PID control of dead-time processes: robustness, dead-time compensation and constraints handling

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Dead-time processes

Dead-time processes are common in industry and other areas

Main dead-time (or delay) causes are:

- Transportation dead time (mass, energy)
- Apparent dead time (cascade of low order processes)
- Communication or processing dead time

Control of dead-time processes

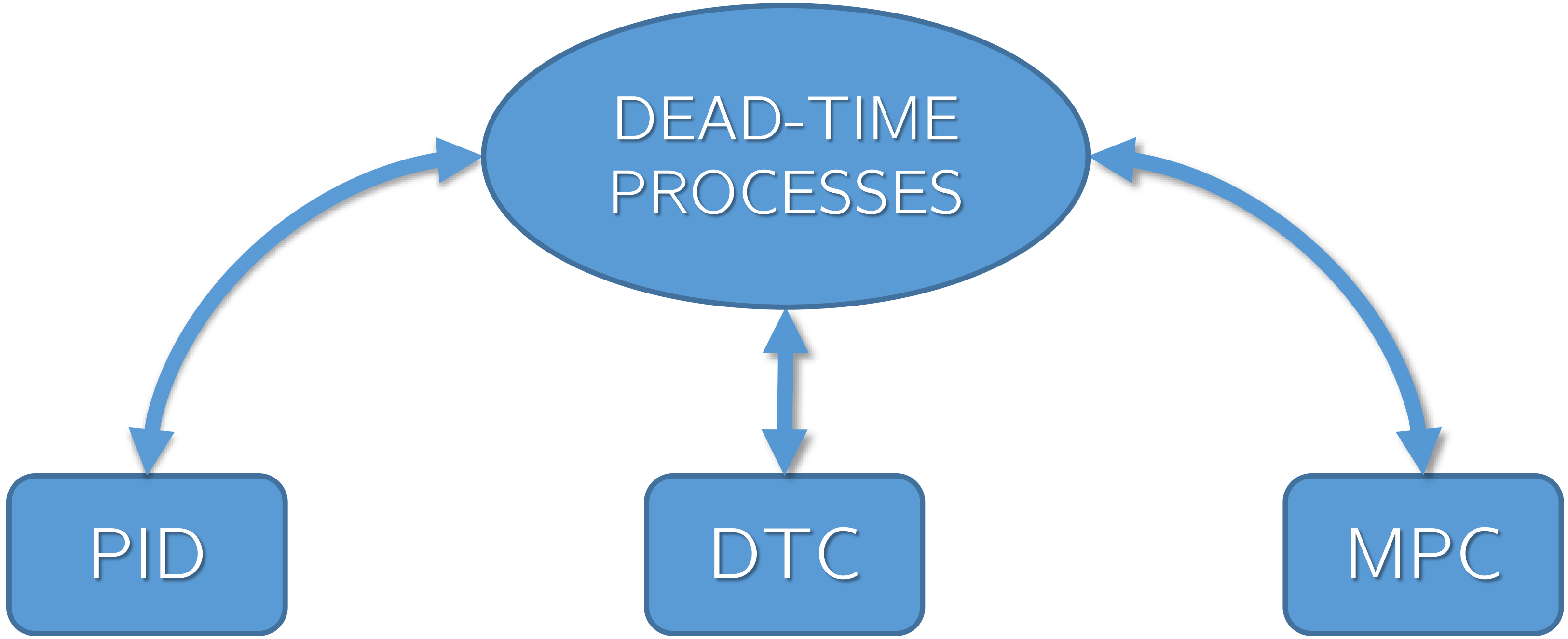
- Dead time makes closed-loop control difficult
- Simplest solution:
  - PID - trade-off robustness and performance
- Basic dead-time compensator - Smith Predictor (SP)
- Improved solutions: Modified SP (ex. FSP)
- Advanced solution: Model Predictive Control - MPC

Most used in industry PID – DTC – MPC *

Industry 4.0 – complex controllers at low level

* A Survey on Industry Impact and Challenges Thereof. IEEE CONTROL SYSTEMS MAGAZINE 17

When to use advanced control?



simple process models

compensates dead-time and can use high order models

is optimal and consider constraints

Objectives: Analysis of PID, DTC and MPC for dead-time processes

Agenda

1. Motivating examples, PID and DTC control.
2. Ideal control of dead-time processes
3. PID tuning using DTC ideas
    1. Unified tuning using FSP (stable and unstable plants)
    2. Trade-off performance-robustness
    3. Comparing PID and DTC
4. MPC, FSP and PID controllers
    1. Unconstrained case
    2. Constrained case – Using anti-windup
5. Conclusions

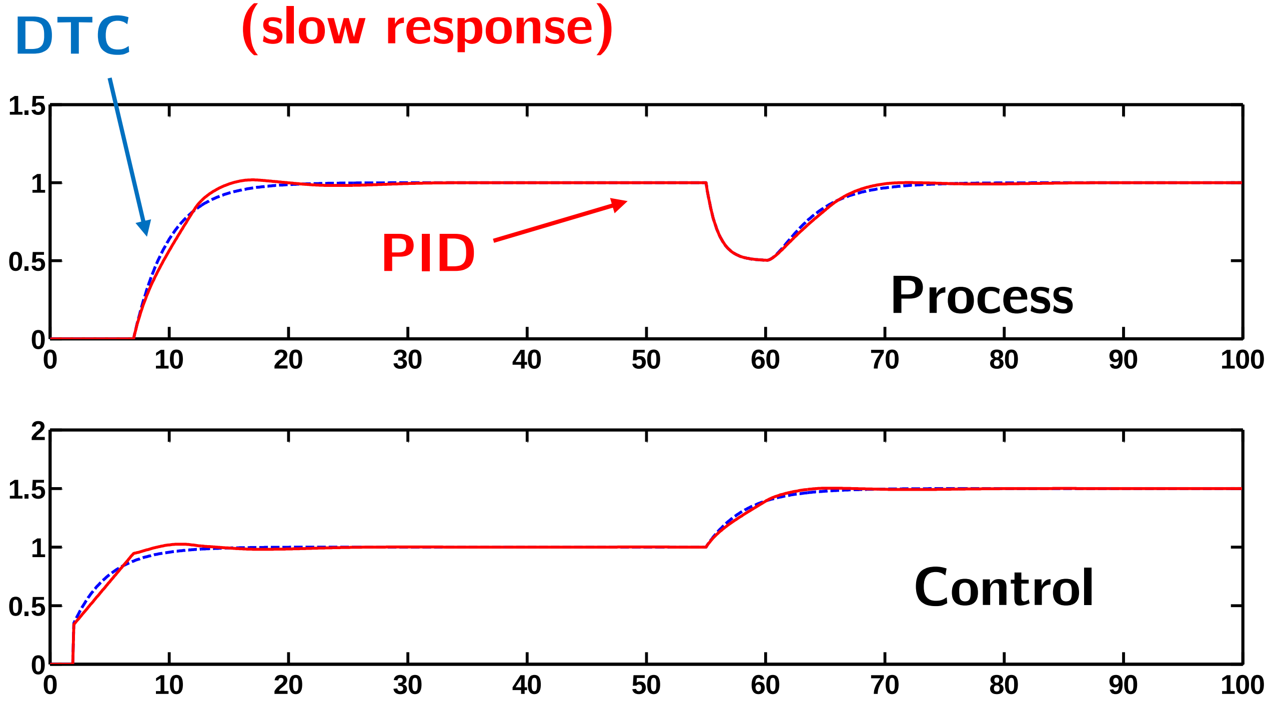
Motivating examples

Simple model – big delay

Simple model with large delay and large modelling error

$$P_n(s) = \frac{e^{-5s}}{s+1}$$

Robust PID and DTC tuning (slow response)



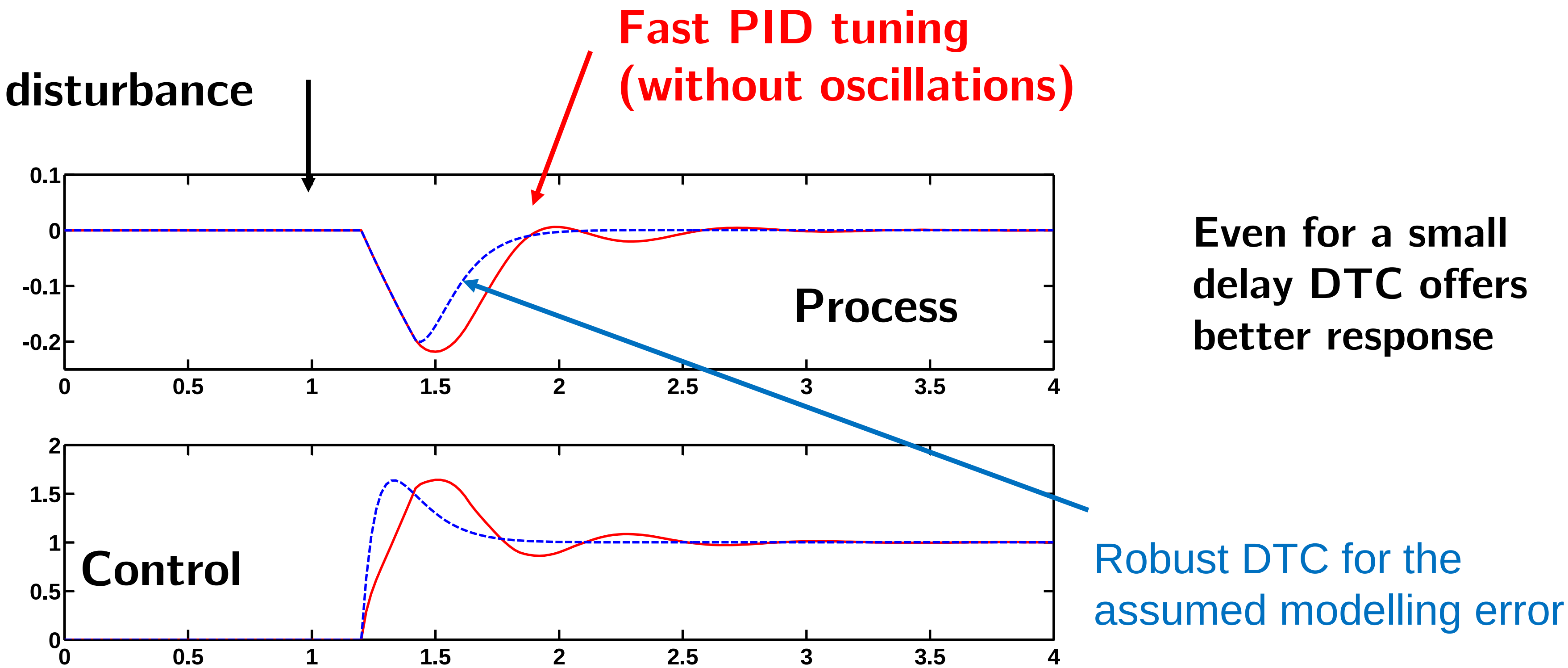
Even for a dominant delay process PID offers a good response

Fast response – small delay

Simple model with small modelling error

Well known delay (network)

$$P_n(s) = \frac{e^{-0.2s}}{s+1}$$



Even for a small delay DTC offers better response

To study the advantages of advanced controllers

for dead-time processes related to:

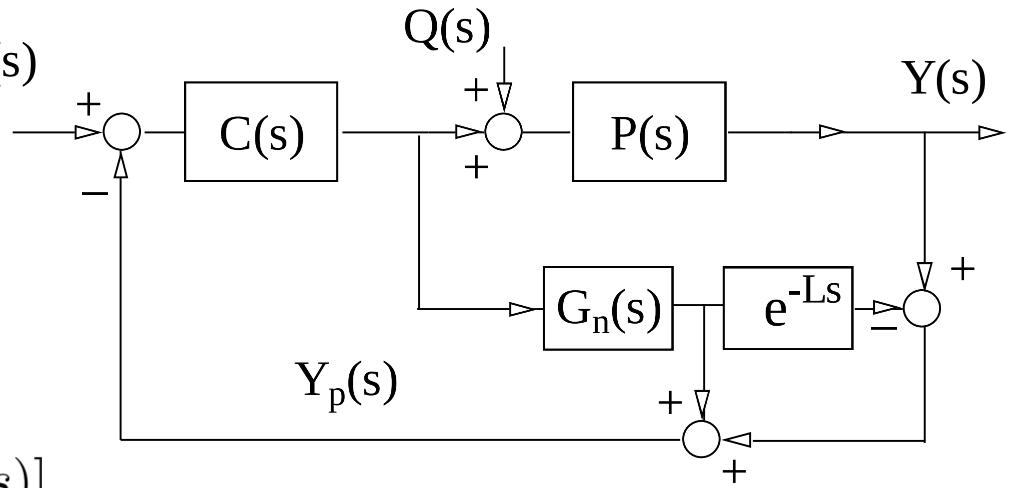
- **Process dead-time**
- **Process modeling error (robustness)**
- **Other aspects:** **Model complexity**

  Constraints handling

Ideal control of dead-time processes

Smith predictor of a pure delay process

$$P(s) = e^{-Ls}$$



$$H_{yr}(s) = \frac{Y(s)}{R(s)} = \frac{C(s)G_n(s)e^{-Ls}}{1 + C(s)G_n(s)}$$

$$H_{yq}(s) = \frac{Y(s)}{Q(s)} = P_n(s)\left[1 - H_{yr}(s)\right]$$

$$G_n(s) = 1 \qquad C(s) = K_c$$

1 delay

Ideal case $K_c \rightarrow \infty$

$$H_{yr}(s) = e^{-Ls}$$

$$H_{yq}(s) = e^{-Ls}\left[1 - e^{-Ls}\right]$$

2 delays

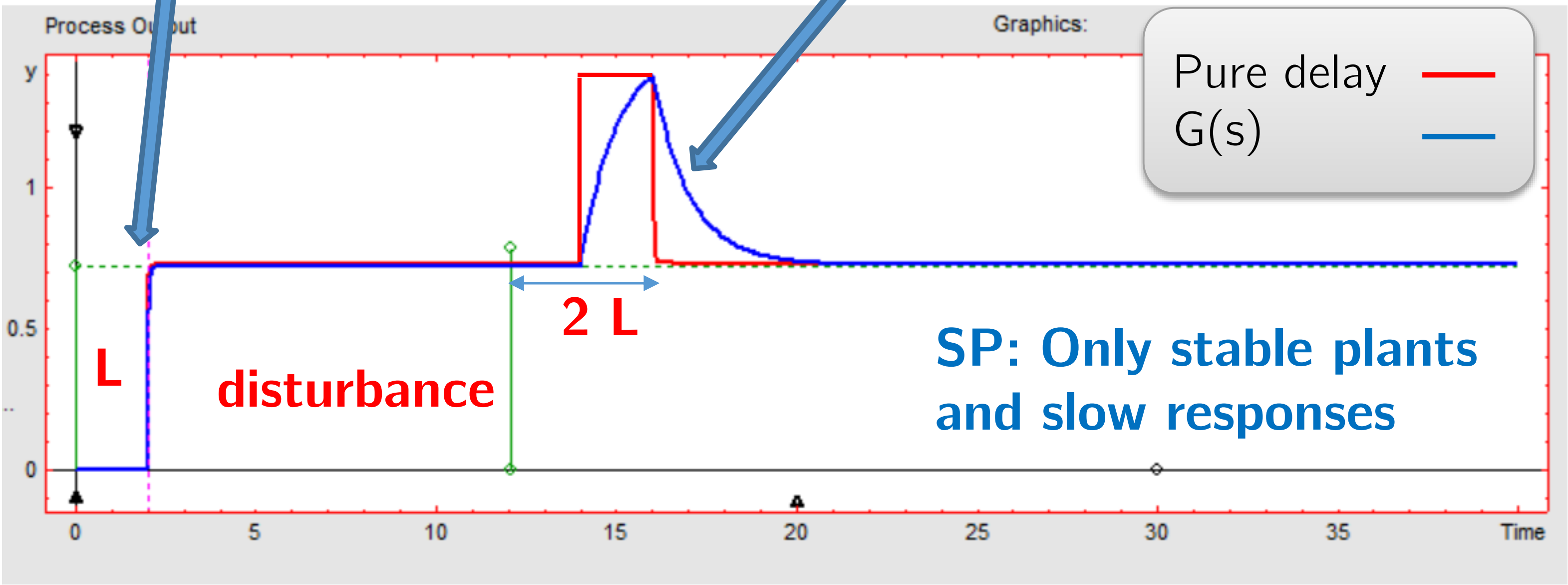
Smith predictor of a FOPDT process

$$P(s) = \frac{K_e}{1+sT} e^{-Ls}$$

Using $C(s) = K_c$ and ideal case $K_c \to \infty$

$$H_{yr}(s) = e^{-Ls} \qquad H_{yq}(s) = \frac{K_e}{1+sT} e^{-Ls} \left[1 - e^{-Ls}\right]$$

