Run-to-run Control of Repetitive Dynamic Processes

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Outline

- Features of repetitive dynamic processes
- Control of RDP
  - On-line control
  - Run-to-run control
    - ✓ Iterative Learning Control (ILC)
    - ✓ Parameterized run-to-run control (R2R)
- Examples
  - Scale-up of semi-batch reactor
  - Optimization of batch distillation column
- Conclusions

Features of RDP

- Repetitive nature
  - System goes through a repetitive cycle of events (or)
  - A process operation is repeated several times
  - One cycle or one process operation is called a run
- Every run is dynamic and of finite duration
  - Operation within a run ends after a finite time

Examples of RDP


Chemical process


Bioreactor

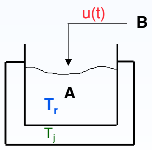

Robot


Semi-conductor manufacturing plant

Scale-up of Semi-batch Reactor

$$A + B \xrightarrow{k_1} C$$
$$2B \xrightarrow{k_2} D$$
$$C + B \xrightarrow{k_3} E$$

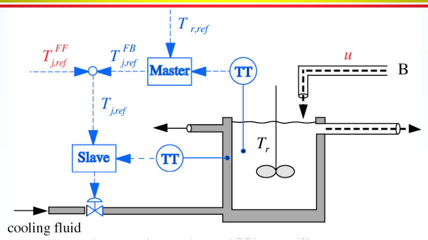
Exothermic reactions



Scale-up from laboratory to production

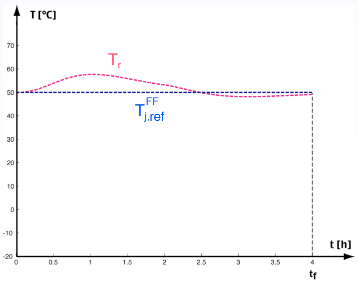
- Differences in reaction rates and heat transfer
- Objectives
  - ✓ Isothermal operation
  - ✓ Meet terminal selectivity constraints $c_B(t_f) \leq c_{B,max}$, $c_D(t_f) \leq c_{D,max}$

Traditional Scale-up Strategy



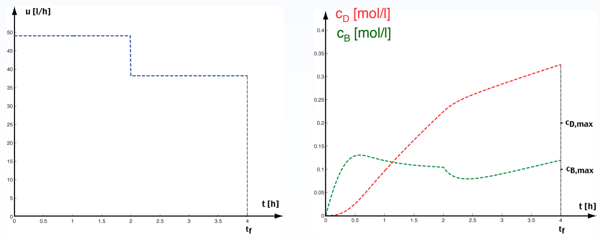
- Reproduce lab results in production via on-line control
- $T^{FF}_{j,ref}$ and u taken from lab experiments

Temperature Profile



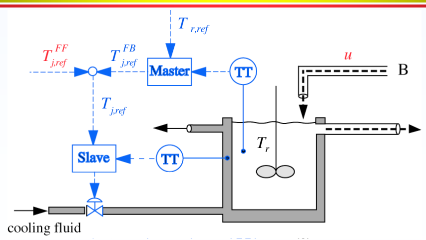
Far from isothermal !

Concentration Profiles
using Nominal Feedrate



Violation of terminal selectivity constraints !

Improved Scale-up Strategy …



… by adjusting $T_{j,\ ref}^{FF}$ and u using run-to-run control

Dynamics of RDP

- Dynamics for Run k

$$\dot{x}_k(t) = F(x_k(t), u_k(t)), \qquad x_k(0)$$
$$y_k(t) = H(x_k(t), u_k(t)) \qquad \text{on-line outputs}$$
$$z_k(t_f) = Z(x_k[0,t_f], u_k[0,t_f]) \qquad \text{run-end outputs}$$

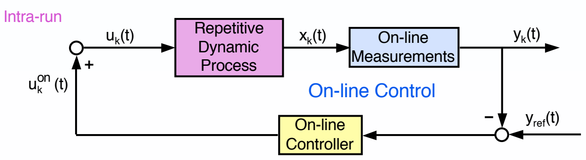
- Remarks
  - $y_k(t)$, with $t \in [0,t_f]$, gives the profile $y_k[0,t_f]$
  - Two time scales: run time t, run index k
  - Inter-run coupling possible through choice of $x_k(0)$ and $u_k[0,t_f]$

