Iterative Learning Control of Supersaturation in Batch Cooling Crystallization

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Outline

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Batch Crystallization

Process Description

Separation and purification process of industrial interest.
A solution is cooled down, solid material (crystals) produced.

1. Hot solution fed into the vessel.
2. Cool to seeding temperature.
3. Introduce seeds.
4. Cool to final temperature.
   Crystal growth (and nucleation).
5. Remove final product.

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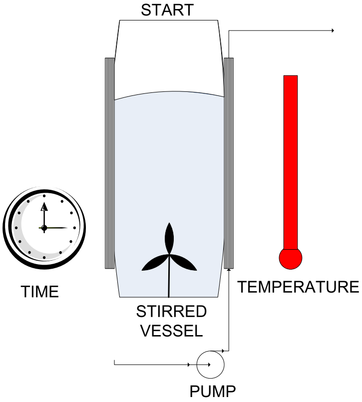

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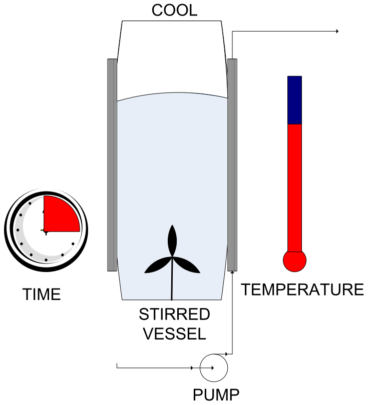

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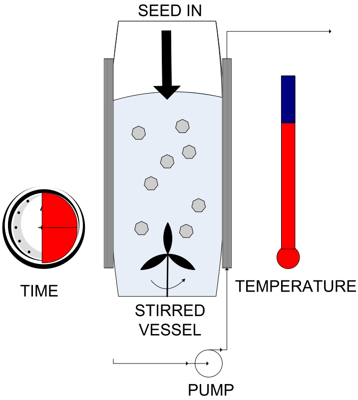

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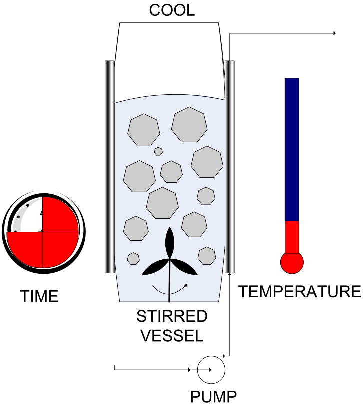

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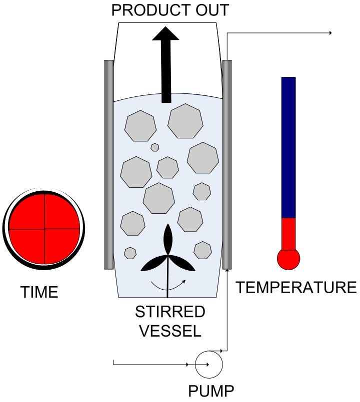

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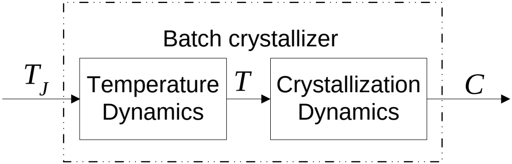
Batch Crystallization

Modeling

Process (after seeding) described by

- Temperature Dynamics (linear, known or easy to estimate)
- Crystallization Dynamics (nonlinear PDE, parametric + structural uncertainties possible)



Batch Crystallization

Modeling

Input

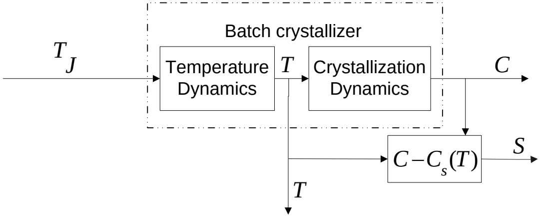
- Jacket temperature T_J

Measured Output

- Vessel Temperature T
- Concentration C

Control Output

- Supersaturation
  $S = C - C_s(T)$



Disturbances

- Low frequency disturbance on the input
- White measurement noise on the outputs

