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Easy to Use Run-to-run Control of Heating Processes with Rapid Thermal Gradients

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Run-to-run Update of Continuous Control

- Processes with continuous control
- Illustrated for thermal processing, applicable to other processes.
- Many applications of run-to-run update for processing parameters based on the end result of the batch
- This talk: update of continuous control
- Focus: robust, simple, reliable, easy to use and setup
- Accommodating to adjustment or change of equipment and recipe

Rapid Thermal Processing Control

- RTP requires tight control
  - rapid temperature ramping rates
  - closely follow temperature profiles
  - keep thermal gradients low
  - continuous control through a run

- Control issues
  - highly nonlinear dynamics of the process
  - heating zone cross-coupling
  - detailed and accurate dynamical models are expensive to get

RTP Control Approaches

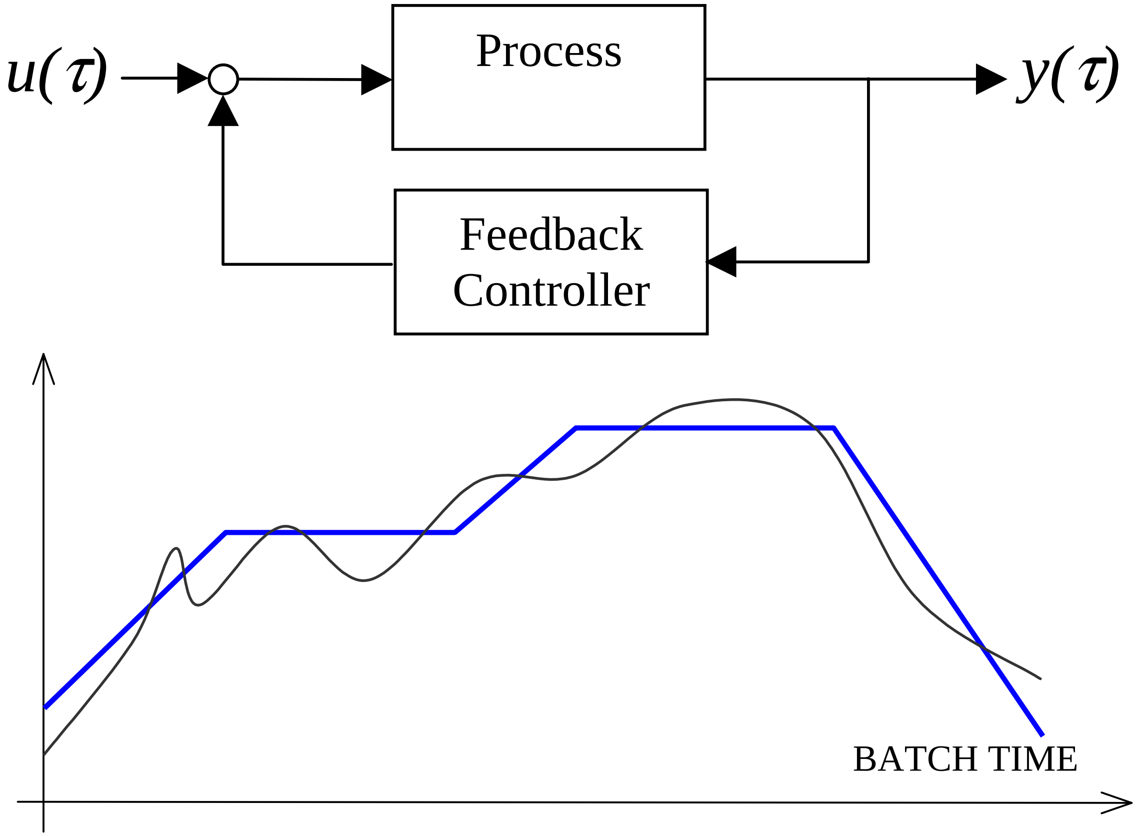
- PID control of each zone temperature
  - simple conceptually
  - easy to maintain, robust to control parameter choice
  - low performance, slow response

- APC: Multivariable feedback control, e.g., MPC
  - conceptually complicated, need for a PhD engineer
  - requires careful model identification and tuning
  - good performance

RTP Control Approaches (cont’d)

- ILC (Iterative Learning Control)
  - ILC = Run-to-run update of the feedforward sequence
  - conceptually simple
  - very robust
  - excellent performance
  - automated identification and tuning is possible
  - subject of this presentation
- ILC history
  - the concept first developed for robotics control
  - now used for process control as well