Control Approaches for RDP

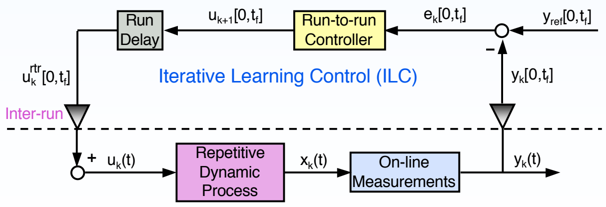
Control object

Control implementation	On-line outputs $y[0,t_f]$	Run-end outputs $z(t_f)$
On-line $\to u_k^{on}(t)$	1 *On-line control* $u(t) \to y(t) \to y[0,t_f]$ (PI)	2 *Predictive control* $u[t,t_f] \to z(t_f)$ (MPC)
Run-to-run $\to u_k^{rtr}[0,t_f]$	3 *Iterative learning control* $u[0,t_f] \to y[0,t_f]$ (ILC)	4 *Parameterized run-to-run control* $\mathcal{U}(\pi) = u[0,t_f] \to z(t_f)$ (R2R)

Control of $y[0, t_f]$ (1)



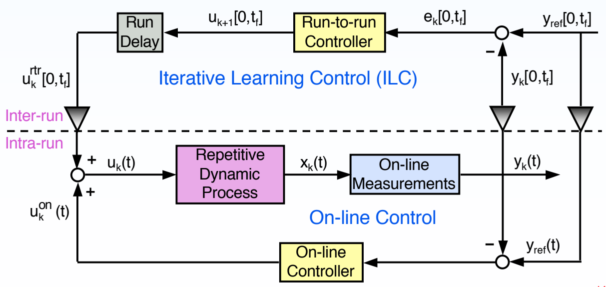
Control of y[0, t$_f$] (3)



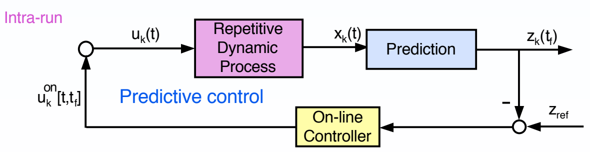
Improve trajectory tracking for repetitive processes

$$u_{k+1}[0,t_f] = Q u_k[0,t_f] + L e_k[0,t_f]$$

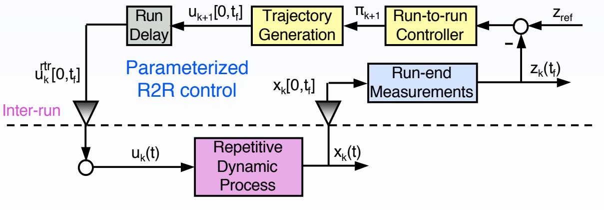
Control of y[0, t$_f$] (1+3)



Control of z(t$_f$) (2   )



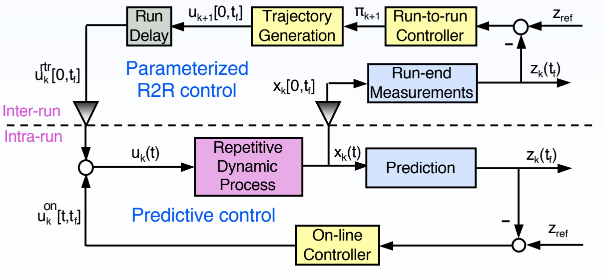
Control of $z(t_f)$ (4)



Parameterize the input trajectories $u_k[0,t_f]$ as $\mathcal{U}(\pi_k)$

$\pi_{k+1} = \mathcal{K}(z_{ref}, z_k(t_f))$ $\quad$ $u_{k+1}[0,t_f] = \mathcal{U}(\pi_{k+1})$

Control of $z(t_f)$ (2+4)



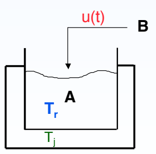
Scale-up of Semi-batch Reactor

$A + B \xrightarrow{k_1} C$

$2B \xrightarrow{k_2} D$

$C + B \xrightarrow{k_3} E$

Exothermic reactions



Control objectives

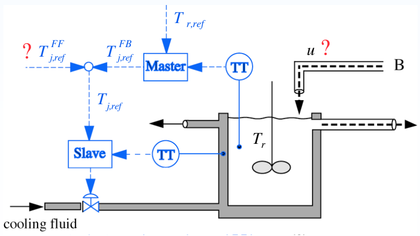
- Isothermal
- Selectivity constraints: $c_B(t_f) = c_{B,max}$, $c_D(t_f) = c_{D,max}$

