Combining regulatory control and online optimization through phasor-based extremum seeking control *

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Froth flotation is one of the most common techniques of mineral separation, utilizing hydrophobic properties to separate desired minerals from gangue by the use of rising air bubbles. The process is complex and characterized by nonlinear dynamics, especially in the froth found on the top of the cell. Consequently, there has been a historical lack of control-oriented models for froth flotation, which has hindered the development of optimization and advanced control of the process [1]. To address this issue, we have previously proposed a model-free optimization algorithm that enables constrained optimization. Such an algorithm is capable of maximising the performance of the flotation cell while maintaining stable operational points. However, this algorithm would replace established regulatory control layers, which might limit its adoption in some industrial settings. On the other hand, other research into extremum seeking control (ESC) of froth flotation has assumed that the regulatory layer is operating successfully and independently from the ESC [2]. This research aims to further investigate the synchronization of regulatory control and optimization by modifying a phasor-based extremum seeking control algorithm [3] to ensure robustness to both the perturbations induced by the ESC and the noise present in such an industrial setting.

Froth flotation has two primary objectives: recovery and grade. The recovery can be related to the stability of the froth, which in turn can be measured online by air recovery α. Optimization of froth flotation can then be achieved by regulating the aeration rate J_g to obtain an optimal air recovery α^*. The operation of froth flotation also requires stable operations, which in this context is related to the pulp level L. Thus, regulatory control of froth flotation aims to maintain its stable operation by manipulating the tail flow Q_{tails}.

A perturbation-based extremum seeking control approach can be used to drive the air recovery α to an optimum α^* by perturbing the aeration rate J_g. However, this perturbation has the potential to disrupt the PI controller of the regulatory layer, causing issues such as instability and incorrect error integration. The Phasor-based extremum seeking control utilises a Kalman filter to estimate the system's response as a phasor $y_i(t) \approx \beta_0 + \Im(re^{i\Phi}e^{i\omega t})$. This filter thus contains a constant offset β_0 which can be used to estimate the filtered pulp level $\hat{L}$. This estimate can then be fed into the PID layer as seen in Figure 1, allowing for the combination of the two approaches.

The method is evaluated in a simulation study, with both measurement noise and process disturbance applied to the state of the simulation model. The ESC algorithm was activated after 40 minutes, and an input disturbance in the form of a step input occurred after 1.5 hours. As shown in Figure 2, the PID controller achieved a rise time of approximately 15 minutes, whereas the optimization algorithm reached its optimum after about 43 minutes, as seen in Figure 3. This is a competitive time compared to similar previous simulation studies that do not explicitly account for regulatory control [2]. This result suggests that these methods can be combined, and that the Kalman filter of the ESC algorithm can assist the PID layer in handling disturbances and noise, improving the robustness of both optimization and regulatory control. A further study would examine whether this result is also possible in a multi-cell circuit with circuit-wide disturbances, allowing for a more comprehensive evaluation of the method's viability for industrial applications.

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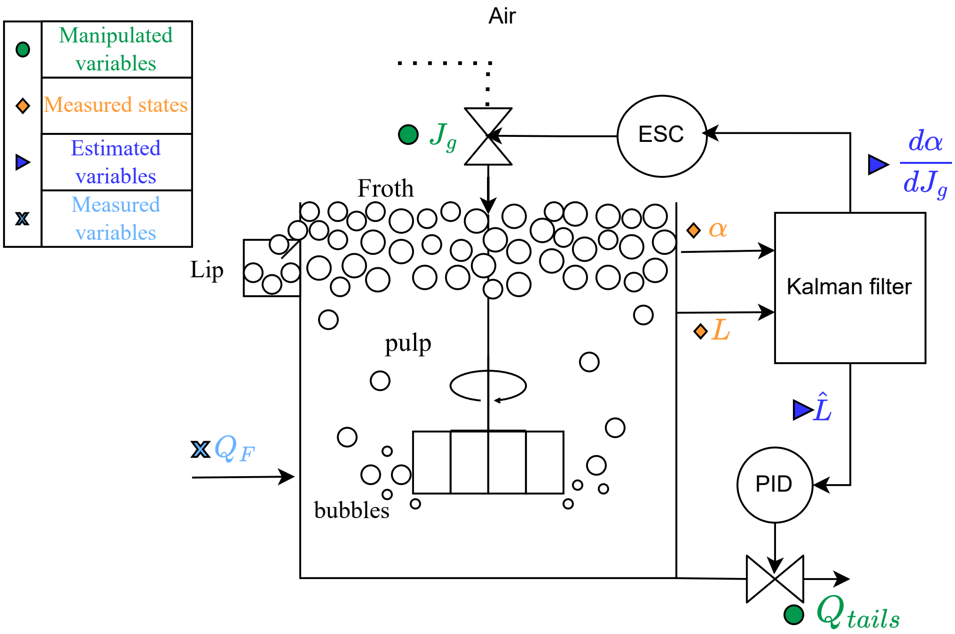

