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# Optimal Coagulant Dosage Control Scheme Using Flocculation Image Sensor and Robust Extremum Seeking

O. Yamanaka *, Y. Onishi* , M. Hirano *, R. Arimura *, and M. Kanadani

* Toshiba Infrastructure Systems & Solutions Corporation, 1-Toshiba-cho, Fuchu-shi, Tokyo, Japan, {, osamu2.yamanaka, yuuta.onishi, masaki5.hirano, ryoichi.arimura }@toshiba.co.jp

**Toshiba Infrastructure Systems & Solutions Corporation, 72-34, Horikawa-cho, Saiwai-ku, Kawasaki-shi, Kanagawa, Japan, michiaki.kanadani@toshiba.co.jp

**Abstract:** A novel coagulant dosage control scheme was developed to minimize the operational cost of the coagulation and sedimentation process. The inner PI loop controller regulates the electrophoretic velocity of flocs after mixing with the coagulant. The outer loop controller, driven by the extremum-seeking (ES) technique, automatically adjusts the set-point of the inner PI controller in response to the total cost index consisting of total operational cost and outlet turbidity constraints. Lab-scale experiments were conducted to evaluate the overall control performance of the proposed scheme. Although the proposed scheme effectively sought the optimal set-point to minimize the operational cost in an online manner, the seeking process can occasionally fail under certain conditions. This paper investigates the cause of the failure and clarifies the phase lag between the input and the output of the ES controller can be the cause. Based on this finding, this paper proposes an improved ES to compensate for the phase lag and demonstrates the effectiveness of the improved ES numerically using a process simulator developed by the authors, which can simulate the water purification process.

**Keywords**: Coagulation; Flocculation image sensor; Extremum seeking, Process simulation

## Introduction

The coagulation and sedimentation process plays an important role in water purification plants and other water treatment facilities. Optimizing coagulant dosage for the process is crucial since insufficient coagulant dosage can cause the failure of water treatment, while excessive coagulant dosage increases operational costs. Manual and/or feedforward coagulant dosage control based on raw water turbidity with the help of the so-called jar test procedure is often adopted. These control schemes, however, are less robust to disturbances such as raw water quality fluctuations and place a heavy operational burden on operators. Feedback control is a promising alternative to address the problem. To this end, we have developed a flocculation image sensor (FIS) that quantifies the electrophoretic velocity (EV) of flocs after coagulant dosing (Arimura et al., 2021) to measure the charge state of flocs and have implemented it in a newly developed feedback dosage control scheme for a coagulant called Poly-Aluminium Chloride (PACl). In the control scheme, the average EV is controlled by an inner loop PI controller to track a set-point. While the proper set-point for average EV is around zero, implying charge neutralization necessary for proper coagulation, the optimum set-point can change over time due to alterations in pH, temperature, flow rate, and other factors. To address this, we have adopted an extremum seeking (ES) controller (Ariyur, K. B., & Krstic, M., 2021) as an outer loop set-point optimizer, where a total cost index considering the operational cost and outlet turbidity constraints is minimized. Previous research has shown that by applying the proposed scheme to a lab-scale coagulation and sedimentation process, optimal operation can be achieved, even when the operational conditions change (Yamanaka et al., 2023, Hirano et al., 2024). However, subsequent experiments revealed rare instances of failure. In this paper, we investigate the cause of the failure through numerical simulations using a coagulation process simulator developed by the authors and illustrate that a robustified ES controller can successfully overcome the problem.

## Coagulation Dosage Control Scheme

Figure 1 illustrates the schematic diagram of the lab-scale water purification process and the proposed overall control scheme. The proposed coagulant dosage controller has a cascade structure consisting of an inner loop PI controller and an outer loop set-point optimizer using an ES

controller. The inner loop PI controller determines the PACl dosing rate based on the EV measured by the FIS. EV has a negative value when flocs move toward the positive electrode (Figure 2), and thus one can identify the charge state of the flocs from the measured EV. The set-point of the EV is optimized by the outer loop ES controller proposed by Yamanaka, O., et al. (2020), which works to minimize the total cost, consisting of operational cost and outlet turbidity constraints, as shown in Table 1.

