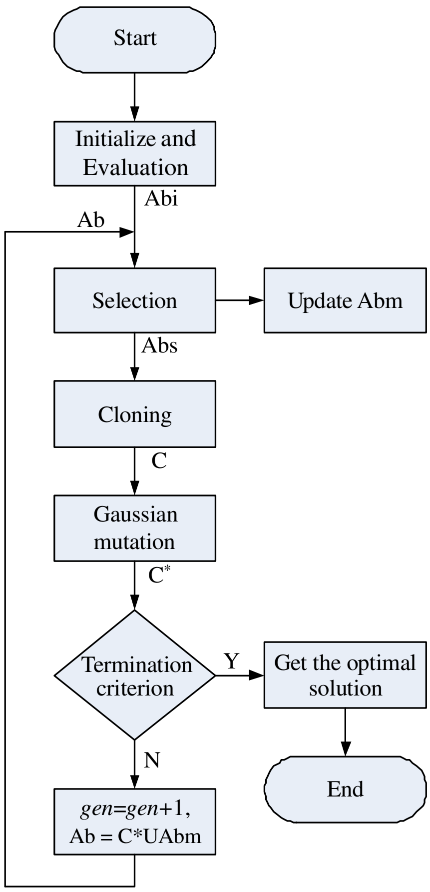
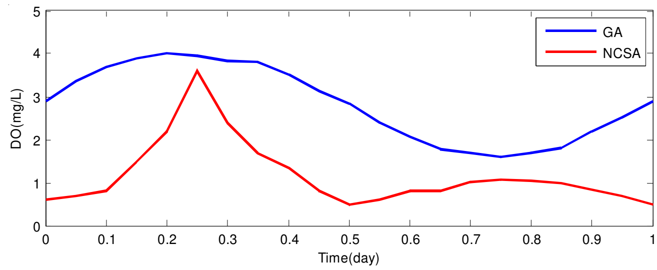


Fig. 2. Novel clonal selection algorithm flow chart

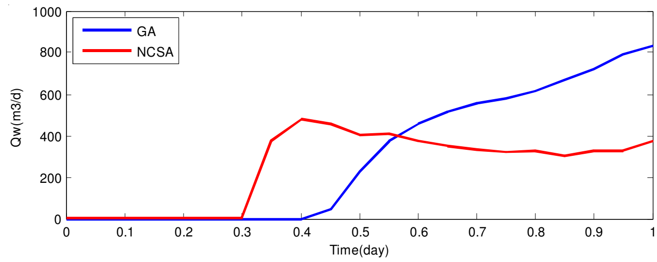
RESULTS AND DISCUSSION

Simulation results: In order to verify the validity of the novel clonal selection algorithm used for optimizing the activated sludge process, we present some simulation results compare with the Generic Algorithm (GA) based optimizing. Parameters in novel clonal selectionare defined as: p = 100, s = 20, maximum evolution generation is 30, mutation probability is 0.1.

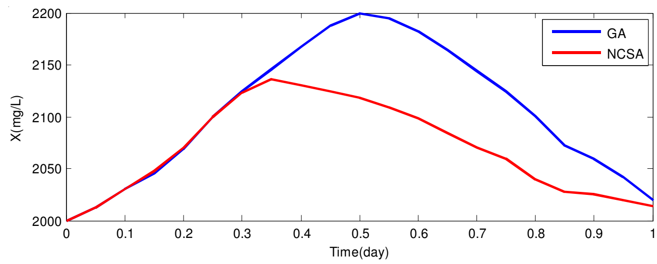
The simulation results shown in Fig. 3(a) indicate that dissolved oxygen concentration should be controlled at 0.50-3.65 mg/L to ensure the total substrate discharge mass not more than 150 kg(BOD)/d. In the optimizing process, the dissolved oxygen concentration (DO) is lower than the traditional



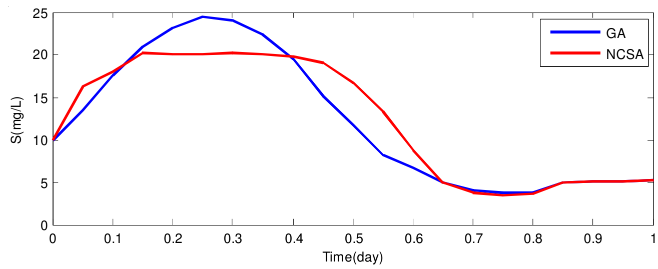
(a) Optimization results of dissolved oxygen



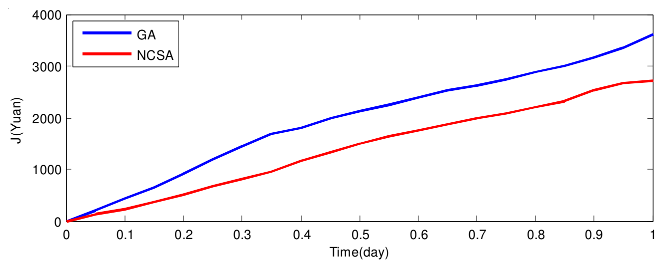
(b) Optimization results of waste sludge flow rate



(c) Optimal control curve of X



(d) Optimal control curve of S



(e) Optimal control curve of J

Fig. 3. Simulation results

optimization algorithm and the total wastage out from the system is less than the traditional optimization algorithm too, which is shown in Fig. 3(b). Fig. 3(e) shows that the total operating costs are lower more.

Conclusion

A novel clonal selection algorithm (NSCA) was proposed by improving the mutation steps in this article and we introduced the NCSA algorithm into the wastewater treatment process for optimal control. The compared simulation results show that the NCSA algorithm is better than the traditional optimization algorithms under the same conditions obtained. It is more effective and practical. It also provides a new approach for optimal control problem in other wastewater treatment systems.

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