Open loop



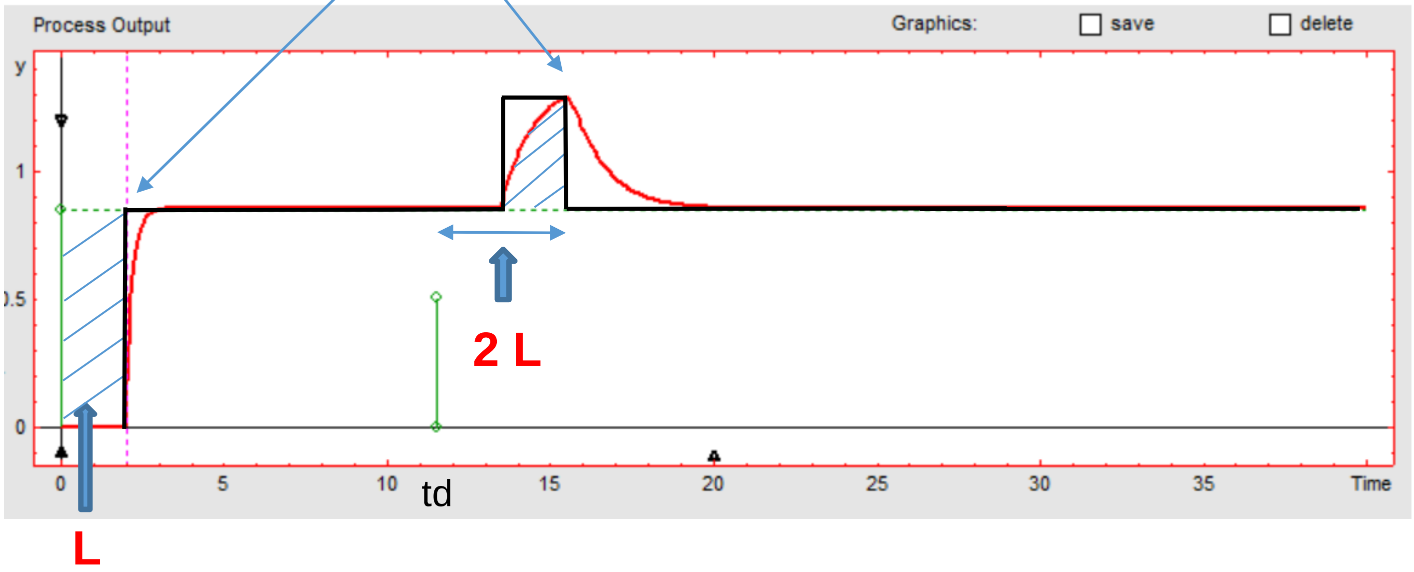
Ideal Control – Achievable Performance

Normal index

$$e(t) = r(t) - y(t)$$

$$J = \int_0^\infty | \, e(t) \, | \, dt$$

No controller can act before



Ideal Control – Achievable Performance

Normal index

$$e(t) = r(t) - y(t)$$

$$J = \int_0^\infty | e(t) | dt$$

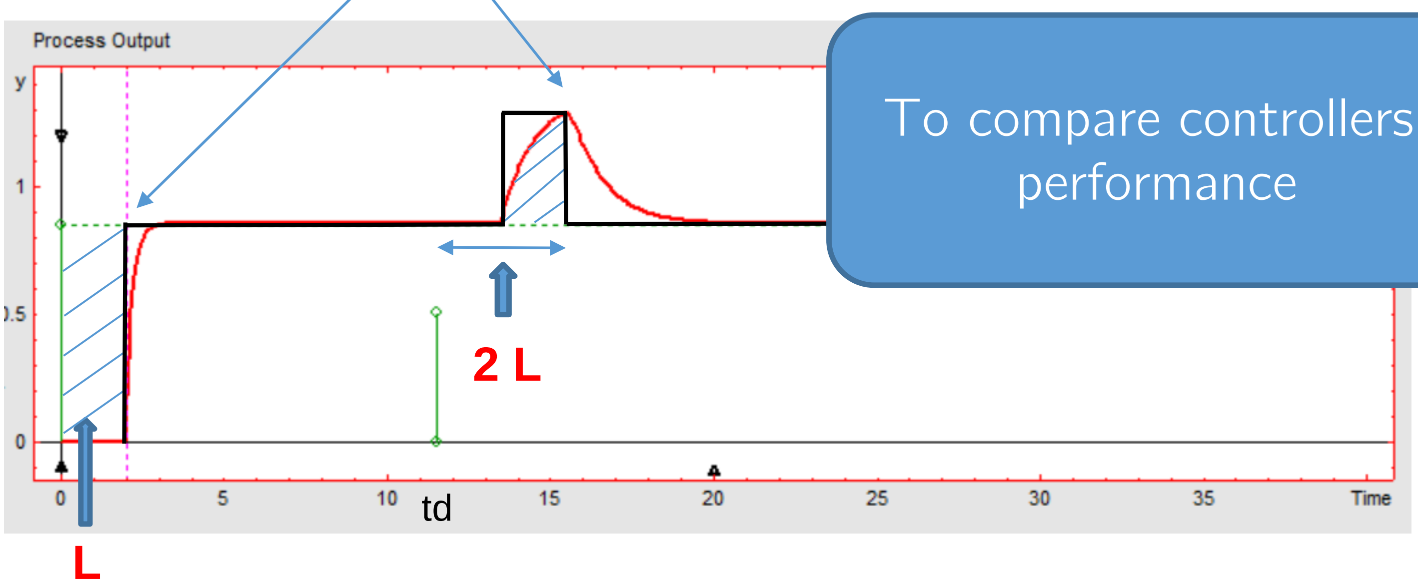
SETPOINT

$$J_{sp} = \int_L^\infty | e(t) | dt$$

DISTURBANCE

$$J_{dr} = \int_{t_d+2L}^\infty | e(t) | dt$$

No controller can act before



To compare controllers' performance

Ideal Control – Achievable Performance

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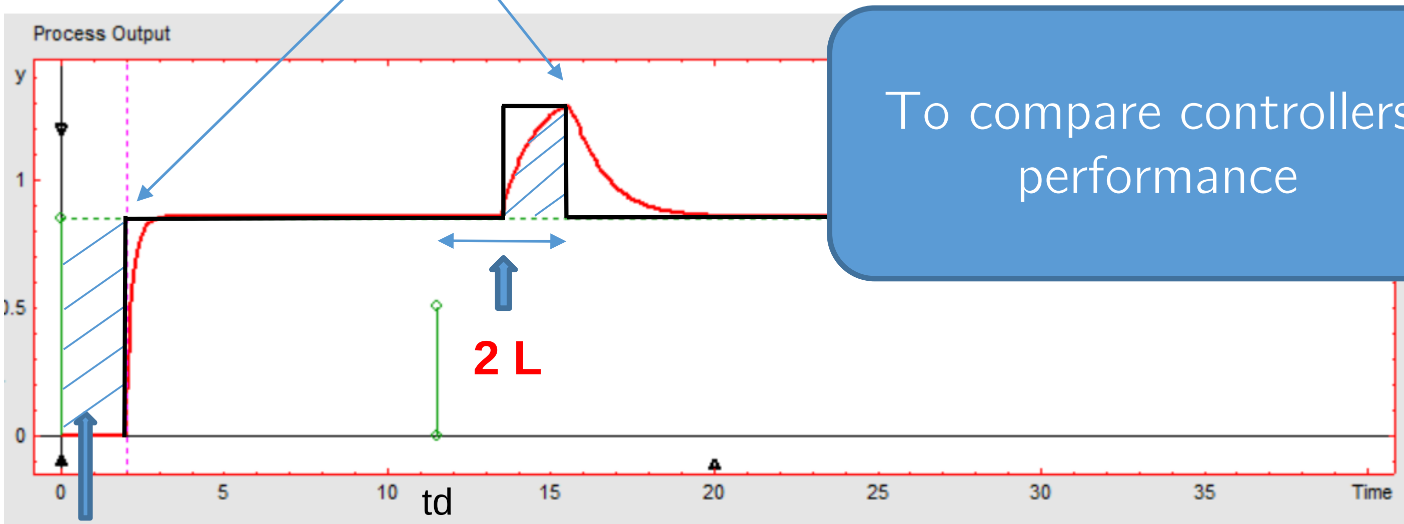

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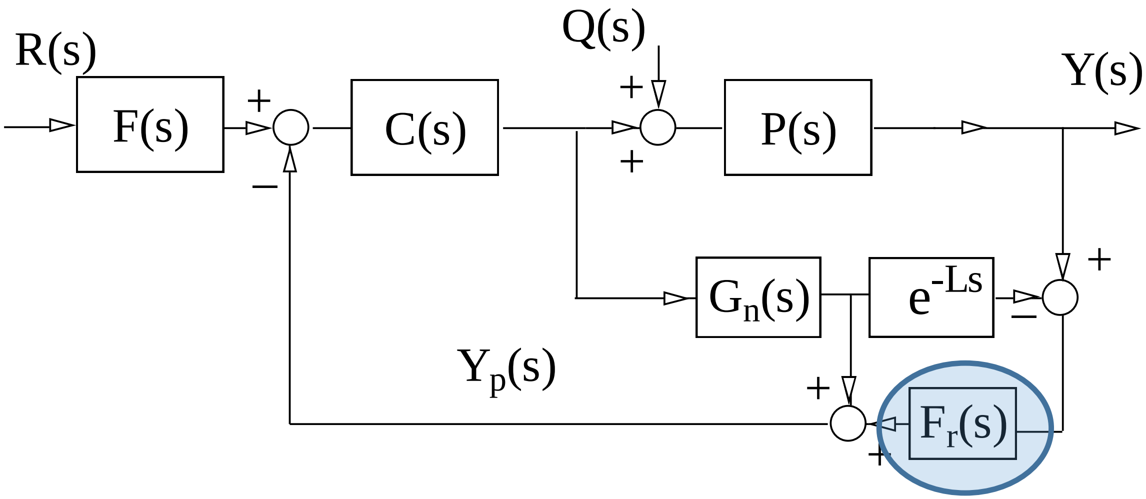
To compare controllers' performance

"Ideal"

$$J_{min} = 0$$

How to achieve ideal response?

Is it ideally possible to achieve $J_{min} = 0$? ⇨ **Filtered Smith Predictor**



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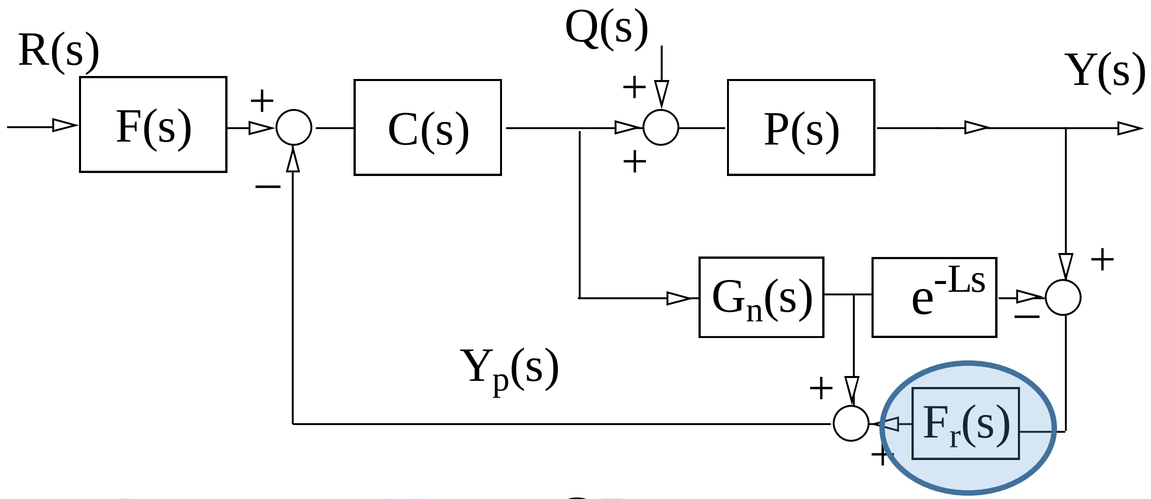