ILC Concept: Feedforward Control



$u(\tau)$

Process

$y(\tau)$

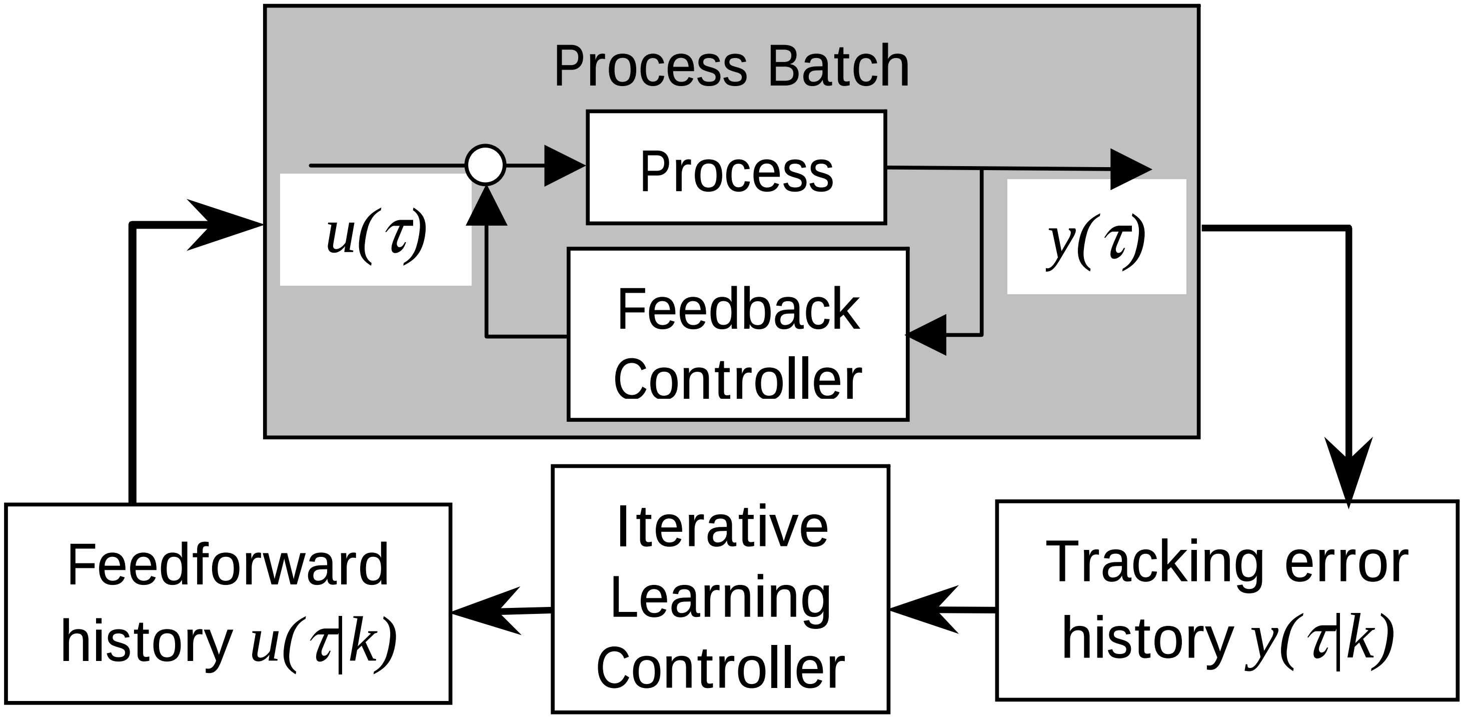
Feedback Controller

BATCH TIME

- τ is local time, $0 \leq \tau \leq T$

ILC Concept: Run-to-run update

Iterative Learning Control (ILC) Concept



- τ is local time, $0 \le \tau \le T$
- k is run number
- 2-D system evolving in τ and k

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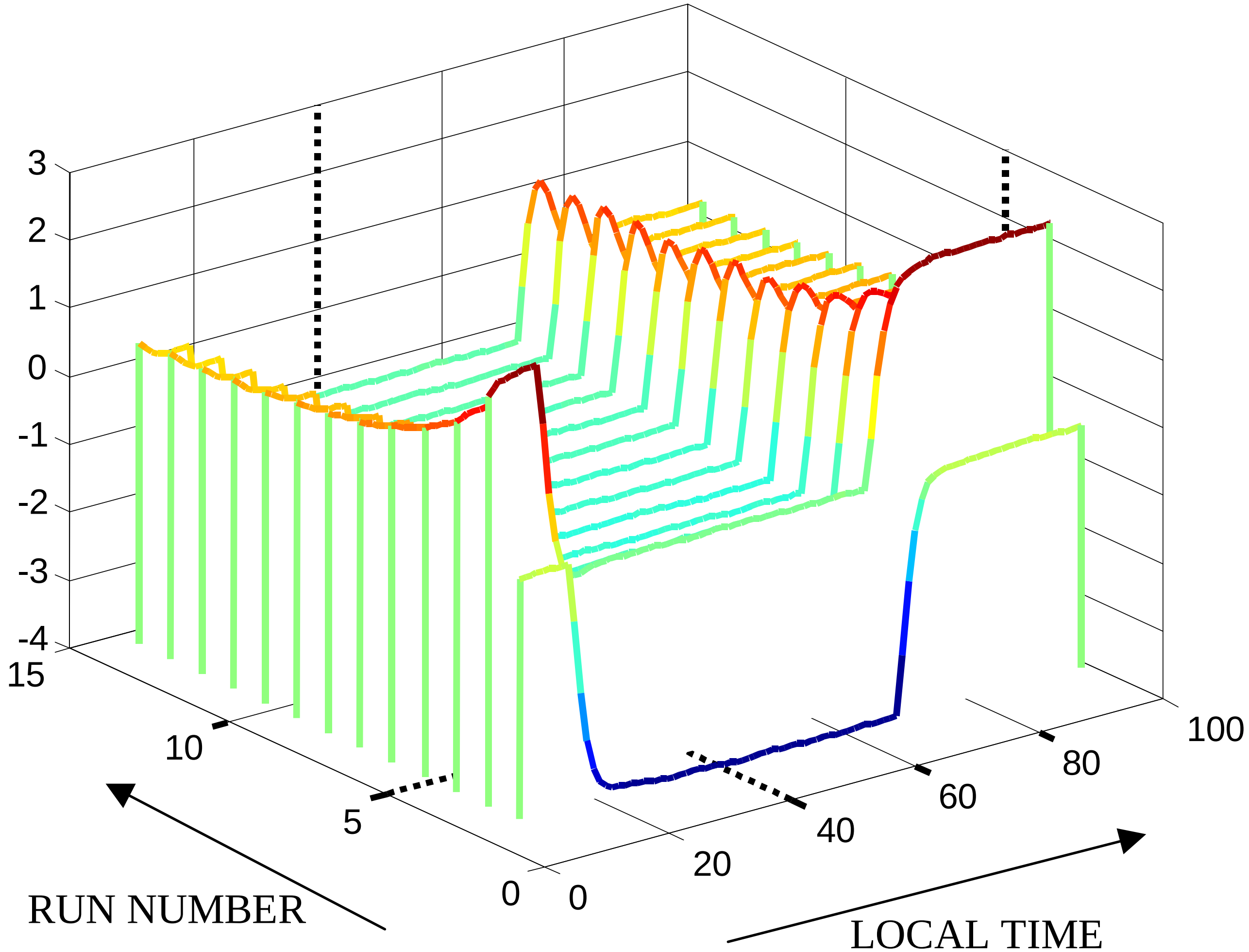
ILC as a 2-Dimensional System