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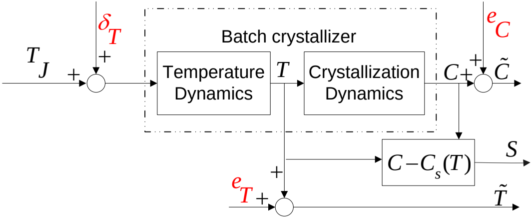

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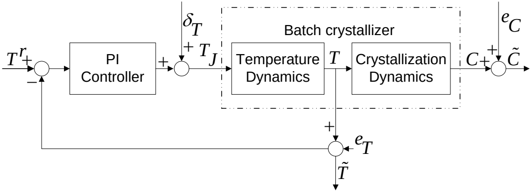
Batch Crystallization

Control Strategies: industrial practice

Only the crystallizer temperature is measured and controlled on-line.
In some cases, T control does not satisfy all requirements.



Advanced strategies in literature. They rely on on-line measurements.
Not always available in practice.

Alternative approach based on Iterative Learning Control.

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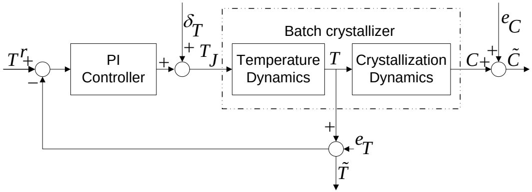

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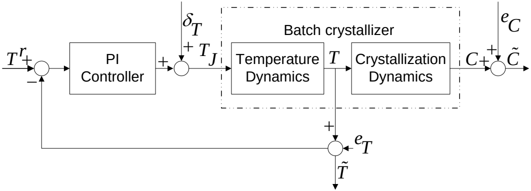

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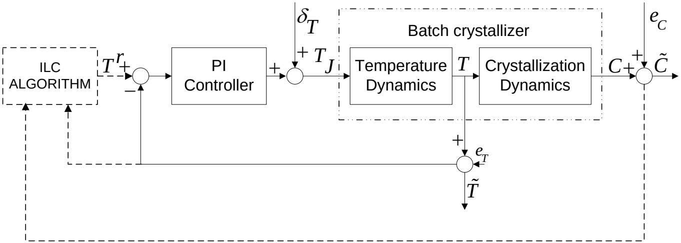
1. Batch Crystallization
2. Iterative Learning Control
3. Simulation Results
4. Conclusions

Iterative Learning Control

Control Scheme

ILC control strategy. $\mathbf{T}_k^r$ updated from batch to batch.

- Can use measurements available at the end of the batch.
- Built on top of the standard industrial T control.



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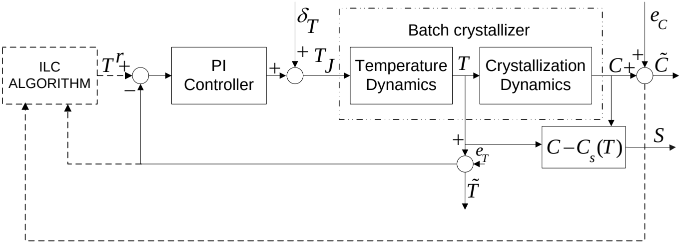

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Iterative Learning Control

General Idea

Based on an additive correction of a nominal model from $\mathbf{T}^r$ to $\mathbf{S}$.

$$\hat{S}(\mathbf{T}^r) \qquad \textit{nominal model}$$

$$\hat{S}_k(\mathbf{T}^r) \triangleq \hat{S}(\mathbf{T}^r) + \boldsymbol{\alpha}_k \qquad \textit{corrected model}$$

Note:

- $\mathbf{T}^r, \boldsymbol{\alpha}$ vectors of samples $\in \mathbb{R}^N$ ($N =$ batch length)

α can compensate the nominal model for

- model mismatch (along a particular trajectory)
- effect of repetitive disturbances

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Iterative Learning Control

Correction vector

How to obtain the correction vector?