The same *Hyr* **as SP**

$$H_{yr}(s) = \frac{C(s)G_n(s)e^{-Ls}}{1 + C(s)G_n(s)}F(s)$$

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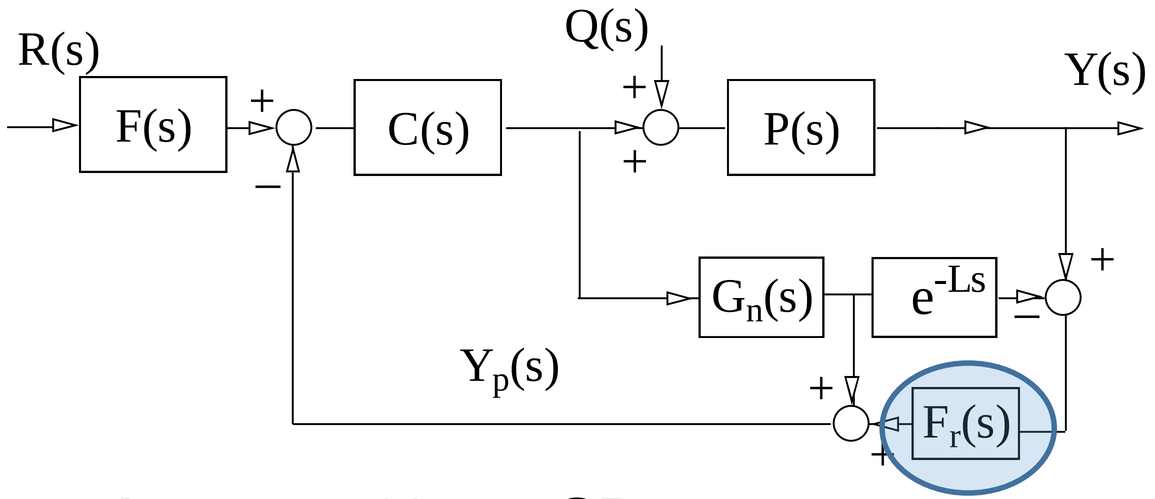
Is it ideally possible to achieve $J_{min} = 0$? ⇨ **Filtered Smith Predictor**



The filter $F_r(s)$ allows:

- Eliminates the open-loop dynamics from the input disturbance response
- FSP for unstable plants
- FSP for ramp and other disturbances
- Robustness-Performance trade-off

The same Hyr **as SP**

$$H_{yr}(s) = \frac{C(s)G_n(s)e^{-Ls}}{1 + C(s)G_n(s)} F(s)$$

$$H_{yq}(s) = P_n(s)\left[1 - H_{yr}(s) F_r(s)\right]$$

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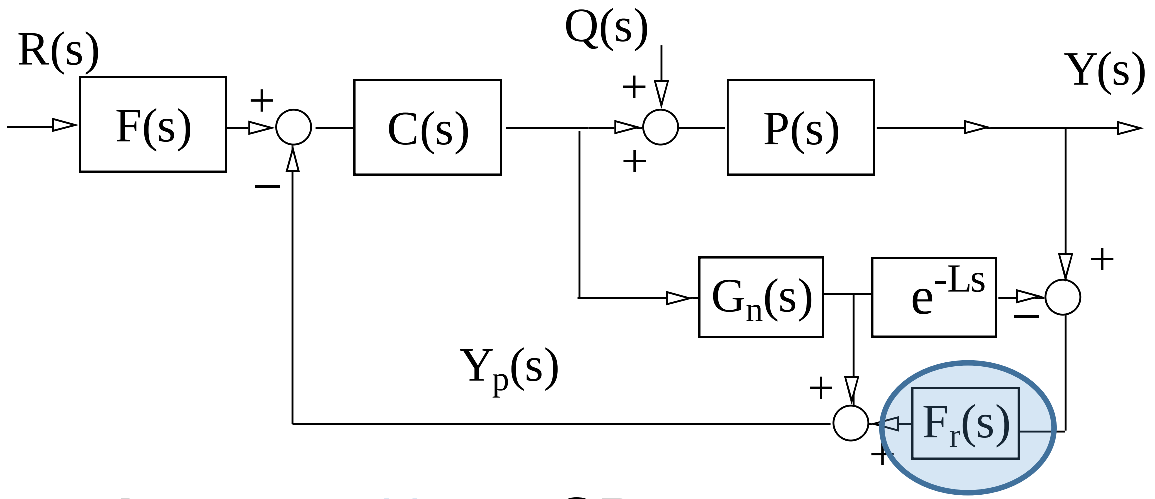

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$$H_{yq}(s) = P_n(s)\left[1 - H_{yr}(s)F_r(s)\right]$$

$$P(s) = \frac{K_e}{1+sT}e^{-Ls}$$

⇨

$$H_{yr}(s) = e^{-Ls}$$

$$H_{yq}(s) = e^{-Ls}\left[1 - e^{-Ls}\right]$$

⇨ J_{min}=0!

Example: Integrative plant

Simple Process $P(s) = \frac{e^{-Ls}}{s}$

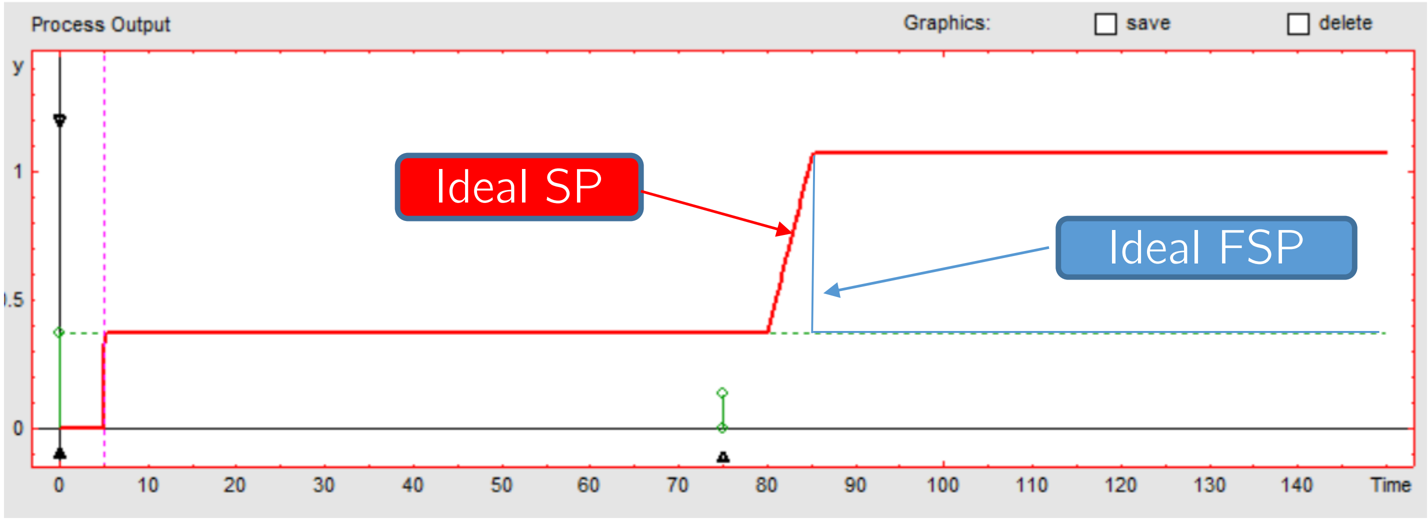
Controller: $C(s) = k_c$

Filter $F_r(s) = 1 + Ls$

Ideal Tuning: $k_c \to \infty$

$$H_{yr}(s) = e^{-Ls}$$

$$H_{yq}(s) = \frac{e^{-Ls}}{s} - \frac{e^{-2Ls}}{s} - Le^{-2Ls}$$



PID design using FSP

Many FSP successful applications in practice:*

Termo-solar systems, Compression systems, Neonatal Care Unit.

FSP autotuning for simple process**

Idea: To derive a PID tuning for dead-time processes using the FSP approach

PID is a low frequency approximation of the FSP.

$$C(s) = \frac{K_c(1+sT_i)(1+sT_d)}{sT_i(1+s\alpha T_d)}$$

*Torrico, Cavalcante, Braga, Normey-Rico, Albuquerque, I&EC Res. 2013.
**Normey-Rico, Sartori, Veronesi,Visioli. Control Eng. Practice, 2014
*Flesch, Normey-Rico, Control Eng. Practice, 2017
* Roca, Guzman, Normey-Rico, Berenguel, Yebra, Solar Energy, 2011

PID tuning using FSP

Tuning procedure

- **Process models: FOPDT, IPDT, UFOPDT**

$$G_n(s) = \frac{K_p}{1+sT} \qquad G_n(s) = \frac{K_p}{s} \qquad G_n(s) = \frac{K_p}{sT-1}$$

- **PI primary controller (only P for the IPDT)** $C(s) = K\frac{1+s\tau_i}{s\tau_i}$

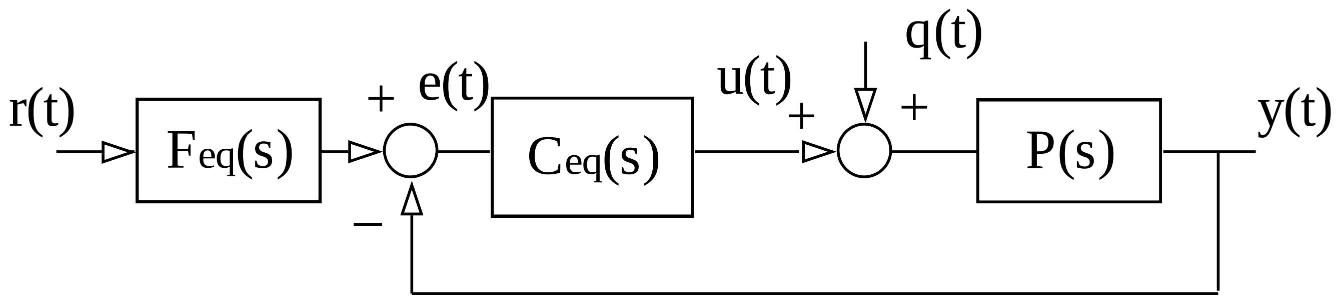
- **FO predictor filter** $F_r(s) = \frac{1+sT_1}{1+sT_2}$ **(tuning for step disturbances)**

- **Tuning for a delay-free-closed-loop system with pole (double pole) in** ***$s=-1/T_0$***

- ***T_0*** **is the only tuning parameter for a trade-off robustness-performance**

Tuning procedure

Equivalent 2DOF controller



$$C_{eq}(s) = \frac{C(s)F_r(s)}{1 + C(s)G_n(s)(1 - e^{-L_n s}F_r(s))}, \quad F_{eq}(s) = \frac{F(s)}{F_r(s)},$$

$$e^{-L_n s} \rightarrow \frac{1-0.5L_n s}{1+0.5L_n s}$$

2DOF PID

- C_{eq} avoids pole-zero cancellation
- T_o free tuning parameter

Tuning procedure

Tuning advantages of the predictor-PID

- Unified approach for FOPDT, IPDT and UFOPDT (L<2T)
- It has only one tuning parameter T_0*
- Has similar performance than well known methods*
- It is a low frequency approximation of the ideal solution for first order dead-time models

Interesting PID tuning method to use in comparisons with dead-time compensators and predictive controllers

Next: To compare PID and FSP

* Normey-Rico and Guzmán. Ind. & Eng. Chem. Res., 2013

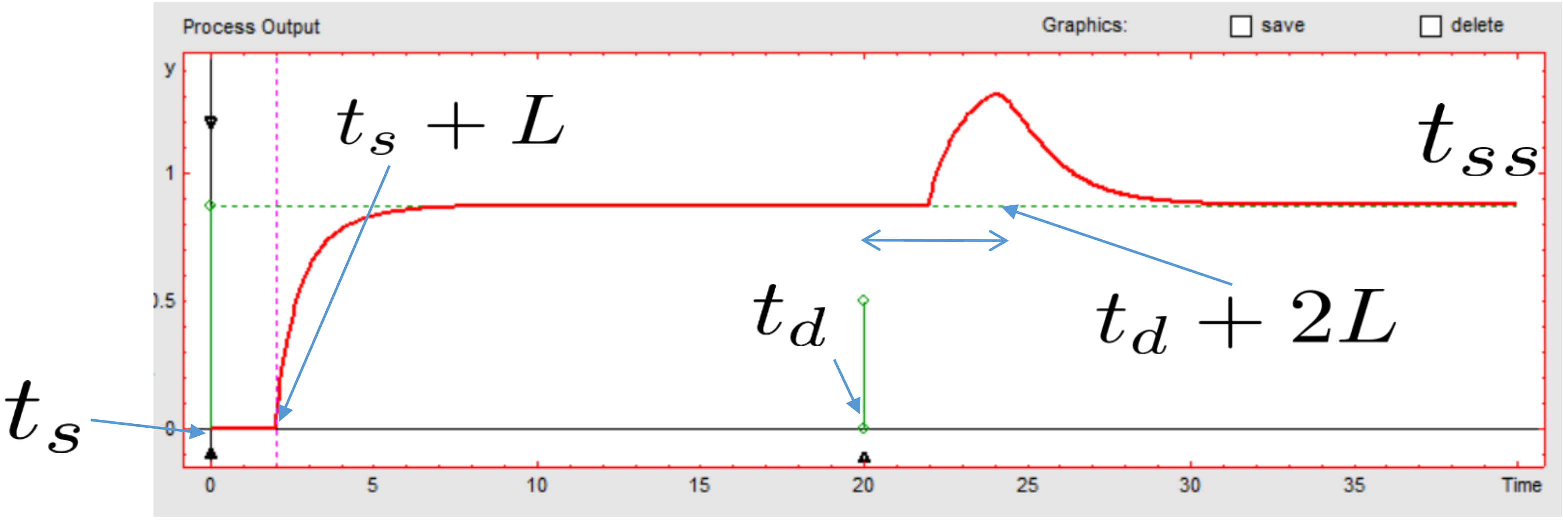
* Astrom and Hagglund, Research Triangle Park, 2006

FSP-PID comparative analysis

Performance Index

$$J = \lambda \int_{t=t_s+L}^{t_d} \mid r(t) - y(t) \mid + (1-\lambda) \int_{t=t_d+2L}^{t_{ss}} \mid r(t) - y(t) \mid$$

$\lambda \in [0,1]$ $\qquad$ $\lambda = 0.5$ in this work

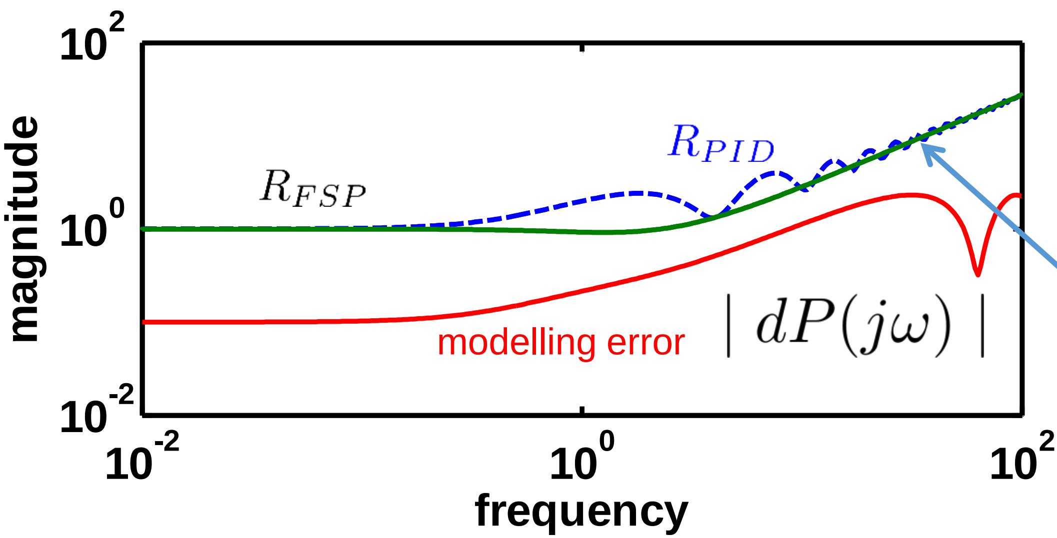


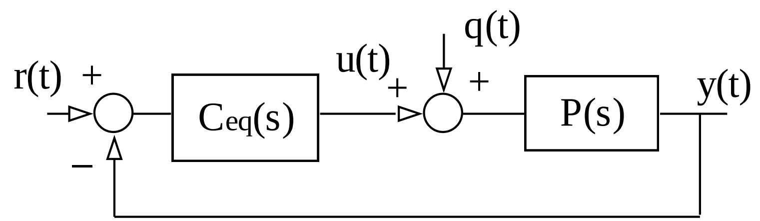
FSP-PID comparative analysis

Robustness

$$P(j\omega) = P_n(j\omega)[1 + dP(j\omega)]$$

$$C_{eq}(s) \text{ stabilizes } P_n(s)$$





$$R(\omega) := \frac{|1+C_{eq}(j\omega)P_n(j\omega)|}{|C_{eq}(j\omega)P_n(j\omega)|}$$