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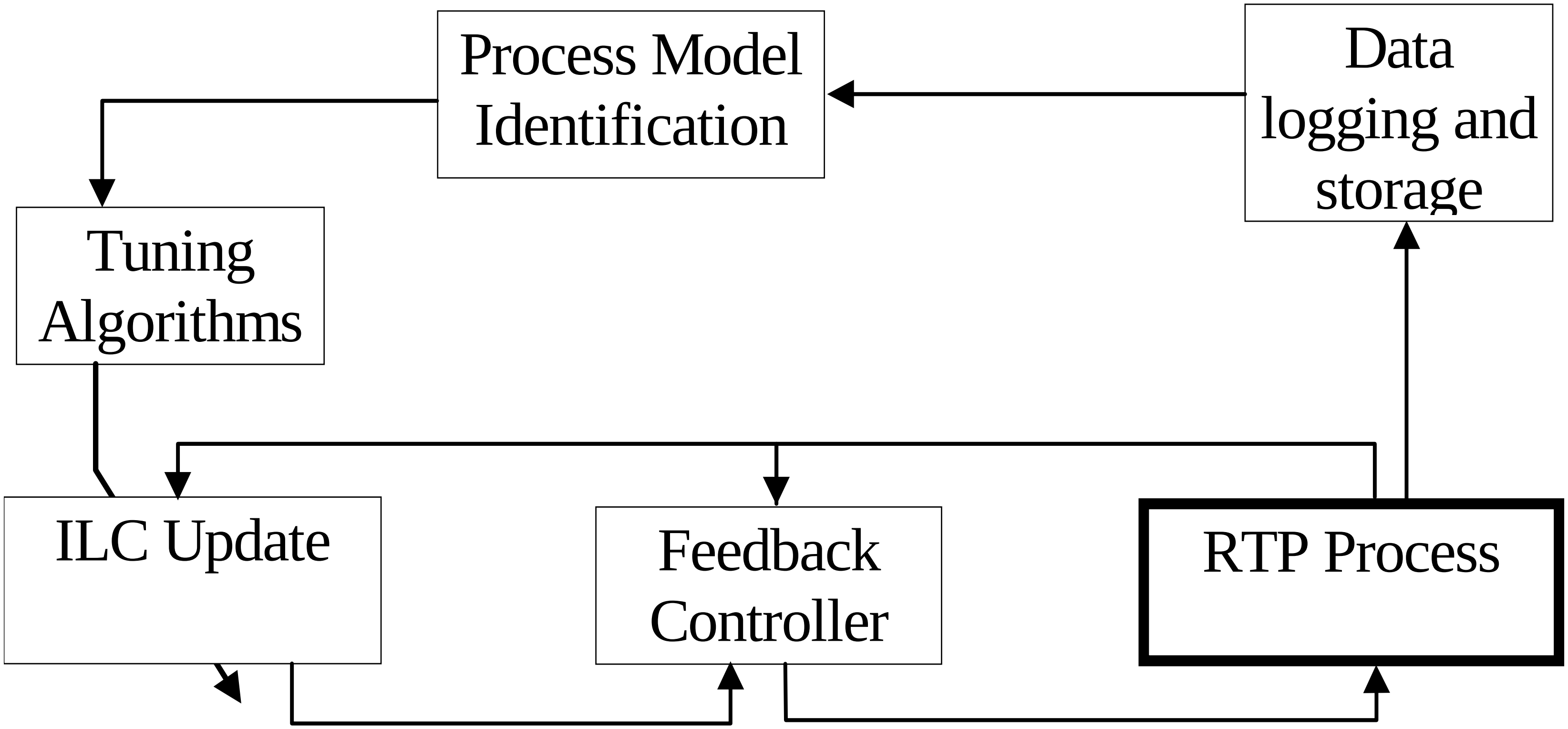
ILC Advantages

- ILC is non-causal in local time - “future” error history is known from the previous run
- No phase lag, hence, very good robustness while maintaining excellent performance
- Approximate model is sufficient, hence, easy process identification and tuning
- Honeywell’s ILC technology comes as a package including:
  - Run-time supervisory controller
  - Tuning tool
  - Identification tool