The lab-scale experimental process consists of a mixing tank, a floc-forming tank, and a sedimentation tank. Raw water, consisting of kaolin, humic acid, and tap water, was supplied to the mixing tank and mixed with PACl. Temperature, flow rate, turbidity at the inlet, EV in the mixing tank, and turbidity at the outlet were transmitted to the controller, in which the proposed control scheme was installed. A process simulator that can numerically simulate the behaviour of the process and the proposed control scheme was also developed on the MATLAB/SIMULINK® platform (details are omitted in this abstract) and used for outcome analysis.

**Results and Conclusion**

Examples of experimental results are shown in Figure 3, where time series of the EV set-point, coagulant dosage, outlet turbidity, and total cost are presented. The graphs in the left and middle columns represent success cases. Both excessive and insufficient dosages were adjusted to the optimal dosage, around 40 mg/L. This is confirmed by the behaviour of the total cost index, which seemed to converge in both cases after dosage adjustment. On the other hand, the graphs in the right column represent a failure case. In this case, the PACl dosage was monotonically increasing, and the total cost index could not be minimized. We investigated the reason for the failure and hypothesized that it was caused by the phase lag or delay between the EV set-point (input) and the total cost index (output). Figure 4 illustrates the cause of the failure and basic idea to avoid the failure. In the ES control, a periodic signal such as a sinusoidal wave is added to the EV set-point to seek the optimal point. Conceptually, the ES decreases the EV set-point if the input and output are in phase and increases it if they are out of phase (left side of Figure 4). However, there are some process delays between the input and output, which creates a phase lag (middle of Figure 4). If the phase lag exceeds $\pi/2$ radian, the seeking can fail. To overcome this problem, we developed an improved ES controller that compensates for the phase lag automatically (right side of Figure 4, but details are omitted). To confirm the robustness of the ES controller, we compared the control results between the original ES and the improved ES, as illustrated in Figure 5. The result of the original ES without phase compensation (graphs in the left column) fails to seek the optimal point as the PACl dosage is monotonically decreasing and the total cost index could not be minimized, while the result of the improved ES (graphs in the right column) successfully seeks the optimal point. Thus, phase compensation is crucial for successful extremum seeking. Additionally, the improved ES is more robust than the original one since the phase lag is automatically compensated.

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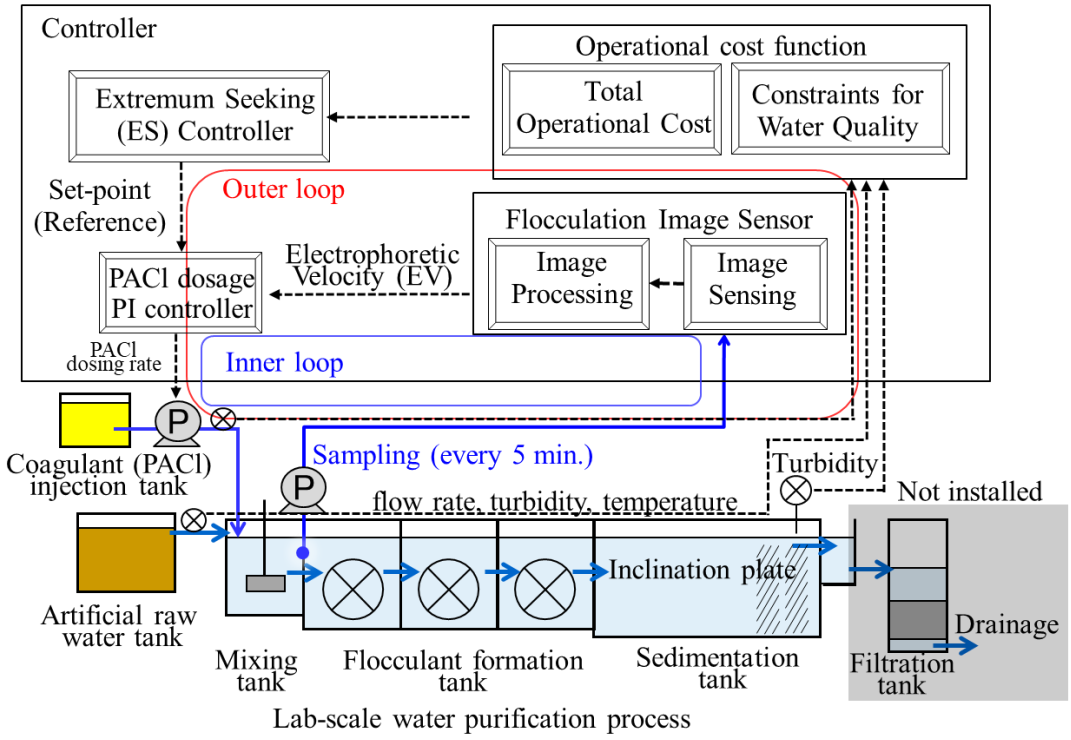