Control for Scale-up

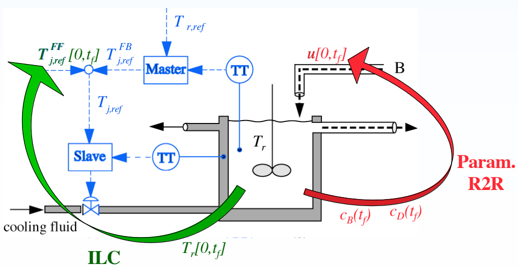
- On-line control
  - Generates $T^{FB}_{j,ref}(t)$ -- typically insufficient for isothermal operation
  - Does not address the selectivity constraints
- Run-to-run control
  - ILC: Efficient control of T_r by adjusting $T^{FF}_{j,ref}[0, t_f]$
  - Parameterized R2R: Meet terminal constraints by adjusting $u[0,t_f]$

	On-line output: $T_r(t)$	Run-end outputs: $c_B(t_f)$, $c_D(t_f)$
On-line	1 On-line control $T^{FB}_{j,ref}(t)$	
Run-to-run	3 ILC $T^{FF}_{j,ref}[0,t_f]$	4 Parameterized R2R control $u[0,t_f]$

Control Strategy



Control Strategy



Temperature Control

- On-line FB using PI-control
- Run-to-run FF using Iterative Learning Control

PI-control

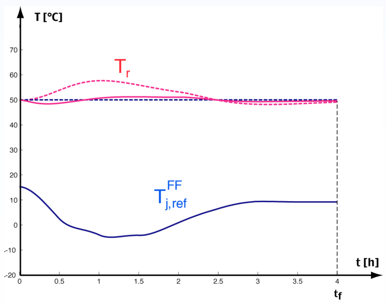
$$T_{j,ref}(t) = T_{j,ref}^{FF}(t) + K_R\left[e(t) + \frac{1}{\tau_I}\int_0^t e(t')dt'\right]$$

$$T_{j,ref,k+1}^{FF}\left[0, t_f - \delta\right] = T_{j,ref,k}^{FF}\left[\delta, t_f\right] + K\, e_k\left[\delta, t_f\right]$$

ILC with input shift to enforce convergence

Contribution of ILC

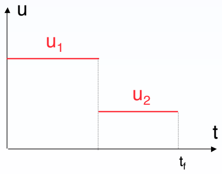
From $T_{j,ref}^{FF}$ = 50 °C (---)
to $T_{j,ref}^{FF}$ profile (—)
in 3 iterations



Parameterized R2R Control
Meet Selectivity Constraints

- Parameterization of input feed rate profile

$$\pi = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$



- Evaluation of sensitivities

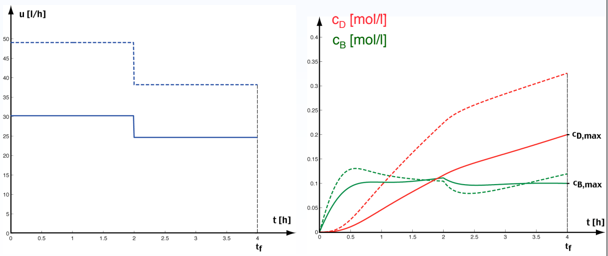
$$z = \begin{bmatrix} c_B(t_f) \\ c_D(t_f) \end{bmatrix} \qquad z = M\pi$$

- Run-to-run update of input parameters

$$\pi_{k+1} = \pi_k + K\, M^+\left[z_{ref} - z_k\right]$$

Parameterized R2R Control

Meet Terminal Constraints in 2 Iterations



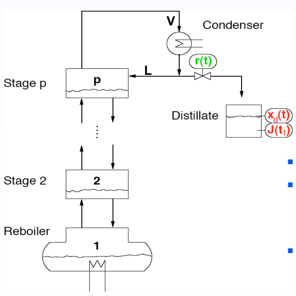
From nominal infeasible profile (---) to a feasible profile (—) in 2 iterations

Control Performance

Operation Scenario	$c_B(t_f)$ (mol/l) .100	$c_D(t_f)$ (mol/l) .200	$T_{r,max}$ (°C) $T_{r,ref} = 50$
Nominal feedrate PI control for T_r	.119	.326	57.1
Nominal feedrate PI control for T_r + ILC for $T_{j,ref}^{FF}$	.118	.327	**52.7**
R2R control for u_1 and u_2 PI control for T_r + ILC for $T_{j,ref}^{FF}$	**.100**	**.200**	**51.5**