ILC Application Package



Process Model Identification

Data logging and storage

Tuning Algorithms

ILC Update

Feedback Controller

RTP Process

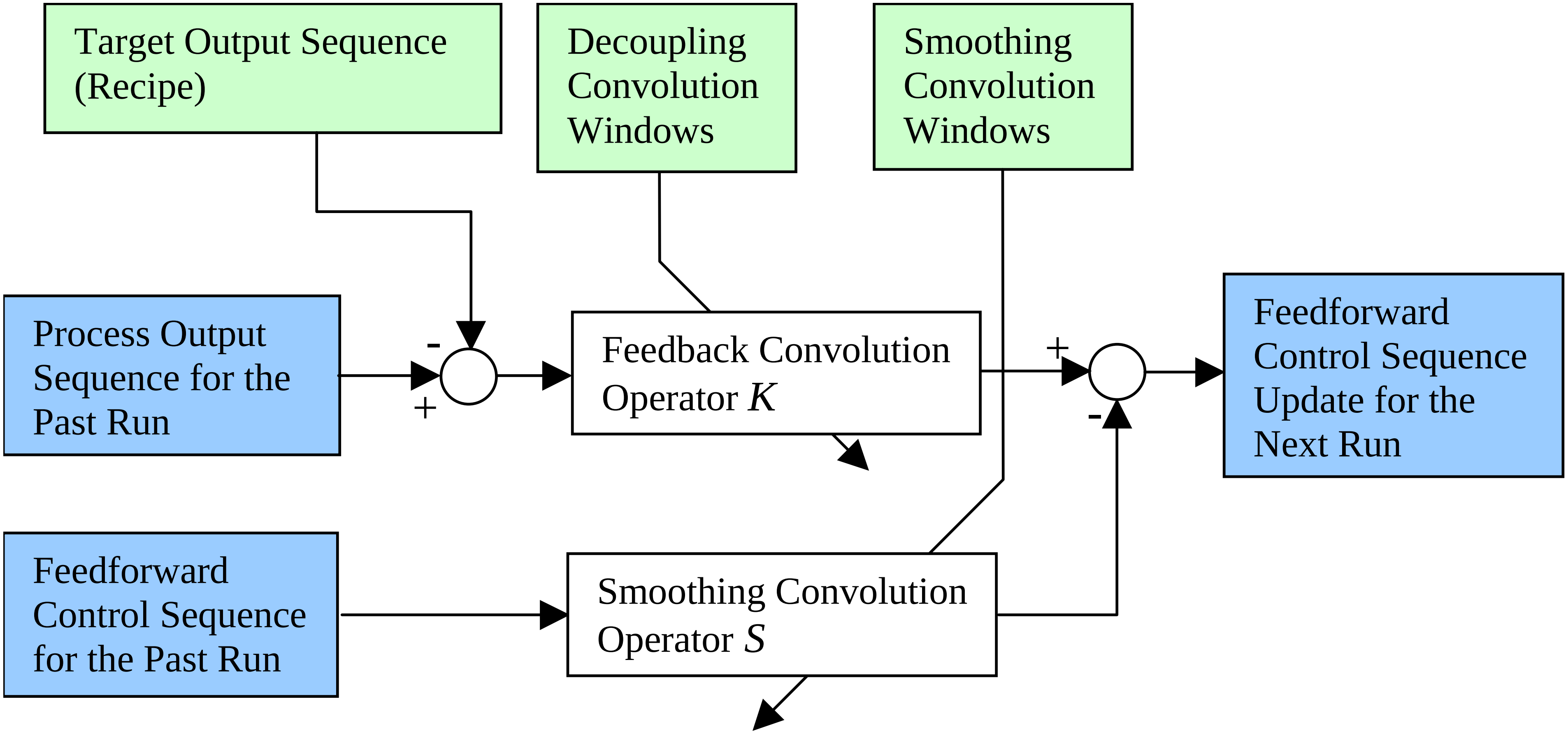
ILC Run-time Update

- ILC update rule

$$u(t \mid n+1) = u(t \mid n) - \left(K * e\right)(t \mid n) - \left(S * u\right)(t \mid n)$$

- t - local time
- n - run number
- $*$ - denotes convolution
- K - decoupling convolution operators
- S - smoothing convolution operators

ILC Run-time Update



Target Output Sequence (Recipe)

Decoupling Convolution Windows

Smoothing Convolution Windows

Process Output Sequence for the Past Run

Feedback Convolution Operator K

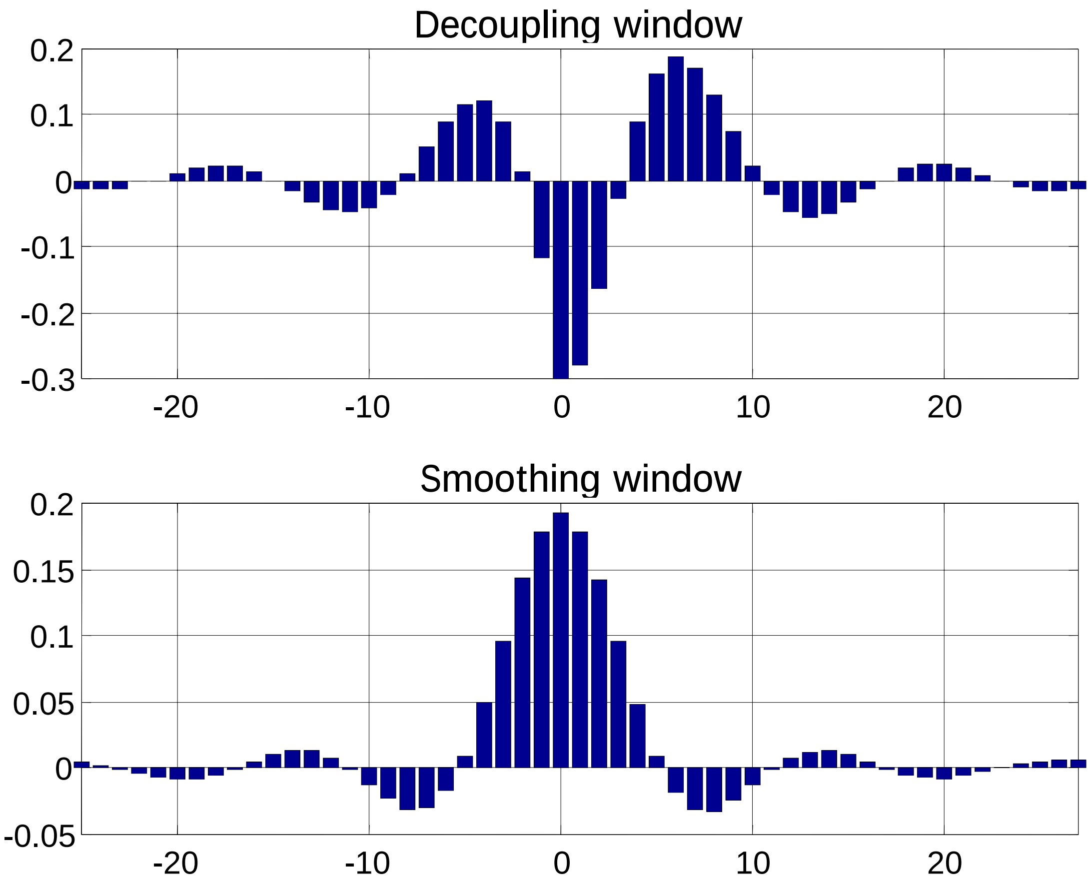
Feedforward Control Sequence Update for the Next Run