- In principle, "match" the last measurement.

$$\boldsymbol{\alpha}_k = \tilde{\mathbf{S}}_k - \hat{S}(\mathbf{T}^r) \qquad = \qquad \text{model error}$$

  Due to disturbances on $\tilde{\mathbf{S}}_k$, might not be a good solution.

- Take into account the deviation from α_{k-1}.

$$\alpha_k = \arg\min_{\alpha \in \mathbb{R}^N} \|\tilde{\mathbf{S}}_k - (\hat{S}(\mathbf{T}^r) + \alpha)\|^2_{Q_\alpha} + \|\alpha - \alpha_{k-1}\|^2_{S_\alpha}$$

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Iterative Learning Control

Algorithm

Steps of the ILC algorithm. At each batch k:

1. $\mathbf{T}_k^r$ is set as the input to the PI controller, the batch is executed. $\tilde{\mathbf{S}}_k$ is estimated from measurements.
2. An additive correction of the nominal model is performed: $\hat{S}_k(\mathbf{T}^r) \triangleq \hat{S}(\mathbf{T}^r) + \boldsymbol{\alpha}_k$.
3. The corrected model is used to design $\mathbf{T}_{k+1}^r$ for the next batch:

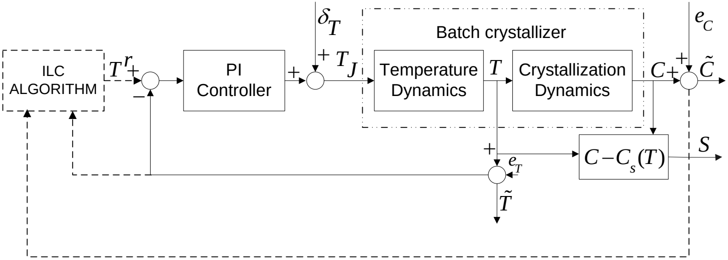
$$\mathbf{T}_{k+1}^r = \arg\min_{\mathbf{T}^r \in \mathbb{R}^N} \|\overline{\mathbf{S}}_{k+1} - \hat{S}_k(\mathbf{T}^r)\|^2 + \lambda \|\mathbf{T}^r - \mathbf{T}_k^r\|^2$$

Outline

Simulation Results

Scenario

- Objective: tracking of a constant set-point $\overline{\mathbf{S}} = 2.5\ g/L$
- $N = 20$ batches
- $\mathbf{T}_k^r$ updated from batch to batch using ILC

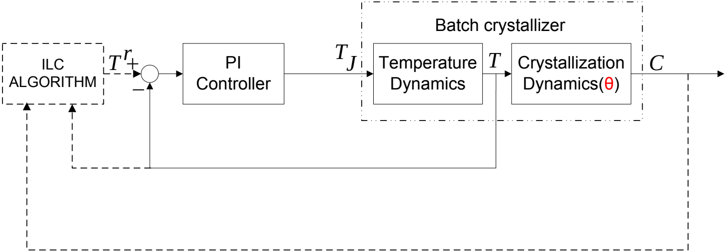


Simulation Results

Cases

Simulation study in four cases

Case 1: No disturbances, parametric model mismatch



Simulation Results
Cases

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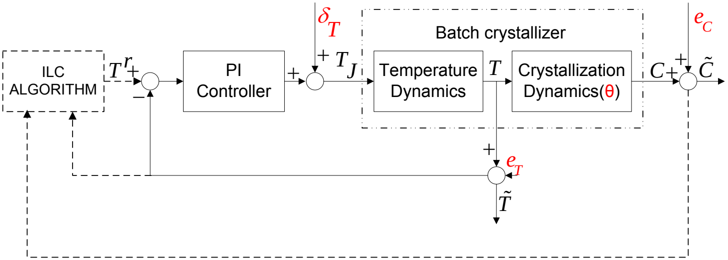
Case 2: Disturbances + parametric model mismatch