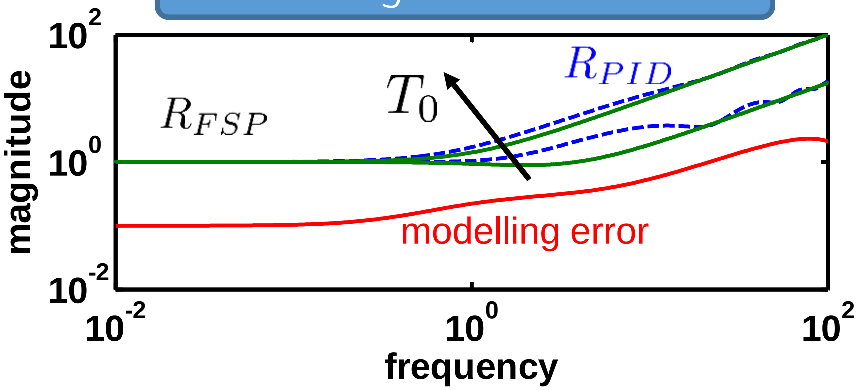
$$\text{Robust condition } R(\omega) > \overline{dP}(\omega) \geq | dP(j\omega) | \quad \forall \omega > 0$$

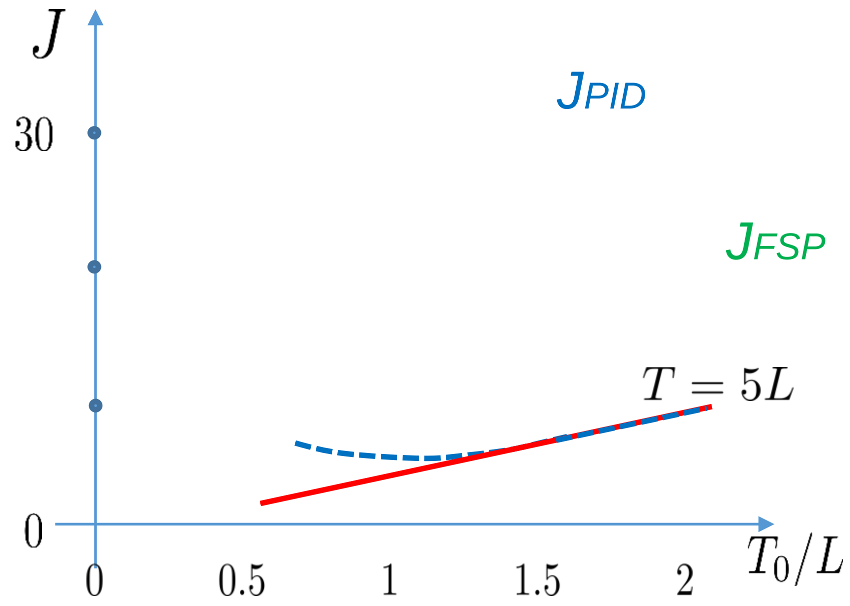
Conservatism can be avoided separating dead-time uncertainties*

*Larsson and Hagglund (2009), ECC 2008

FSP-PID comparative analysis

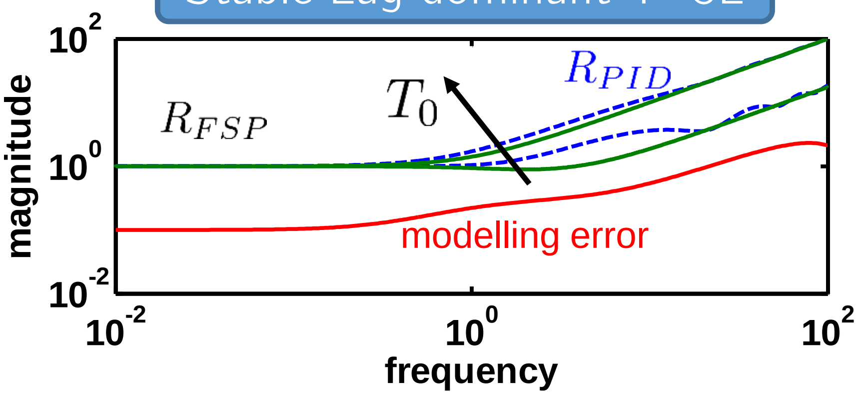
Stable Lag dominant T=5L



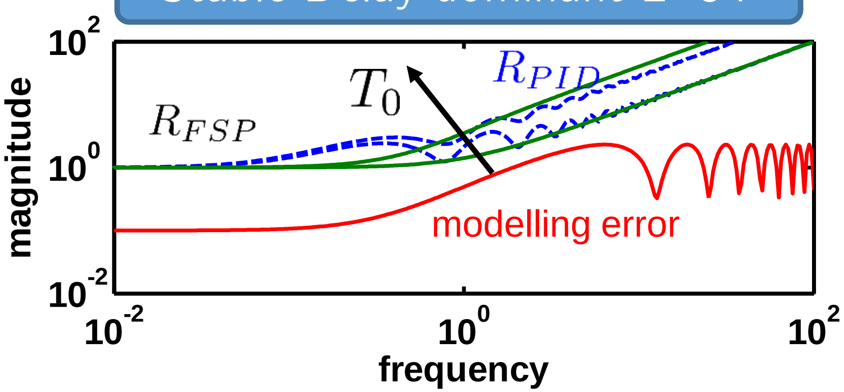


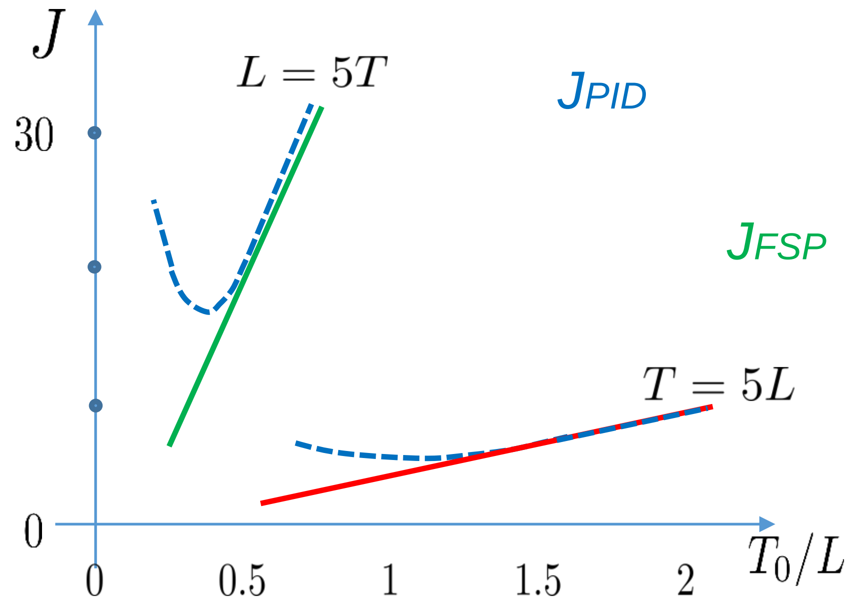
FSP-PID comparative analysis

Stable Lag dominant T=5L

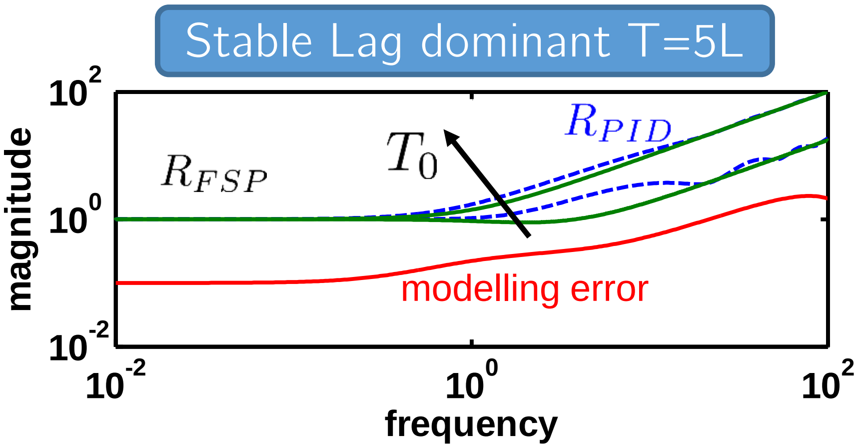


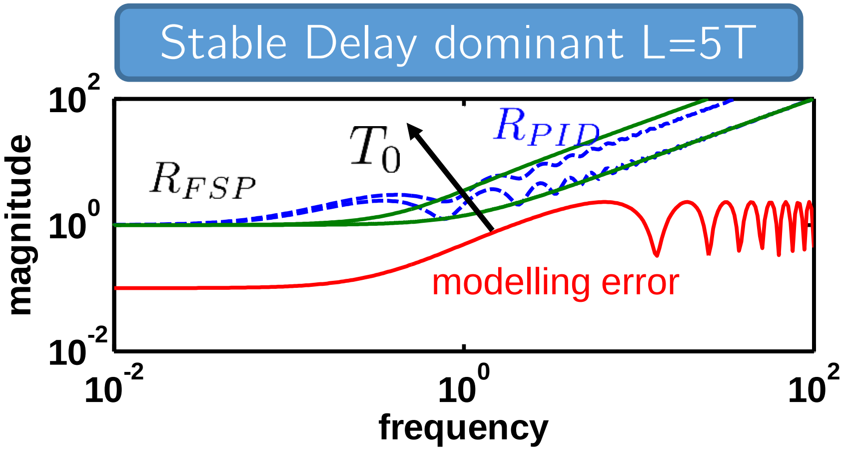
Stable Delay dominant L=5T

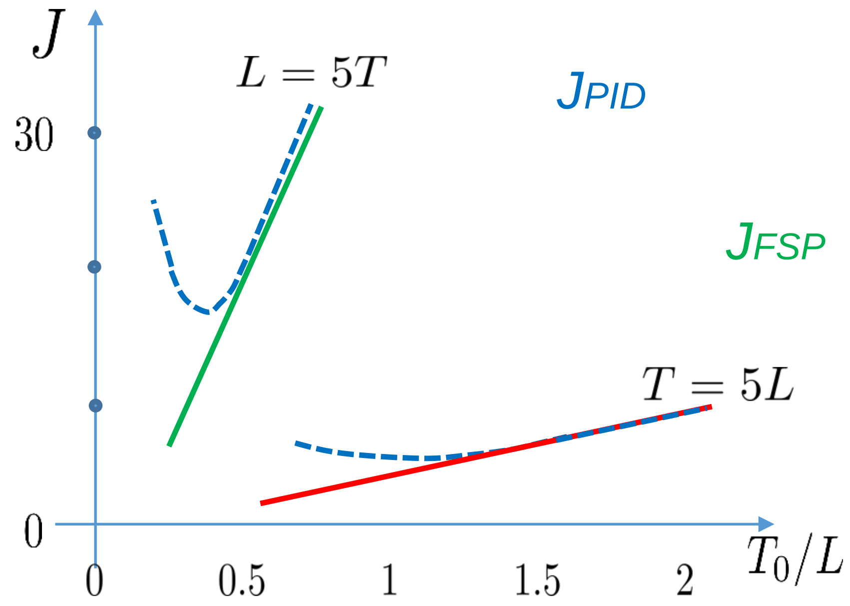




FSP-PID comparative analysis



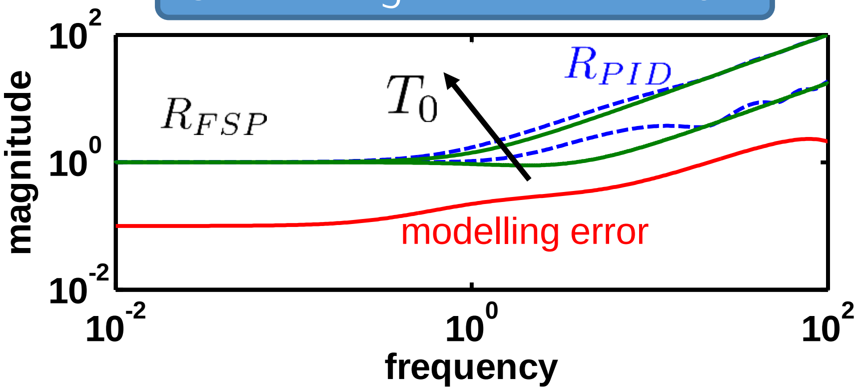




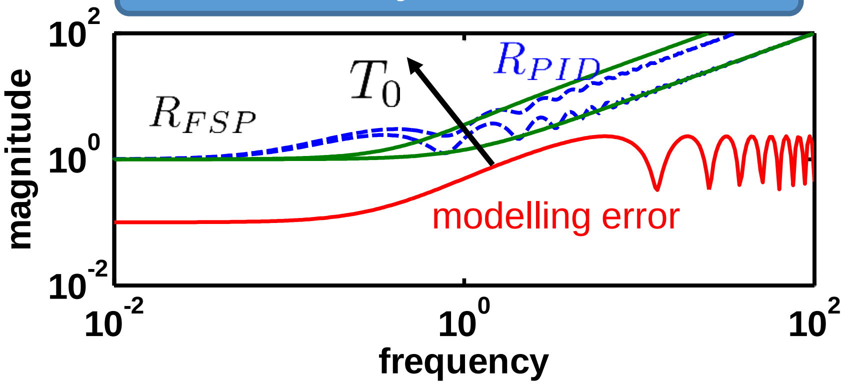
- Robust tuning $J_{FSP} \approx J_{PID}$
- Fast tuning $J_{FSP} < J_{PID}$