Feedforward Control Sequence for the Past Run

Smoothing Convolution Operator S

ILC Run-time Update

- Example: Convolution windows for ILC update

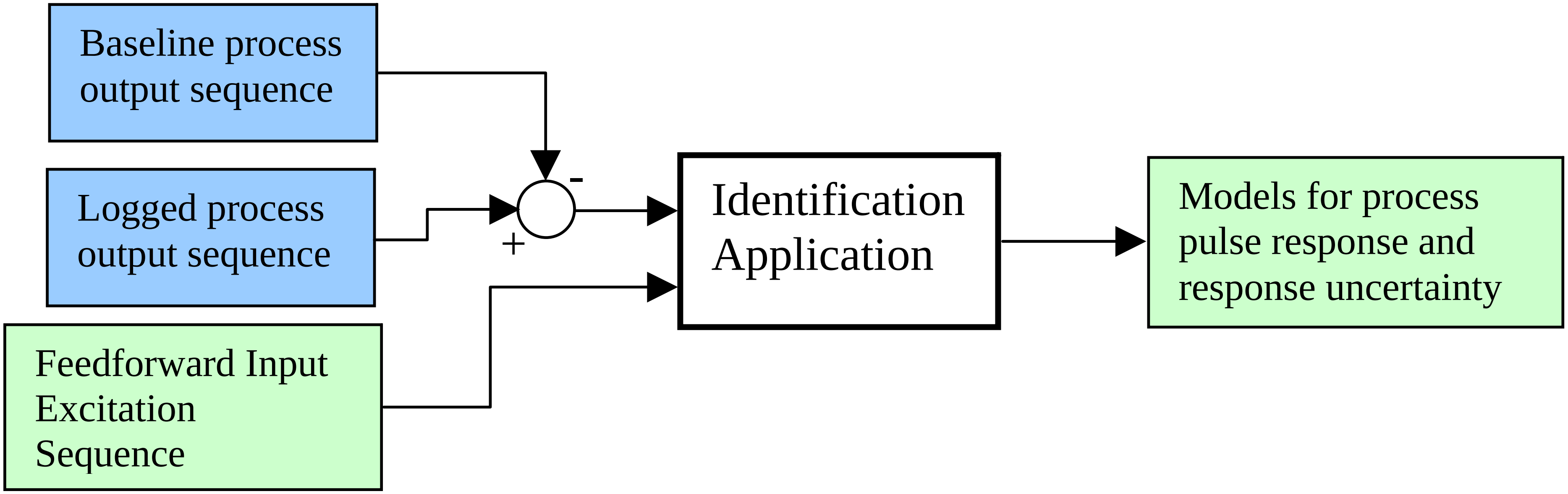


Identification Application

Feedforward Input Excitation Sequence

Process Batch Run and Data Logging Application

Process output sequence



Baseline process output sequence

Logged process output sequence

Feedforward Input Excitation Sequence

Identification Application

Models for process pulse response and response uncertainty

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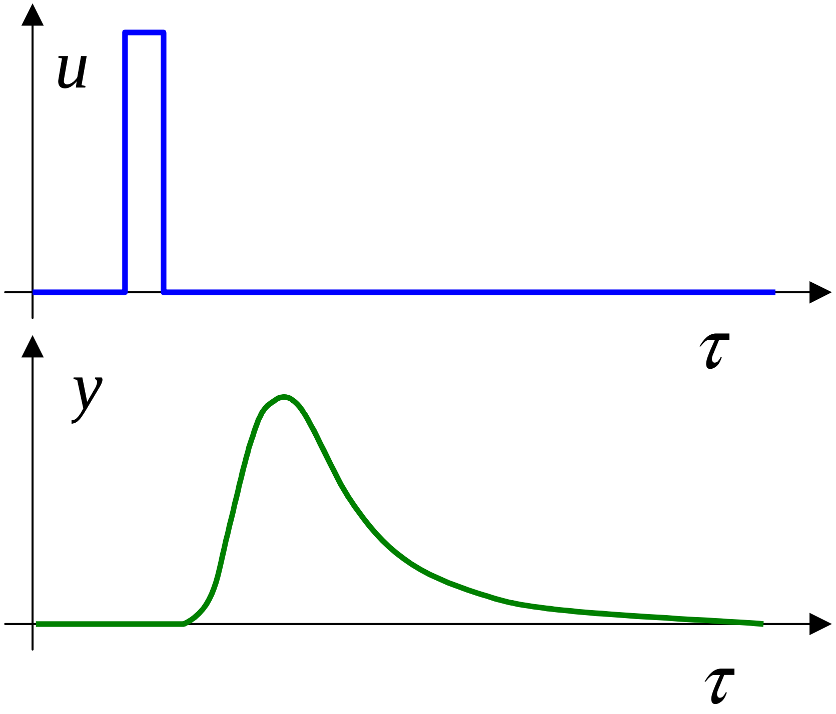
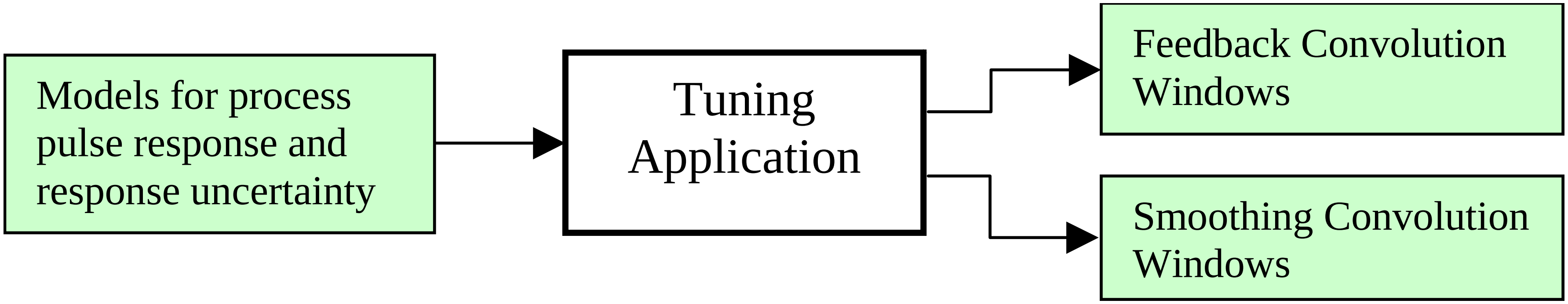
Model Identification: FIR model