Binary Batch Distillation Column

Optimization via Control

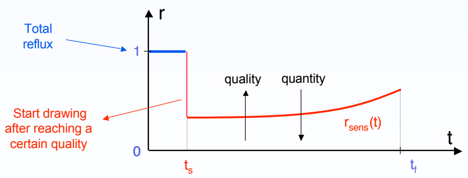


Optimization problem

$$\max_{r(t)} \quad J(t_f)$$
$$s.t. \quad DAE$$
$$x_d(t_f) \geq x_{d,des}$$
$$0 \leq r(t) \leq 1$$

- Input: Internal reflux ratio $r(t) = L/V$
- Constraints:
  - Path constraints: bounds on r(t)
  - Terminal constraint: distillate quality $x_d(t_f)$
- Measurements:
  - Accumulated distillate composition $x_d(t)$
  - Distillate quantity $J(t_f)$

Optimal Input

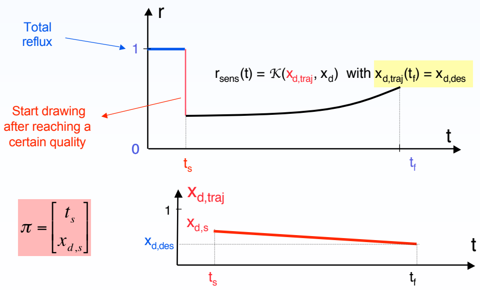


Terminal quality constraint is active, $x_d(t_f) = x_{d,des}$

Sensitivity is minimal, $\partial J(t_f)/\partial r = 0$

Control objective: Adjust r(t) in order to reach $x_d(t_f) = x_{d,des}$ and $\partial J(t_f)/\partial r = 0$

Another View of Optimal Input



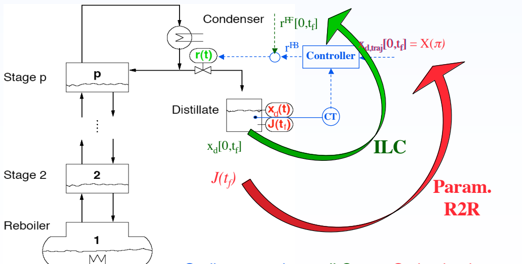
Adjust π in order to enforce $\partial J(t_f)/\partial \pi = 0$

Control Strategy

Control object

Control implementation	On-line output: $x_d(t)$	Run-to-run output: $\partial J(t_f)/\partial \pi$
On-line	1 On-line control $r^{FF}(t)$	
Run-to-run	3 ILC $r^{FF}[0, t_f]$	4 Parameterized R2R $\pi_{k+1} = \pi_k - K \frac{\partial J(t_f)}{\partial \pi}$
	Track $x_{d,traj}[0,t_f]$ to enforce $x_{d,traj}(t_f) = x_{d,des}$	Update $x_{d,traj}[0,t_f] = \mathcal{X}(\pi)$ to enforce $\partial J(t_f)/\partial \pi = 0$

Control Strategy



On-line control $r^{FB}(t)$ + ILC $r^{FF}[0,t_f]$ + Optimal trajectory $x_{d,traj}[0,t_f]$

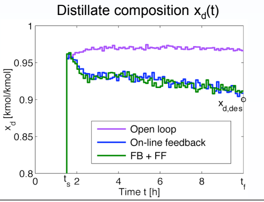
Simulation Results

Uncertainty

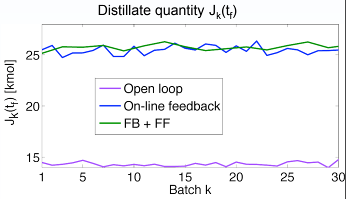
- Relative volatility (1.4 - 1.6), Boilup rate (13-17 kmol/h)
- Measurement noise (5 %)

→ Feasible but sub-optimal operation

Distillate composition $x_d(t)$



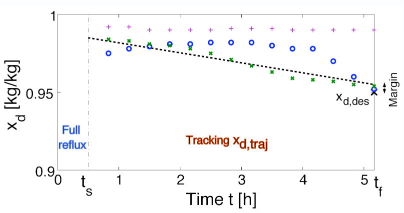
Distillate quantity $J_k(t_f)$



Experimental Results

Operation

- Initially full reflux
- Then, tracking purity reference trajectory



	$J(t_f)$
+ Open-loop	0.154 kg
o Tracking	0.176 kg
x Tracking + FF	0.187 kg
… $x_{d,traj}$	

Conclusions

- Many industrial systems are dynamic and repetitive
  - Use information from previous runs to improve performance of current run
- Implementation point of view
  - Coordinated use of on-line and run-end information
  - Possibility of optimizing processes via control (NCO tracking)
- Theoretical point of view
  - Need for new analysis tools (stability, controllability, etc.)