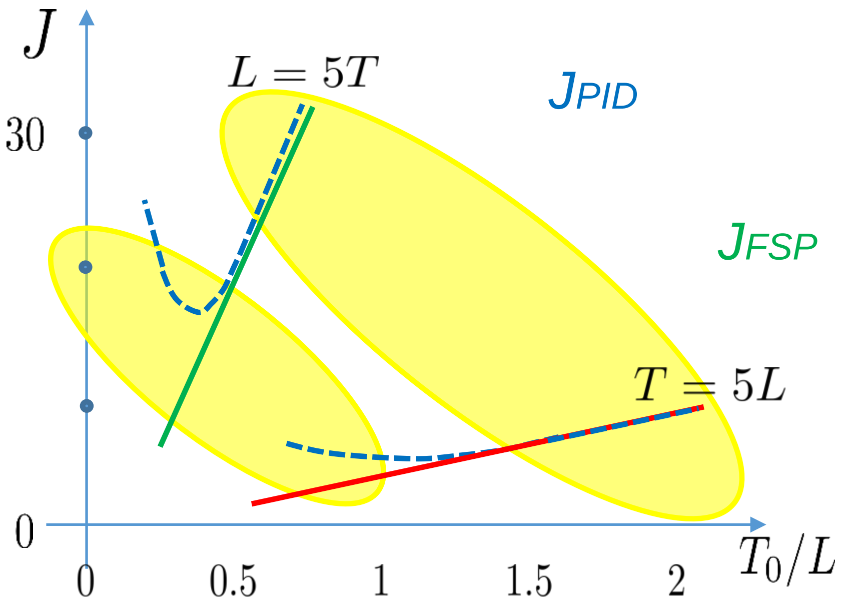
FSP-PID comparative analysis

Stable Lag dominant T=5L



Stable Delay dominant L=5T





- Robust tuning $J_{FSP} \approx J_{PID}$
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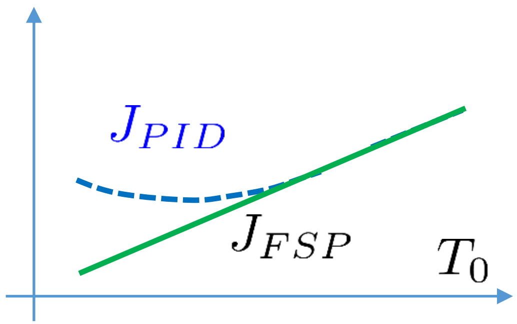
PID for robust solutions
FSP has advantages with good models

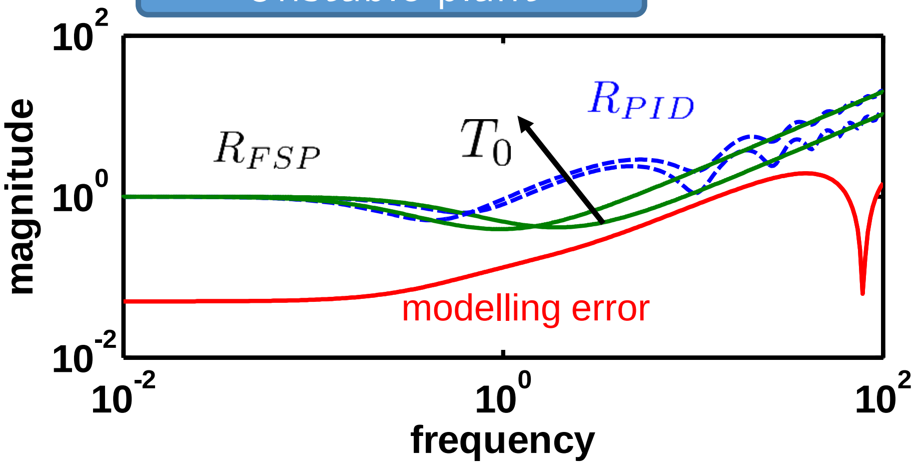
FSP-PID comparative analysis

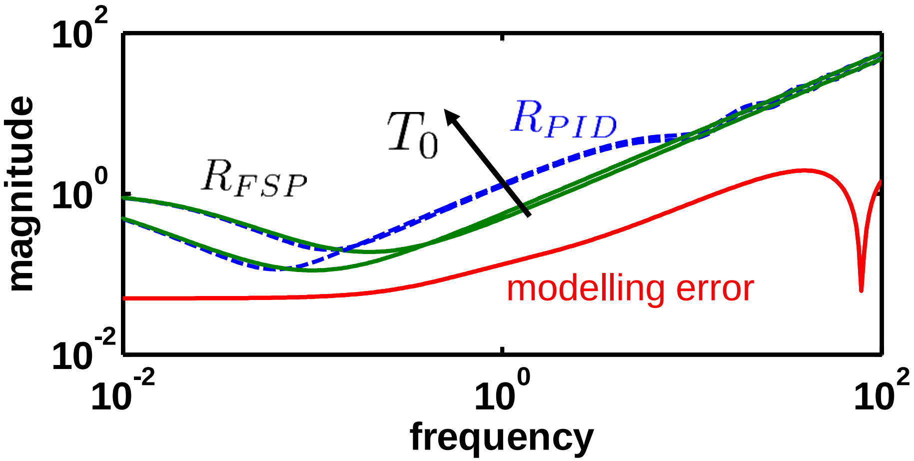
Integrative plant

- Similar to Lag-dominant plants



Unstable plant





- Same conclusions as in FOPDT
- UFOPDT Robustness has a limit increasing T_0 *

* Normey-Rico and Camacho, 2007, Springer

FSP-PID comparative analysis

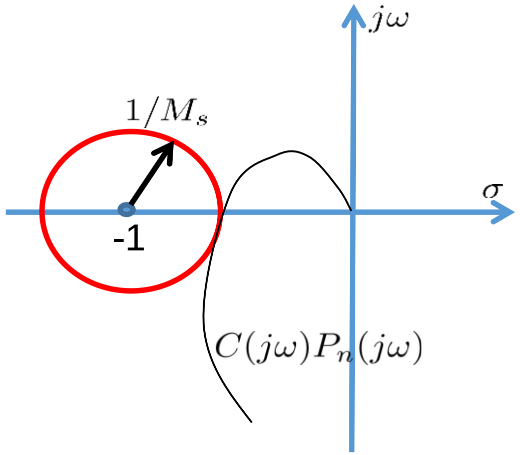
Tuning: Trade-off Robustness-Performance

- **Minimise *J* for robust stability for a given modelling error**

Particular tuning using: $R(\omega) > \overline{dP}(\omega) \;\; \forall\omega > 0$

- **Minimise *J* for robust stability for a given** $R_m = \min_\omega R(\omega)$

General tuning using R_m (or M_S)



* Grimholt and Skogestad 2012, IFAC PID 2012.

FSP-PID comparative analysis

Tuning: Trade-off Robustness-Performance

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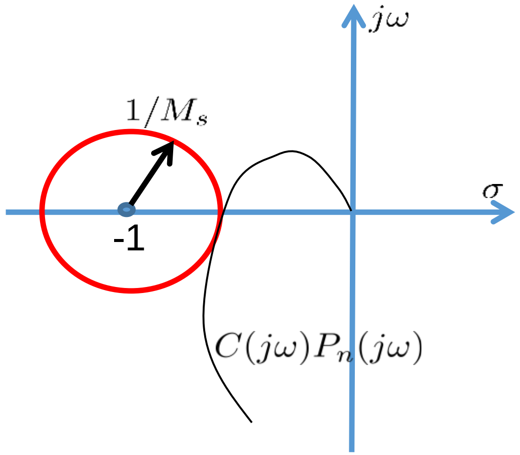
- Minimise *J* for robust stability for a given $R_m = \min_\omega R(\omega)$

General tuning using R_m (or M_S)

Control effort (total variation) and noise attenuation are directly related to robustness indexes as *Rm (or Ms)**



* Grimholt and Skogestad 2012, IFAC PID 2012.

FSP-PID comparative analysis

Conclusions

- **Case 1: poor model information (large modelling error)**
  - **Simple model is used for tuning**
  - **High robustness is mandatory**
  - **Step disturbances**

PID will be the best solution, even for dead-time dominant systems

- **Case 2: good model is available (small modelling error)**
  - **Fast responses are required**
  - **Low robustness is enough**
  - **Complex models or disturbances**

FSP will be better (even for lag-dominant systems) because of the PID nominal limitations

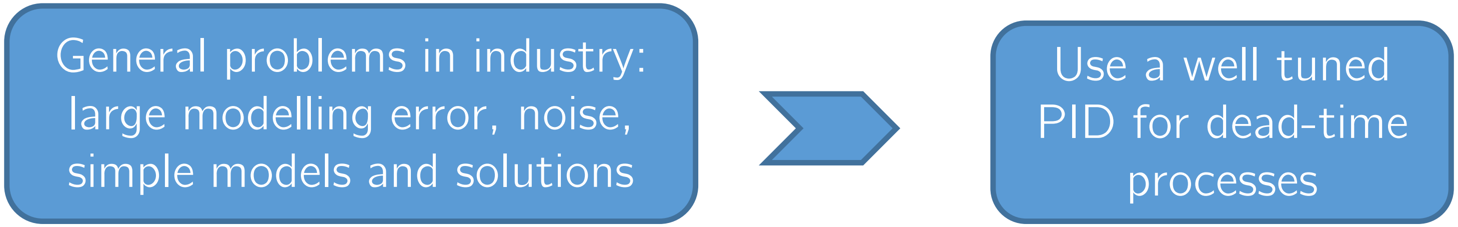
FSP-PID comparative analysis

Conclusions

Concerning dead-time: dead-time value is less important than dead-time modelling error.

Implementation issues:

- FSP is implemented as a 2DOF discrete controller
- FSP is a complex algorithm (delay order (in samples) + model order)
- PID is simple to implement



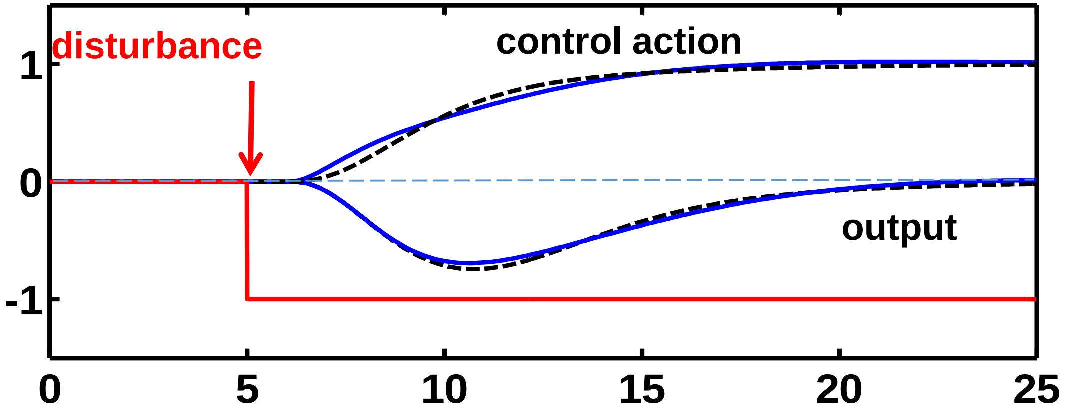
Example 1: High-order system

$$P(s) = \frac{e^{-s}}{(s+1)^3}$$

$$P_n(s) = \frac{e^{-2s}}{(2s+1)}$$

Prediction Model for FSP

Robust tuning for *Ms=1.2*



PID tuning using SWORD * tool

FSP and PID have the same performance

**Garpinger, O. and T. Hägglund (2015), Journal of Process Control.

** SWORD Matlab software tool.

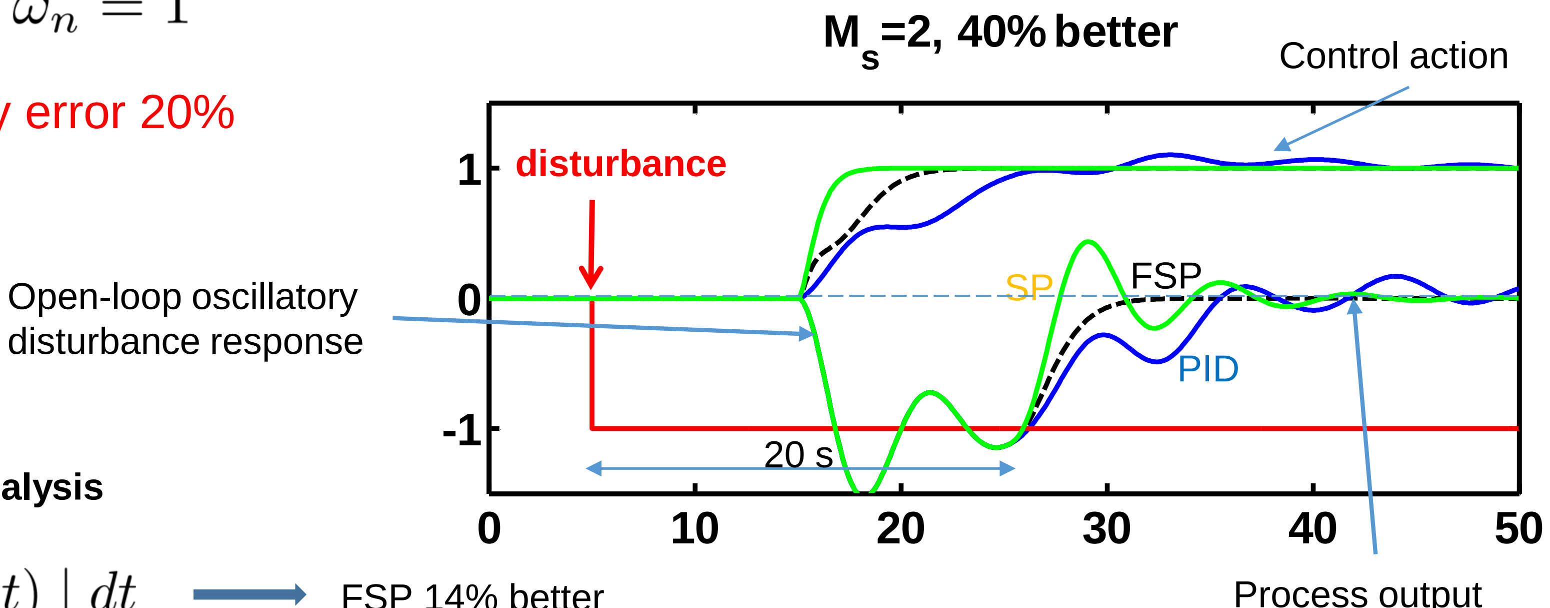
Example 2: PID, SP and FSP

$$P(s) = \frac{e^{-10s}}{1 + \frac{2\xi s}{\omega_n} + \frac{s^2}{\omega_n^2}}$$

$$\xi = 0.2, \; \omega_n = 1$$

Max. delay error 20%

- SP and FSP with the same primary PID controller
- PID tuning for min IAE for *Ms*=2 (using sword tool)