- FIR model identification from data is standard for industrial MPC packages
- Robust identification of an average FIR model from an experiment with a single batch run is possible

Tuning Application



Models for process pulse response and response uncertainty

Tuning Application

Feedback Convolution Windows

Smoothing Convolution Windows

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ILC Update Tuning (Controller Design)

ILC Design Problem**:**

- The update converges quickly
- The update is robust to modeling errors
- Limited control effort is required
- Insensitive to noise
- Automated design

ILC Analysis Problem**:**

- Evaluate stability (convergence)
- Find robust stability margin
- Estimate control effort required

Controller Design

$$y = Gu$$

$$J(\omega) = |e(\omega)|^2 + |R(\omega)u(\omega)|^2 \to \min$$

$$u_{new}(\omega) = u_{old}(\omega) - K(\omega)e(\omega) - S(\omega)u_{old}(\omega)$$

$$K = \left(G^*(\omega)G(\omega) + R^*(\omega)R(\omega)\right)^{-1} G^*(\omega)$$

$$S = \left(G^*(\omega)G(\omega) + R^*(\omega)R(\omega)\right)^{-1} R^*(\omega) - I$$

Frequency Domain Controller Design

- Robust stability condition
- Control amplitude constraint

$$R(\omega) > w_0 |G(\omega)| - |G(\omega)|^2$$

- Performance requirement: minimize steady-state error

$$R(\omega) \to \min$$

- Noise insensitivity

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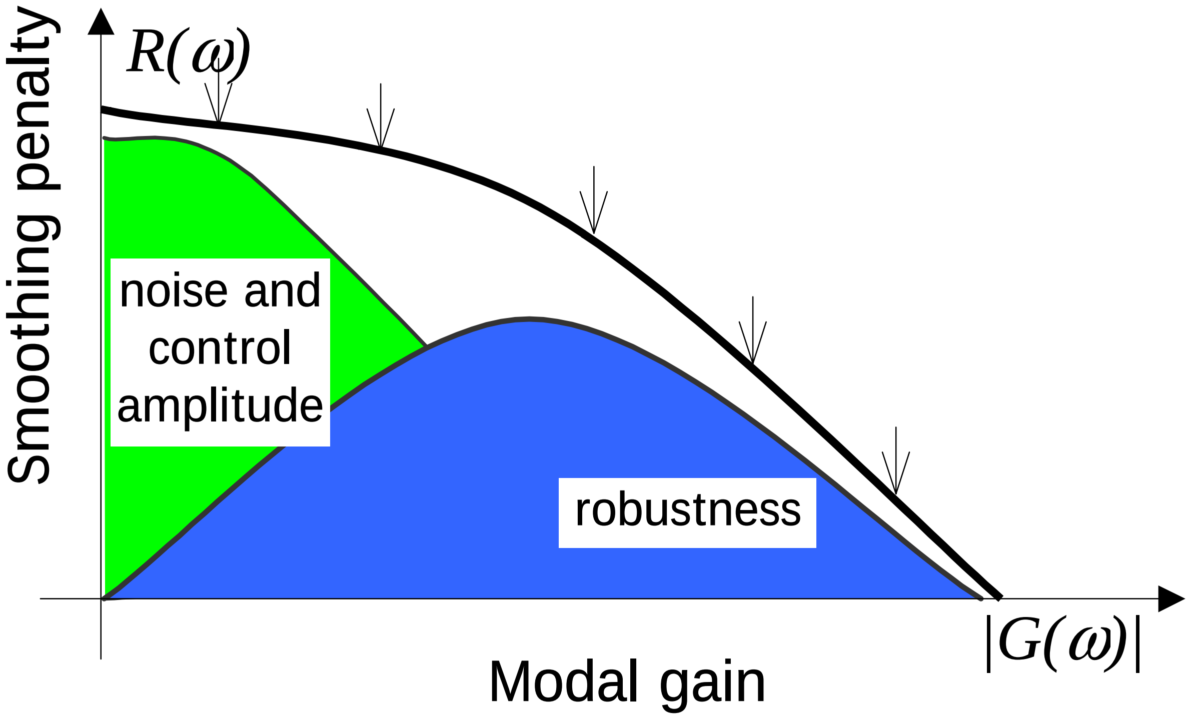
Frequency Domain Controller Design