Simulation Results

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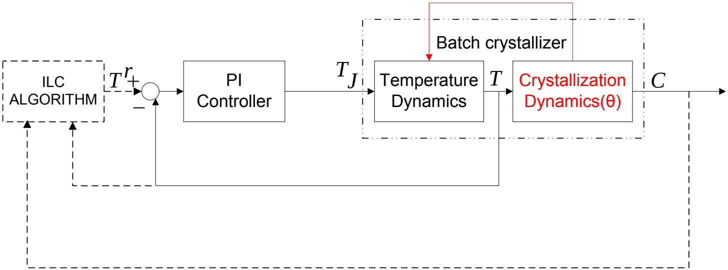
Case 3: No disturbances, structural model mismatch



Simulation Results

Cases

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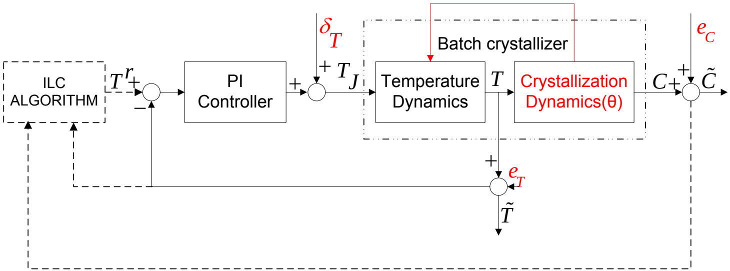
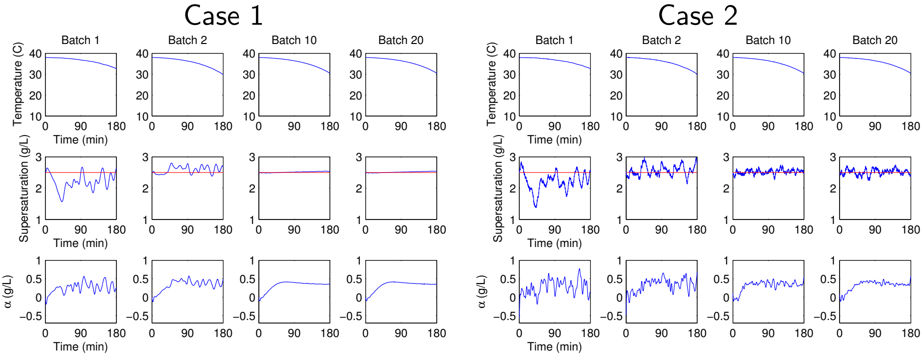
Case 4: Disturbances + structural model mismatch



Simulation Results

Cases 1 & 2



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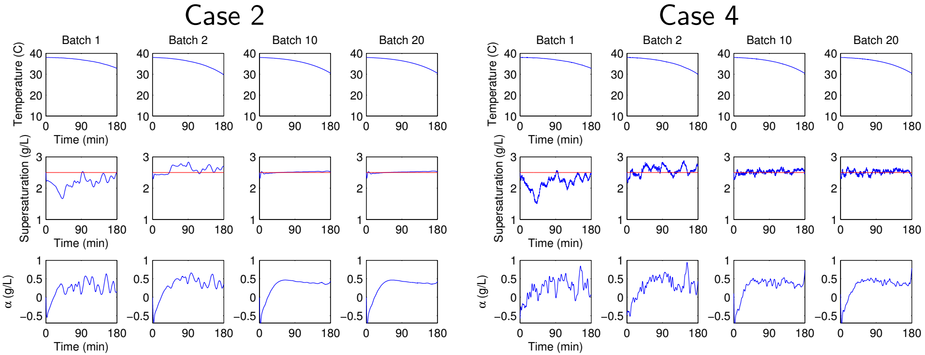
Cases 2 & 4



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Conclusions

An Iterative Learning Control scheme for batch cooling crystallization.

- Can use measurements available at the end of a batch.
- Built on top of standard T control
- Can cope with model mismatches and disturbances.

Future/current work

- Practical implementation.
- Control more properties (growth rate, CSD).
- Improve the tuning of the algorithm.
- Comparison with parametric estimation.

Thank you.
Questions?