Performance Analysis

$J = \int_0^\infty \mid e(t) \mid dt$ → FSP 14% better

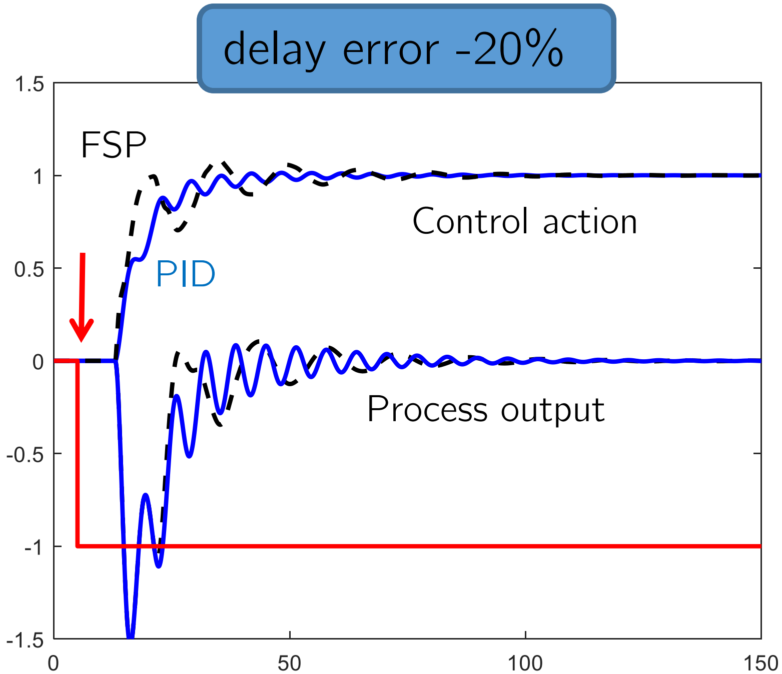
$J_{dr} = \int_{t_d+2L}^\infty \mid e(t) \mid dt$ → FSP 40% better

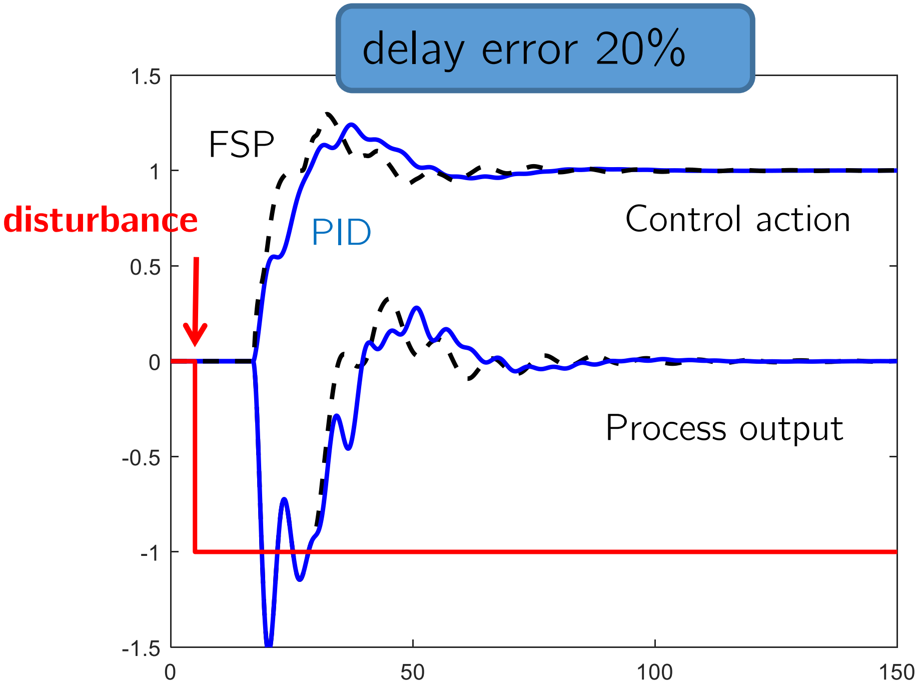
Robustness : FSP stable up to -35% or +35% delay error, SP unstable for 20% delay error

Example 2: PID, SP and FSP

$$P(s) = \frac{e^{-10s}}{1+\frac{2\xi s}{\omega_n}+\frac{s^2}{\omega_n^2}}$$

$$\xi = 0.2,\ \omega_n = 1$$





- SP unstable for this case
- PID and FSP similar responses

FSP and PID with plant constraints

- In real process control action is limited, as well as slew rate
- Also, process output should be between limits
- Anti-windup (AW) can be used to mitigate the effect of the saturation in the integral action in PID and FSP
- MPC appears as a direct solution to implement optimal control under system constraints

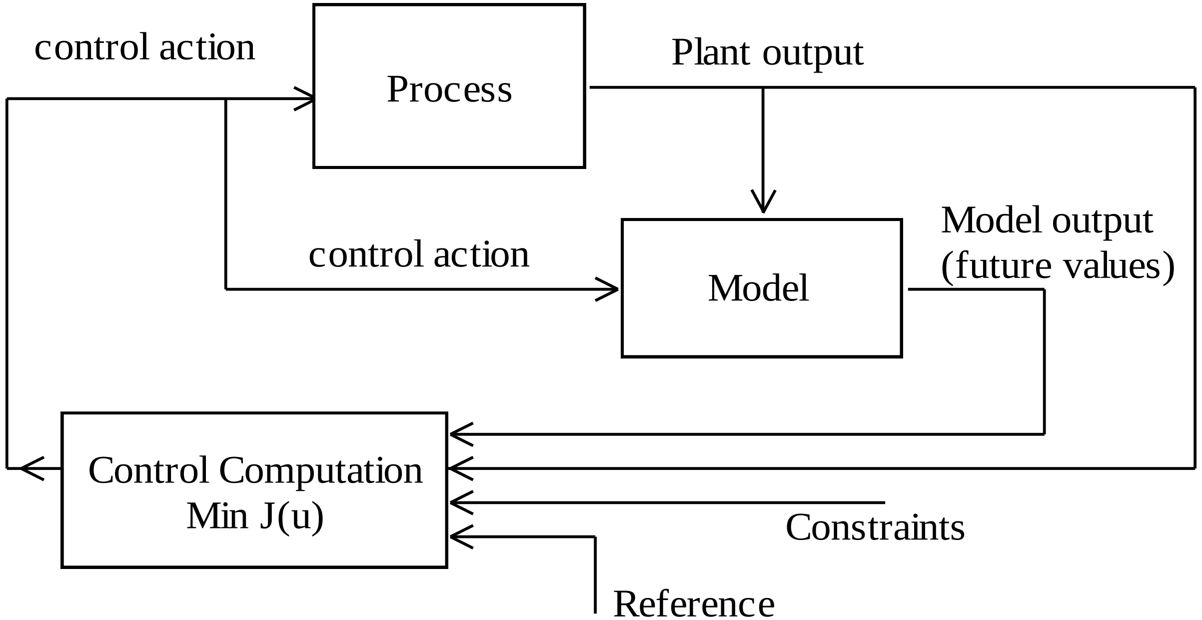
When is MPC a better choice?

MPC, FSP and PID

GPC – Generalized predictive controller

GPC analysis for Dead-time Processes

General MPC idea



GPC analysis for Dead-time Processes

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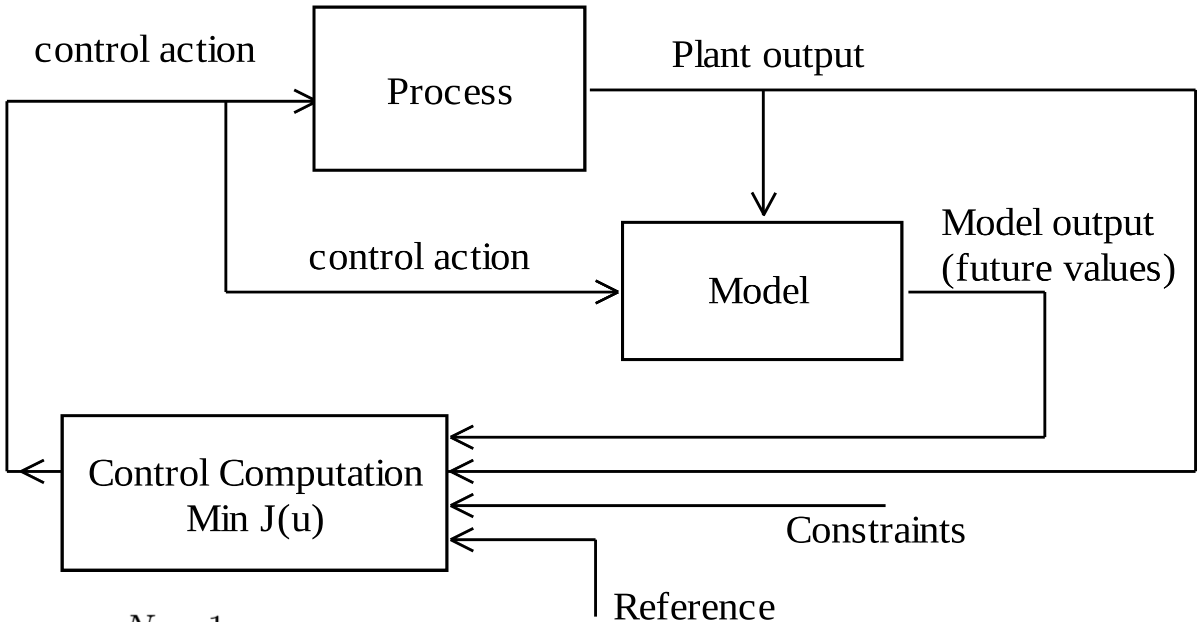

GPC cost

$$J = \sum_{j=d+1}^{d+N_y} [y(k+j|k) - w(k+j)]^2 + \sum_{j=0}^{N_u-1} \lambda[\triangle u(k+j)]^2,$$

GPC Model

$$A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k-1) + \frac{e(t)}{\triangle} \qquad L = dT_s$$

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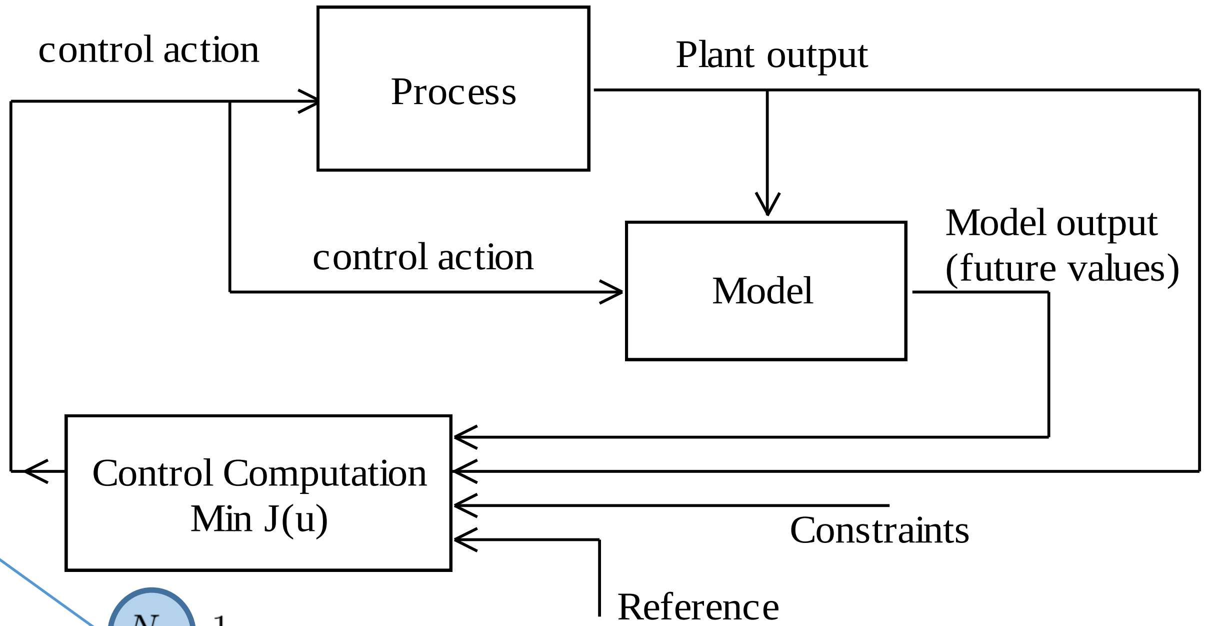

TUNNING

GPC cost

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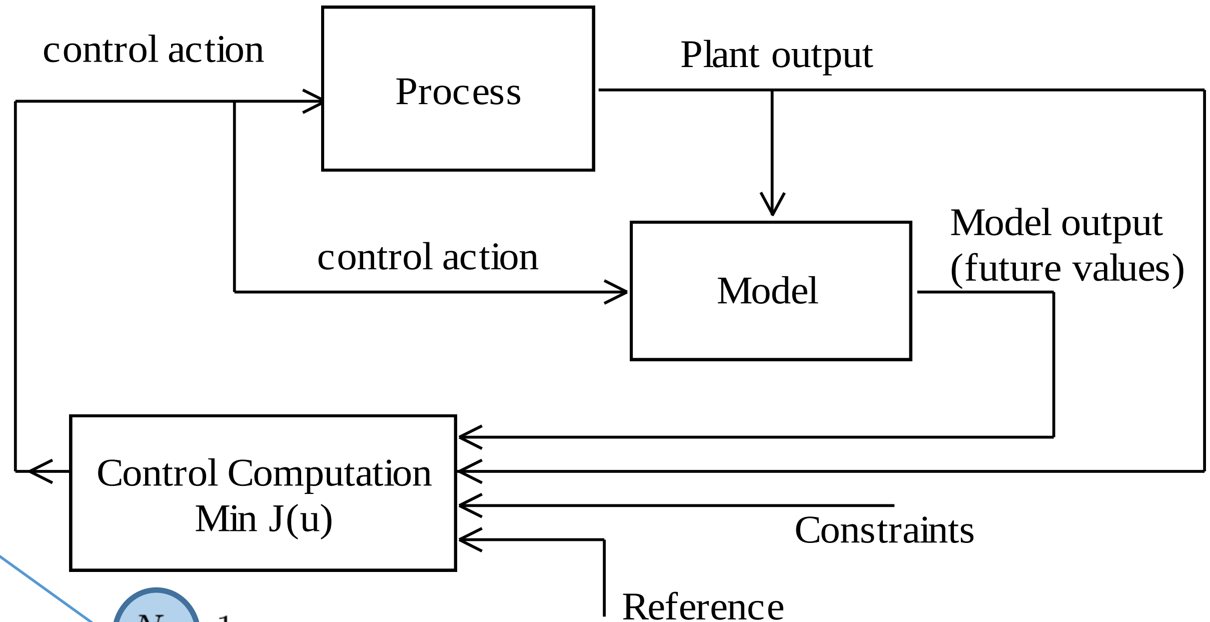

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$$y(k+d+j/k) = f(u_{fut}, y_{past}, u_{past})$$