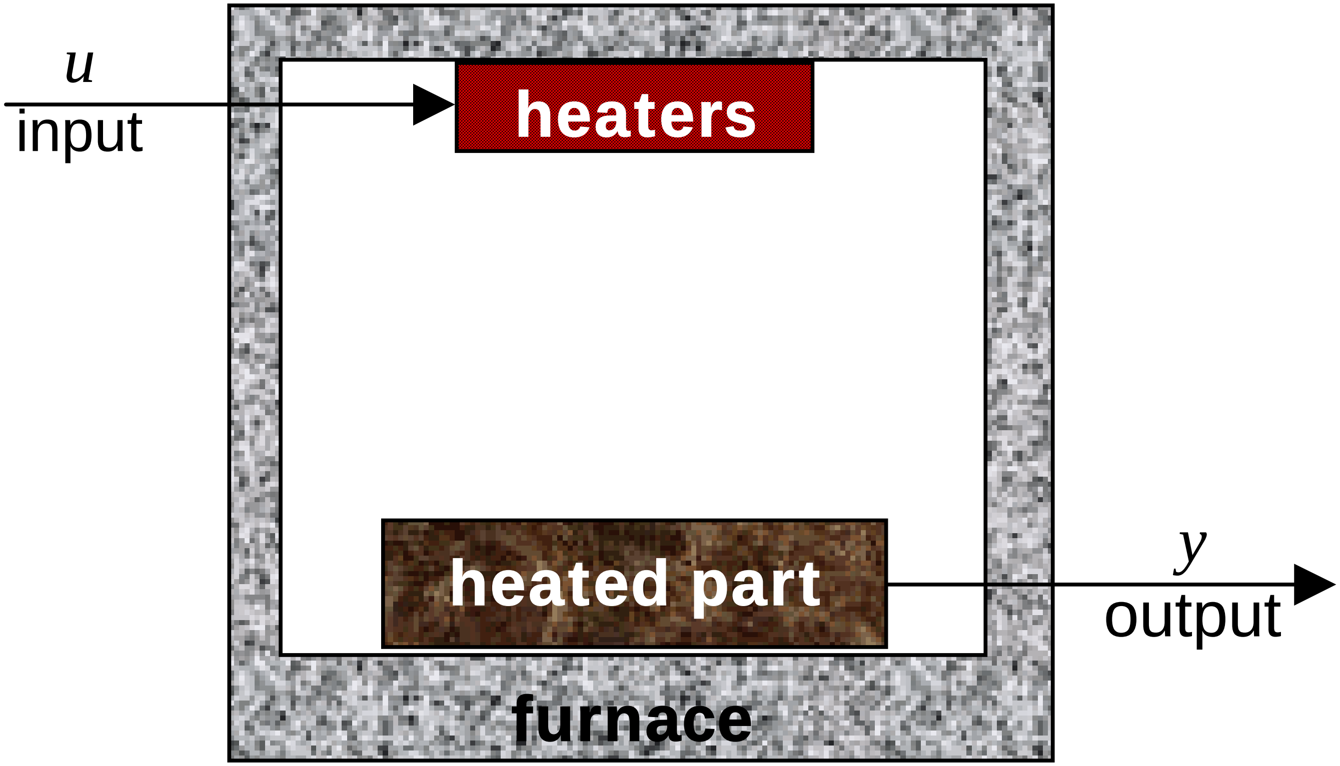


- Noncausal loopshaping design for local time operators
- Related to LQG/LTR and loopshaping control design methods used for flight control design

Thermal Processing Application

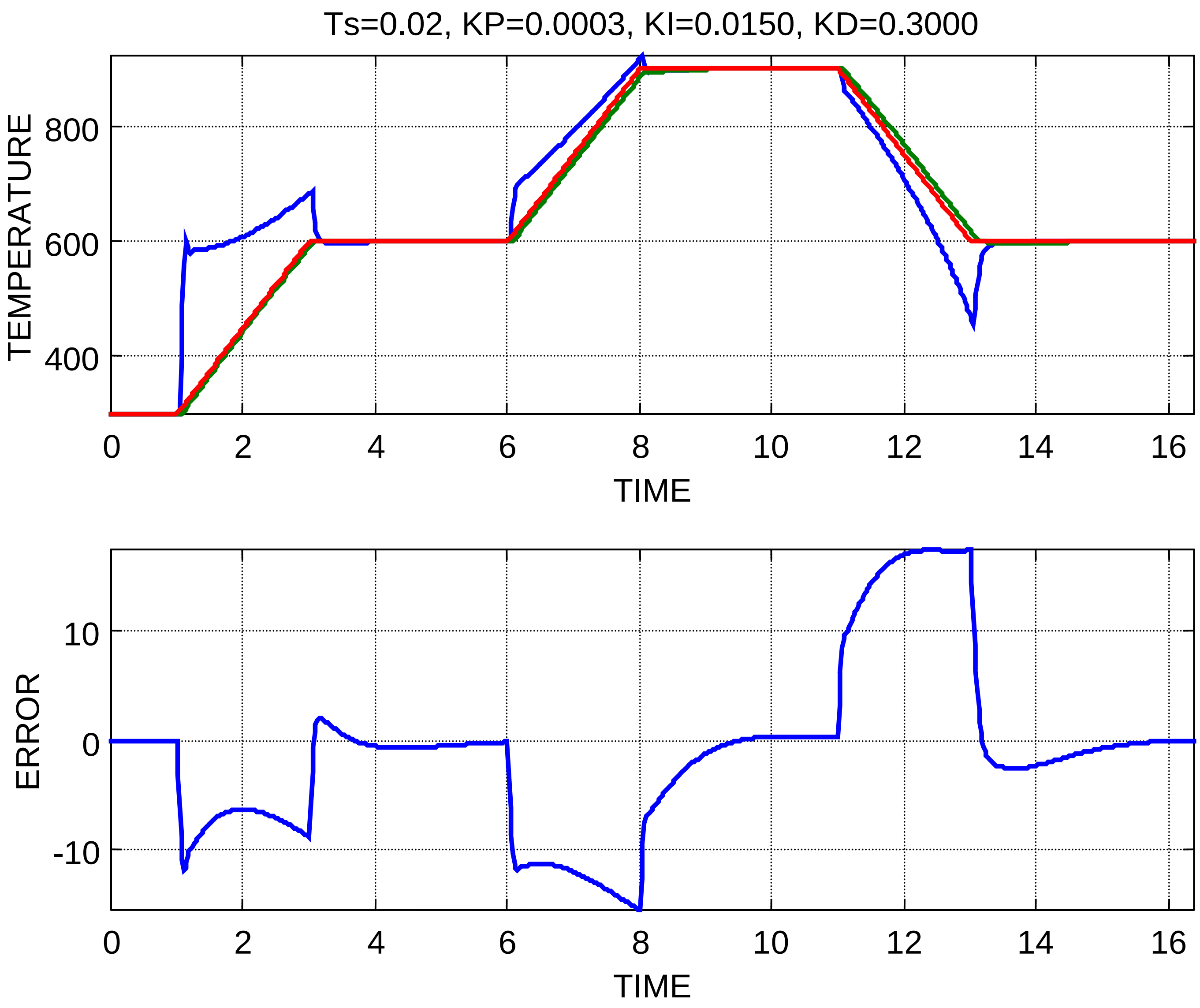
- Carbon composite annealing process
- Military/Aerospace relevant
- More difficult to control than RTP - furnace thermal inertia
- Time scale is proportionally slower than for both process and control