Figure 1: Phasor-based extremum seeking control with PID sublayer.

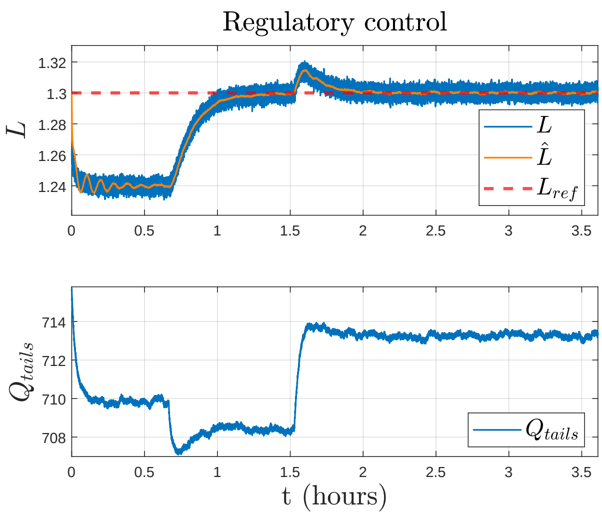

Figure 2: Pulp level response to the PID.

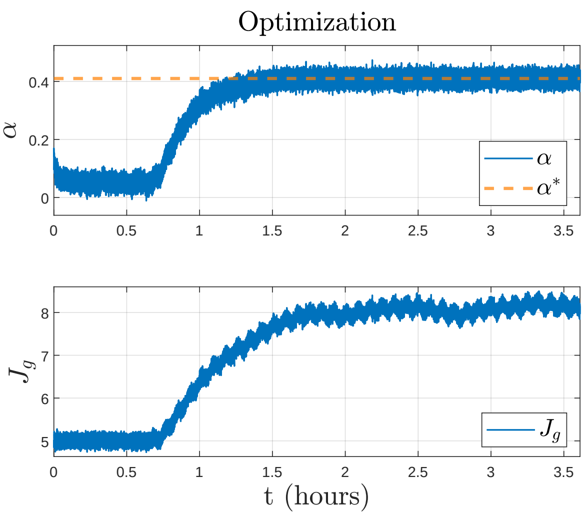

Figure 3: Air recovery response to the ESC.

References

[1] Paulina Quintanilla, Stephen J. Neethling, and Pablo R. Brito-Parada. Modelling for froth flotation control: A review. *Minerals Engineering*, 162:106718, 2021. ISSN 0892-6875. doi: https://doi.org/10.1016/j.mineng.2020.106718. URL `https://www.sciencedirect.com/science/article/pii/S0892687520305380`.

[2] D.A. Wepener, J.D. le Roux, and I.K. Craig. Extremum seeking control to optimize mineral recovery of a flotation circuit using peak air recovery. *Journal of Process Control*, 129: 103033, 2023. ISSN 0959-1524. doi: https://doi.org/10.1016/j.jprocont.2023.103033. URL `https://www.sciencedirect.com/science/article/pii/S0959152423001208`.

[3] Khalid Tourkey Atta, Andreas Johansson, and Thomas Gustafsson. Extremum seeking control based on phasor estimation. *Systems Control Letters*, 85:37–45, 2015. ISSN 0167-6911. doi: https://doi.org/10.1016/j.sysconle.2015.08.010. URL `https://www.sciencedirect.com/science/article/pii/S0167691115001772`.