GPC analysis for Dead-time Processes

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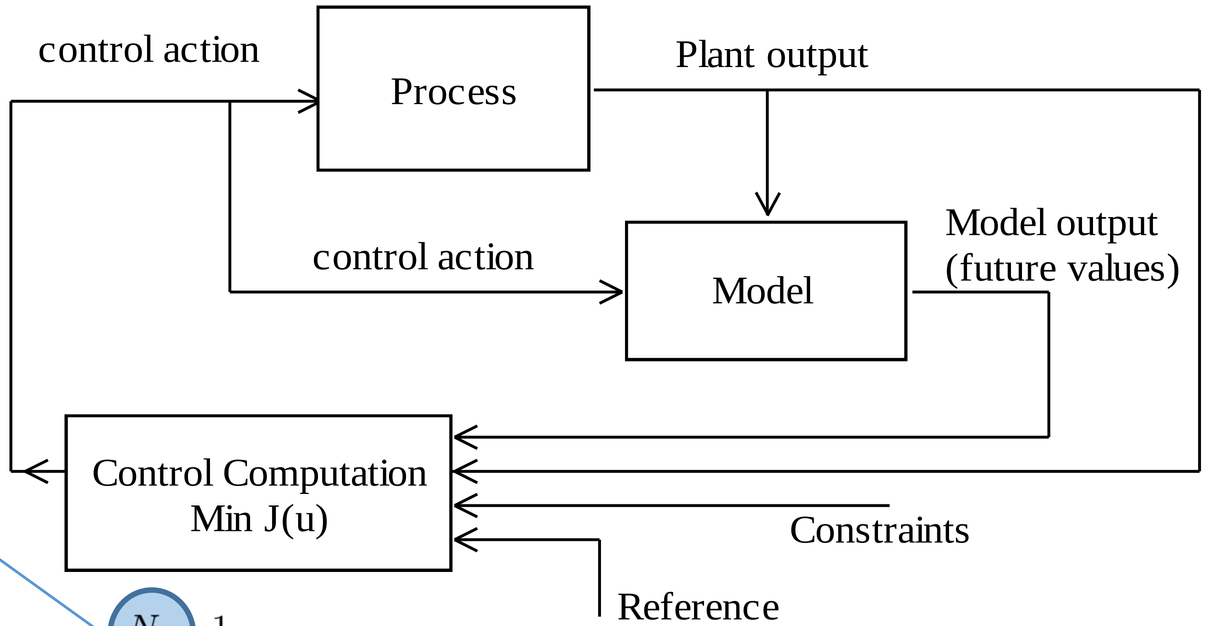

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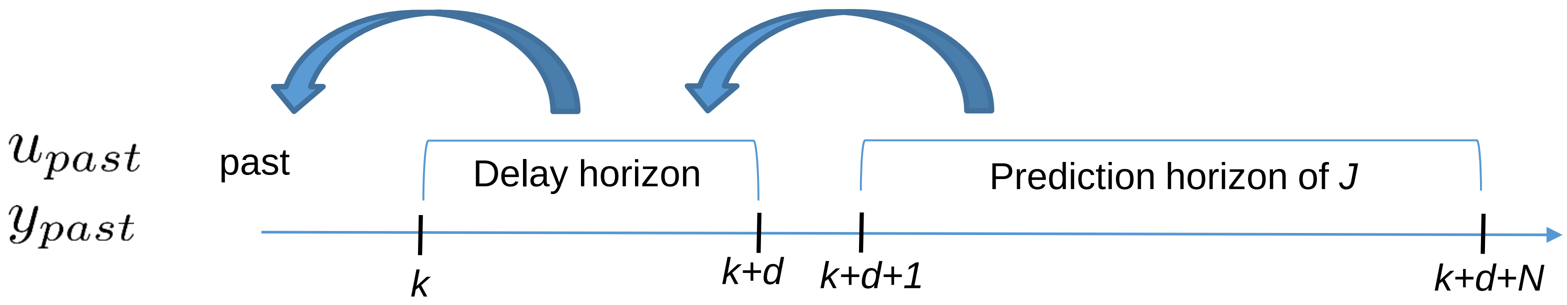
$$J = J(u_{fut})$$

GPC analysis for Dead-time Processes

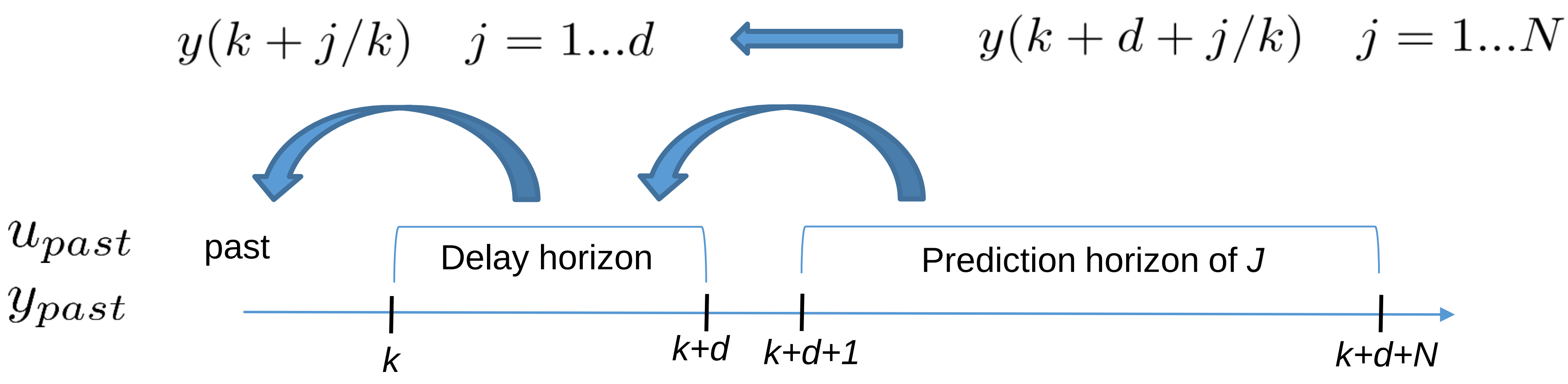
Prediction computation

$y(k+j/k) \quad j=1...d$ ← $y(k+d+j/k) \quad j=1...N$



GPC analysis for Dead-time Processes

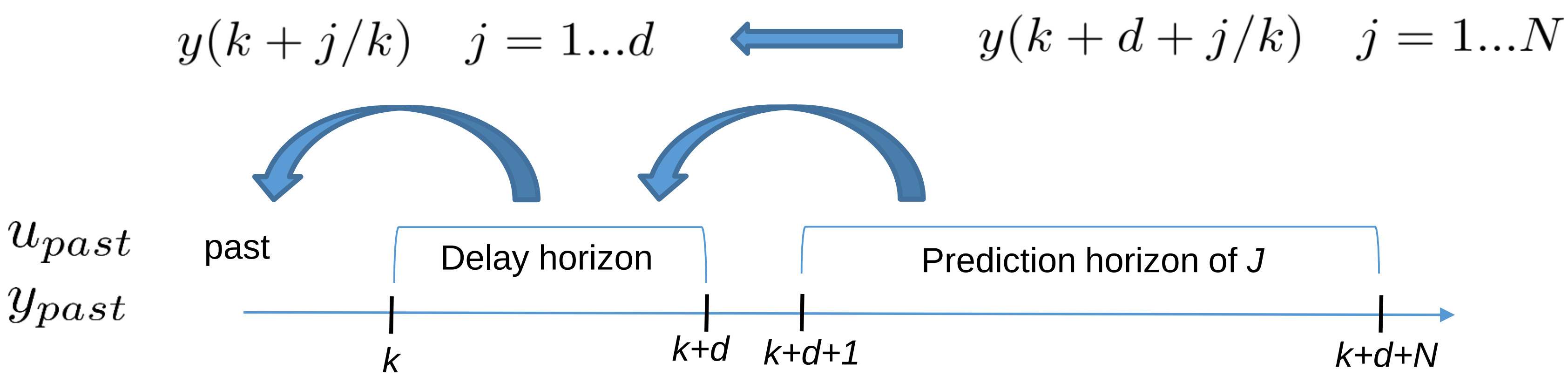
Prediction computation



GPC structure ?

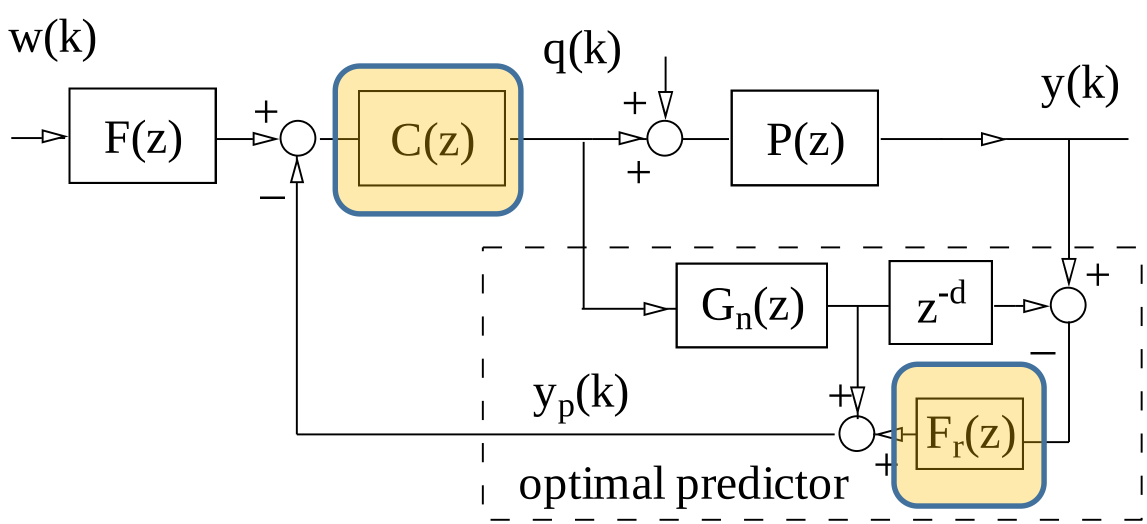
GPC analysis for Dead-time Processes

Prediction computation



GPC structure ?

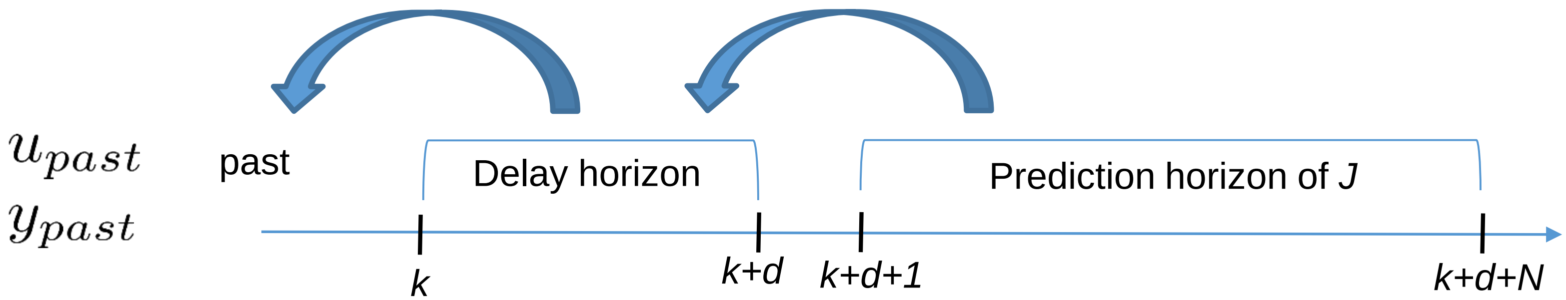
(unconstrained)



GPC analysis for Dead-time Processes

Prediction computation

$y(k+j/k) \quad j = 1...d$ ⟵ $y(k+d+j/k) \quad j = 1...N$



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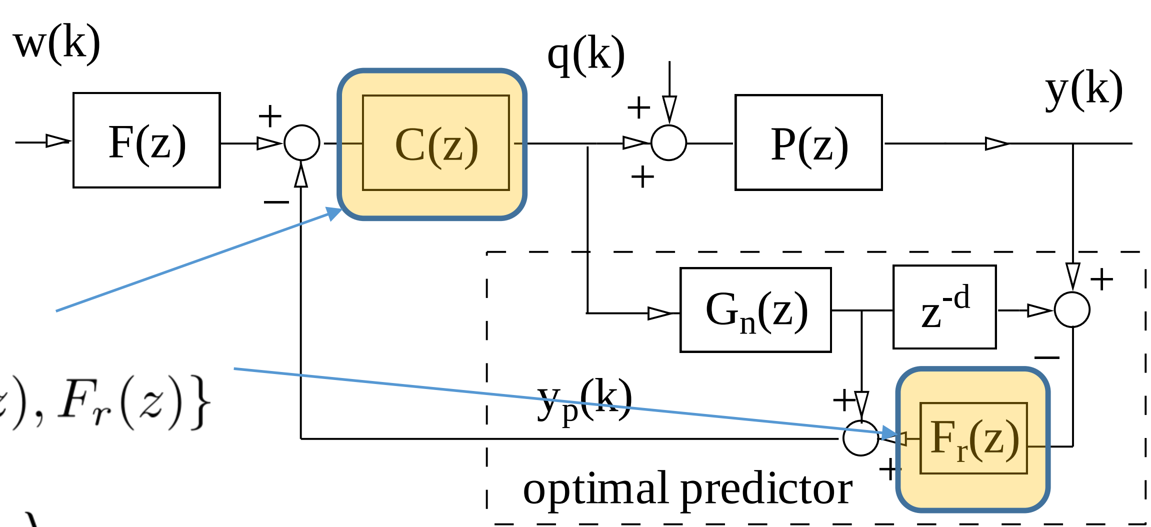


$C(z)$ integral action

order$\{G_n(z)\} \rightarrow$ order $\{C(z), F_r(z)\}$

coeficients related to N, N_u, λ

GPC analysis for Dead-time Processes

Unconstrained GPC structure

- GPC is equivalent to a discrete FSP
- FSP can be tuned using GPC method (exactly the same solution)
- FSP-MPC can be used (for robust controllers and easy tuning)*
- For 1^{st} order models → GPC ⇨ 2DOF FSP (PI primary controller)

Comparison FSP-PID is valid for GPC-PID for 1^{st} order models

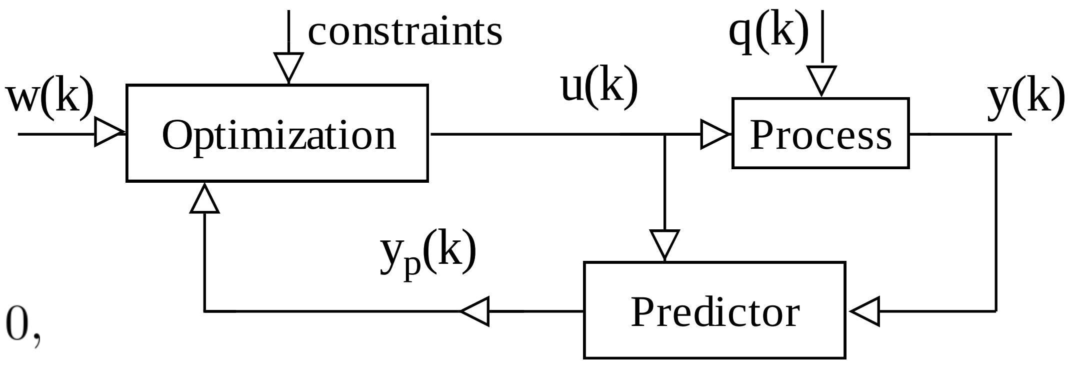
Is valid for other linear MPC (simply a model rearrangement)

Constrained case?