Thermal Processing Model



- Two states: plant and furnace temperatures
- Nonlinear dynamics: radiation and convection heat transfer

Thermal Processing with PID Control



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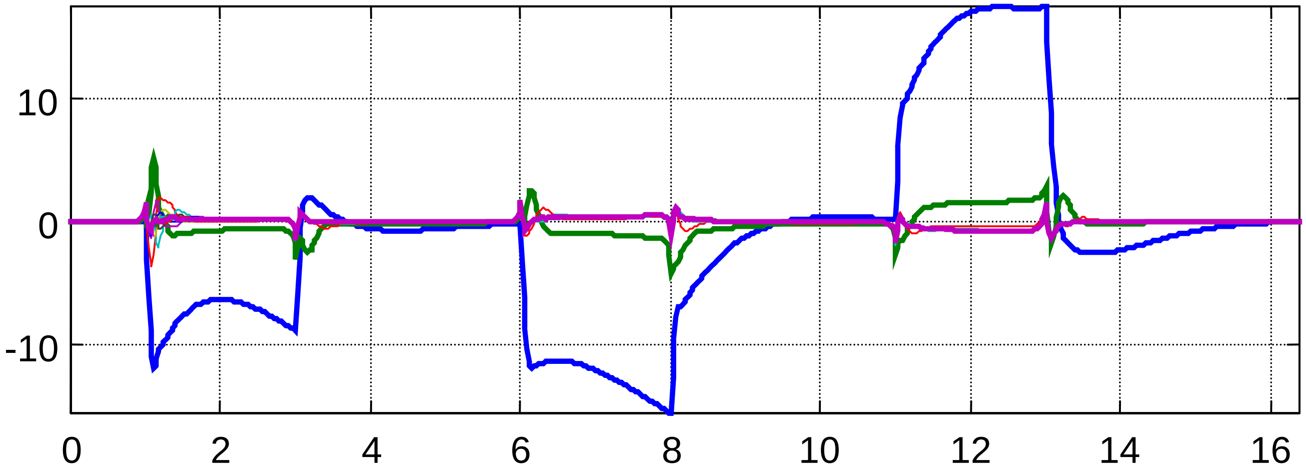
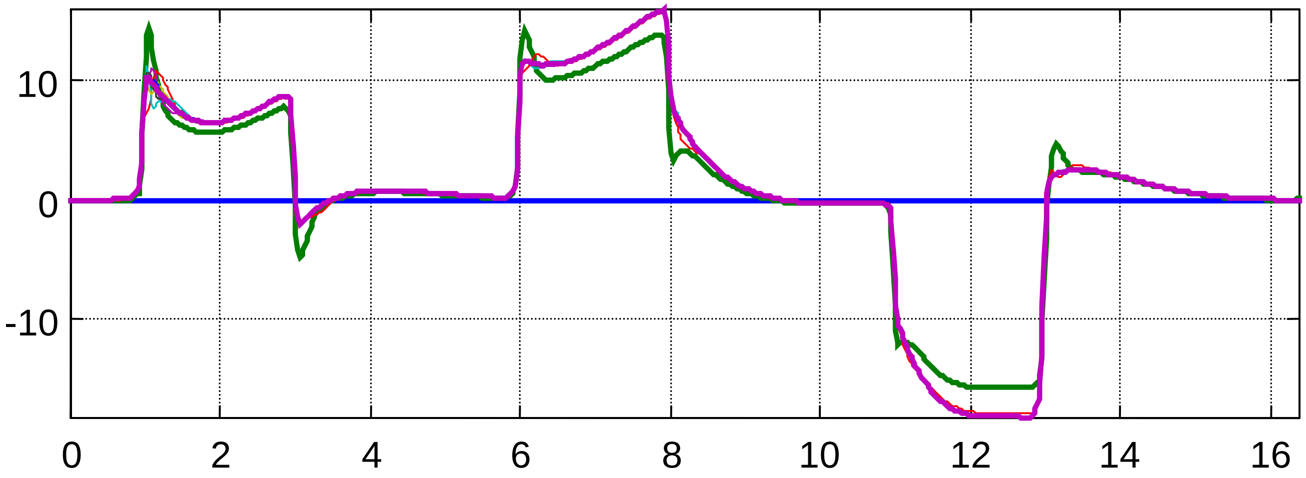
ILC Update for Thermal Processing


OUTPUT ERROR UPDATE HISTORY


FEEDFORWARD UPDATE HISTORY

ILC Results for Annealing

- Because of the furnace thermal inertia the process is more difficult to control than RTP
- 30% linear model uncertainty because of the process nonlinearity
- ILC feedforward is used on top of a PID feedback control
- Extremely good control performance achieved
  - ILC update converges in 4-5 steps
  - less that 1 degree maximal error
  - ILC feedforward modification is smooth and small

Conclusions

- Simple and consistent ILC approach for RTP control
- Superior performance, robust, easy to use and maintain
- Simple on-line computations, can be implemented in a low-end processor
- Integrated identification and tuning package based on industrial FIR model
- Automated tuning for operator use
- Control design based on specs: performance, robustness margin, etc; similar to LQG/LTR