**Figure 1** Schematic diagram of lab-scale water purification plant and overall control scheme

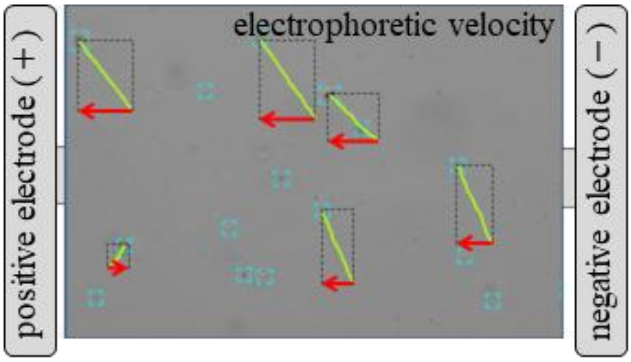
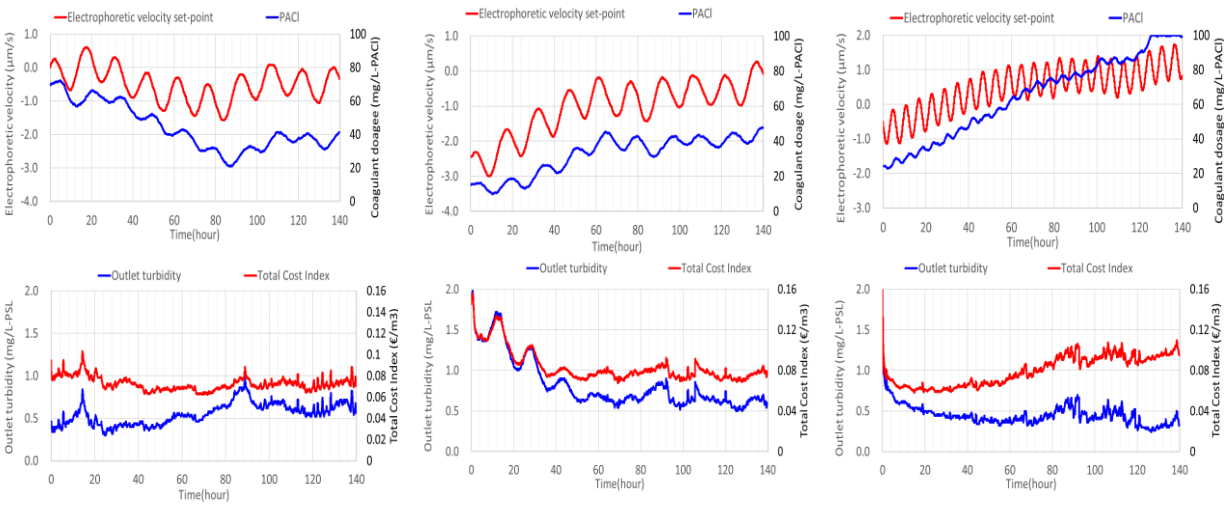



**Figure 2** An example of floc image and movement speed taken by FIS




**Success Case (from excessive dose)** **Success Case (from insufficient dose)** **Failure Case**

**Figure 3** Success and failure examples of control results in lab-scale experiment

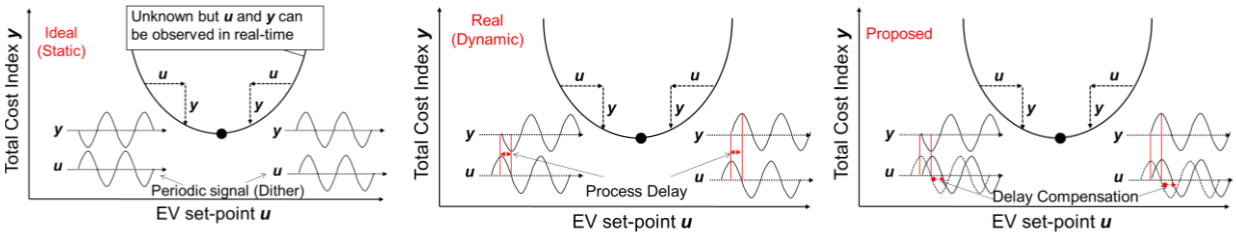
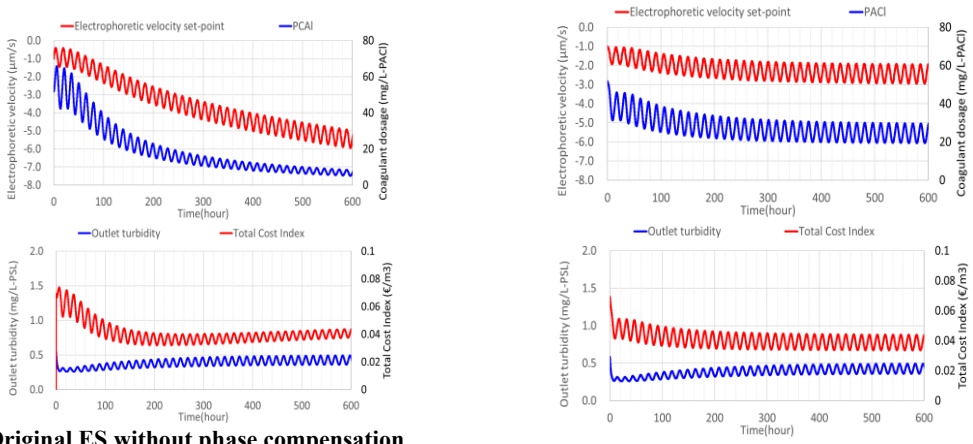



**Figure 4** Conceptual explanation of the extremum seeking (ES) and the basic idea for the improved ES




**Original ES without phase compensation** **Improved ES with phase compensation**

**Figure 5** Simulation examples of control results with and without phase compensation for the ES controller

**Table 1** Definition of Total Cost Index

$$\mathrm{TCI} = \mathrm{TC} + \mathrm{PF} \quad (1)$$

$$\mathrm{TC} = \mathrm{OC}_1 + \mathrm{OC}_2 + \mathrm{OC}_3 \quad (2)$$

$$\mathrm{OC}_1 = \mathrm{f}_1(\mathrm{PACl}, \mathrm{Q}, \mathrm{w}_{\mathrm{pac}}) \quad (3)$$

$$\mathrm{OC}_2 = \mathrm{f}_2(\mathrm{Tb}_{\mathrm{in}}, \mathrm{PACl}, \mathrm{Q}, \mathrm{w}_{\mathrm{sd}}) \quad (4)$$

$$\mathrm{OC}_3 = \mathrm{f}_3(\mathrm{Tb}_{\mathrm{out}}, \mathrm{T}, \mathrm{PACl}, \mathrm{w}_{\mathrm{bw}}) \quad (5)$$

$$\mathrm{PF} = \begin{cases} exp(\mathrm{Tb}_{\mathrm{out}} - \mathrm{Tb}_{\mathrm{lim}}) - 1, & \text{if } \mathrm{Tb}_{\mathrm{out}} > \mathrm{Tb}_{\mathrm{lim}} \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

TCI: Total cost index
TC [€/m$^3$]:total operational cost
PF[-]:Penalty function for outlet turbidity constraint
$OC_1$ [€/m$^3$]: chemical cost of PACl
$OC_2$ [€/m$^3$]: sludge disposal cost
$OC_3$ [€/m$^3$]: back-wash cleaning cost of the filter in the filtration tank
PACL[mg/L]: Poly-Aluminium Chloride
Q [m$^3$/h]:treated water flow rate
$Tb_{in}$ [mg/L-PSL]:inlet turbidity
$Tb_{out}$ [mg/L-PSL]: outlet turbidity
T[℃]: raw water temperature
$w_{pac}$ [USD/L]: PACl unit cost
$w_{sd}$ [USD/ton]: sludge disposal unit cost
$w_{bw}$ [USD/time]: cost per back-wash cleaning
$Tb_{lim}$: upper control limit of the outlet turbidity.