* Normey-Rico and Camacho, 2007, Springer
* Lima, Santos and Normey-Rico, 2015, ISA Transactions

GPC for dead-time processes

Constrained GPC



$$\underline{U} \leq u(k) \leq \overline{U} \quad \forall k \geq 0,$$
$$\underline{u} \leq u(k) - u(k-1) \leq \overline{u} \quad \forall t \geq 0,$$
$$\underline{y} \leq y(k) \leq \overline{y} \quad \forall k \geq 0.$$

$$\mathbf{u} = [\Delta u(k) \ldots \Delta u(k + N_u - 1)]$$

GPC for dead-time processes

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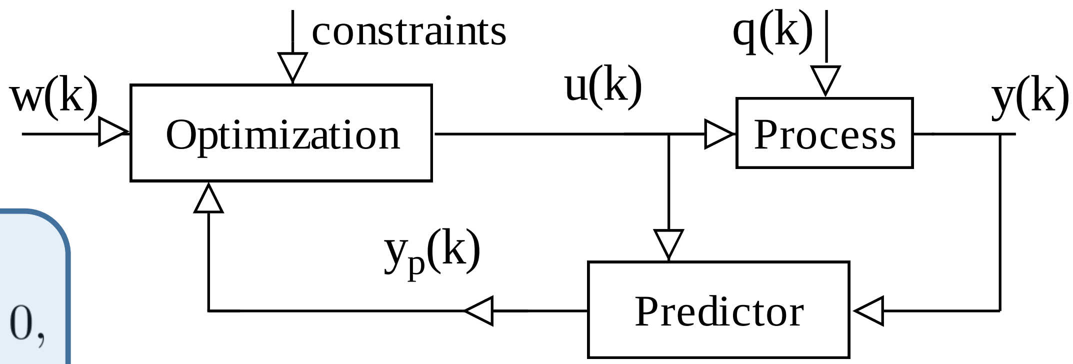

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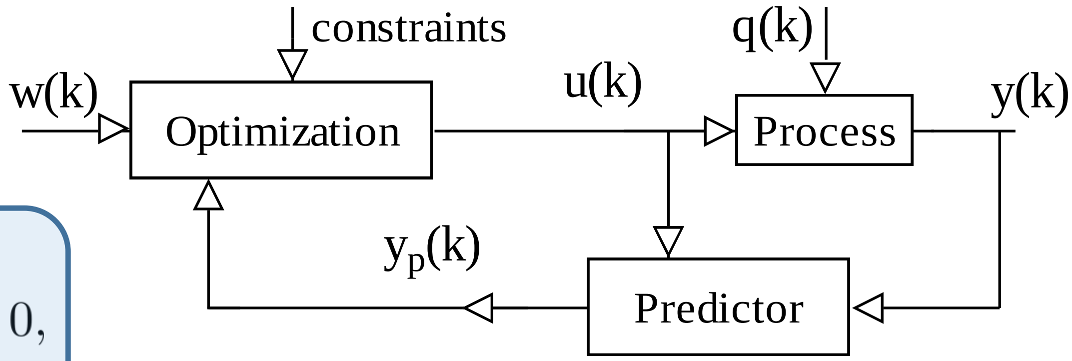

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$$\min_{\mathbf{u}} \quad \frac{1}{2}\mathbf{u}^T \mathbf{H} \mathbf{u} + \mathbf{b}^T \mathbf{u} + f_0,$$
$$\text{s. t.} \quad \mathbf{R}\mathbf{u} \leq \mathbf{r}$$

All constraints are written as a linear inequality on u

GPC for dead-time processes

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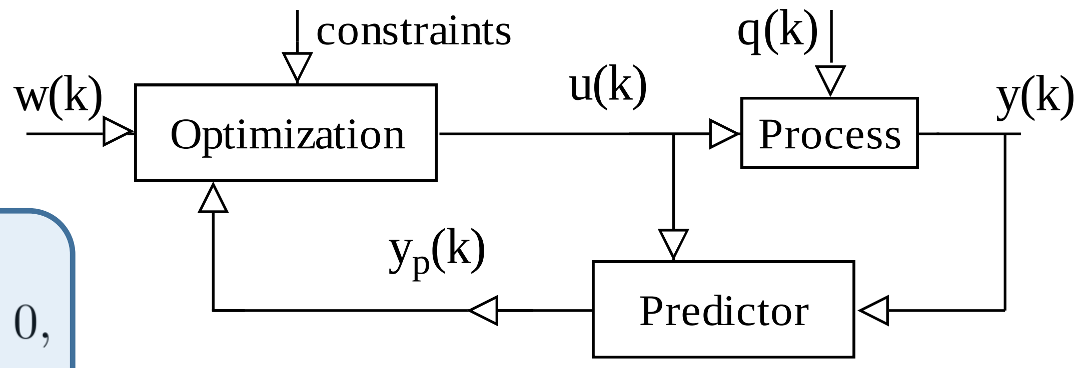

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- **QP solved at each sample time**
- **Only *u(k)* is applied**
- **The horizon window is displaced**

GPC for dead-time processes

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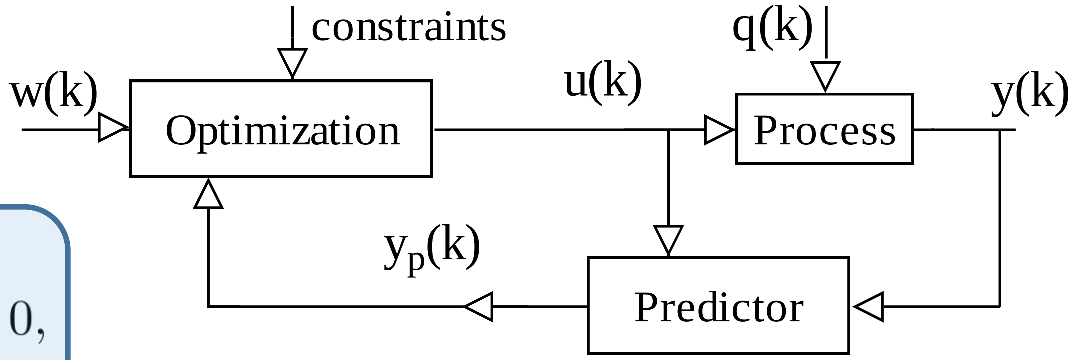

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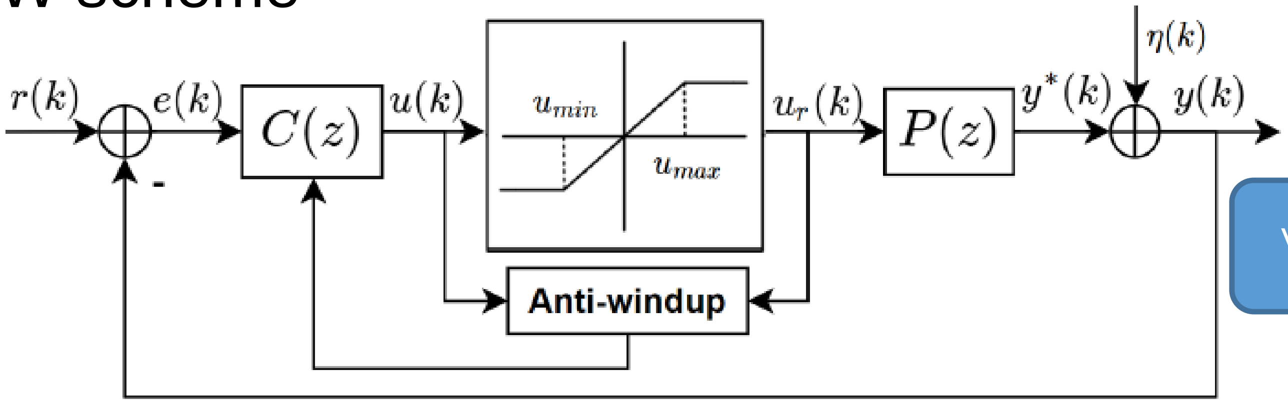
GPC gives goods results with small N_u (in many applications $N_u=1$ is enough*)

* De Keyser and Ionescu, IEEE CCA 2003

AW for FSP and PID

AW scheme



Valid for PID and FSP

$u_i(k)$ has the integral action of PID or FSP

$$u(k) = u_i(k) + u_d(k)$$

$u_d(k)$ has the rest of the control action of PID or FSP

AW originally derived for control action constraints

Several AW strategies in literature

AWP with error recalculation (ER)

Recalculation of the error signal at every sample

Objective: to maintain the consistence between $u(k)$ (computed) and $u_r(k)$ (applied)

* Flesch and Normey-Rico, Control Eng. Practice, 2017

*Silva, Flesch and Normey-Rico, IFAC PID 18

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PID case

$$u(k) = u(k-1) + n_0 e(k) + n_1 e(k-1) + n_2 e(k-2)$$

$$u(k) > u_{max} \rightarrow u_r(k) = u_{max}$$

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Consider:

$$u_r(k) = u(k-1) + n_0 e^*(k) + n_1 e(k-1) + n_2 e(k-2)$$

?

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Consider: $u_r(k) = u(k-1) + n_0 e^*(k) + n_1 e(k-1) + n_2 e(k-2)$

?

$$\Rightarrow \quad e^*(k) = e(k) + \frac{u_r(k) - u(k)}{n_0}$$

Used in the code to *update the error:*

e(k-1)=e(k)*

* Flesch and Normey-Rico, Control Eng. Practice, 2017

*Silva, Flesch and Normey-Rico, IFAC PID 18

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?

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Used in the code to *update the error:*

e(k-1)=e(k)*

ER* better results, principally in noise environment

* Flesch and Normey-Rico, Control Eng. Practice, 2017

*Silva, Flesch and Normey-Rico, IFAC PID 18

AW for dead-time processes

Including several constraints in AW scheme

$u(k) < U_{max}$ $\Delta u(k) < \Delta u_{max}$ $y(k) < y_{max}$

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Direct

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Direct

$$\Delta u(k) = u(k) - u(k-1) < \Delta u_{max}$$

$$u(k) < \Delta u_{max} + u(k-1)$$

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$u(k) < U_{max}$

Direct

$\Delta u(k) < \Delta u_{max}$

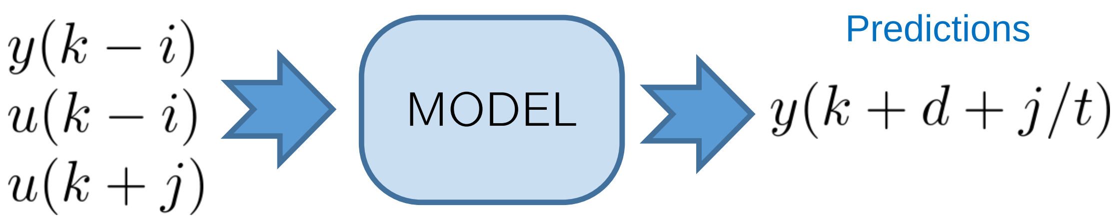
$\Delta u(k) = u(k) - u(k-1) < \Delta u_{max}$

$u(k) < \Delta u_{max} + u(k-1)$

$y(k) < y_{max}$

Using prediction ideas

$y(k+j) < y_{max} \quad \forall \quad j = 1 ... N_y$



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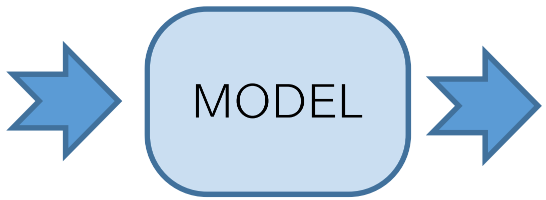
$y(k-i)$
$u(k-i)$
$u(k+j)$



Predictions

$y(k+d+j/t)$

Assuming $N_u = 1$
$u(k+j) = u(k) \quad \forall j$

$$y(k+d+j/k) = f(u(k), y(k-i), u(k-i))$$

AW for dead-time processes

SIMPLE CASE: FOPDT $y(k) = ay(k-1) + bu(k-d-1)$

AW for dead-time processes

SIMPLE CASE: FOPDT $$y(k) = ay(k-1) + bu(k-d-1)$$

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$$y(k+d+j) < y_{max} \Rightarrow u(k) < \frac{y_{max} - a^j y(k+d)}{K_j}$$

AW for dead-time processes

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$y(k+d+j) < y_{max}$ ⇒ $u(k) < \frac{y_{max} - a^j y(k+d)}{K_j}$

$$u(k) < \min\{U_{max}; \Delta u_{max} + u(k-1); \frac{y_{max} - a^j y(k+d)}{K_j}\}$$

GPC or FSP(PID) ER-AW?

- Constrained GPC or FSP-ER-AW
  - Good tuned FSP with ER-AWP **equivalent** to GPC (Nu=1)
  - On-line **optimization is avoided** with FSP
  - FSP filter tuning is **easy** in practice

Several successful applications in solar systems and refrigeration plants *

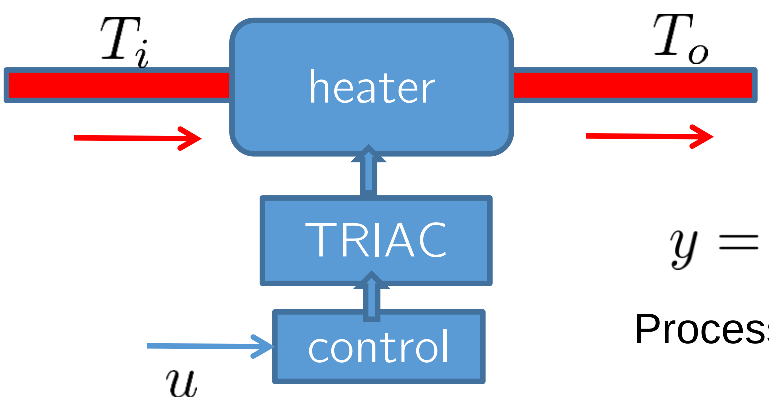
- In robust industrial solutions → PID-ER-AW
  - **Simple models** are used
  - **Robust tuning** (low M_s or high R_m values)

* Roca, Guzman, Normey-Rico, Berenguel and Yebra, Solar Energy, 2011

* Flesch and Normey-Rico, Control Eng. Practice, 2017

Water temperature control

Experiments: Electrical water heater



$$y = T_o - T_i$$

Process variable

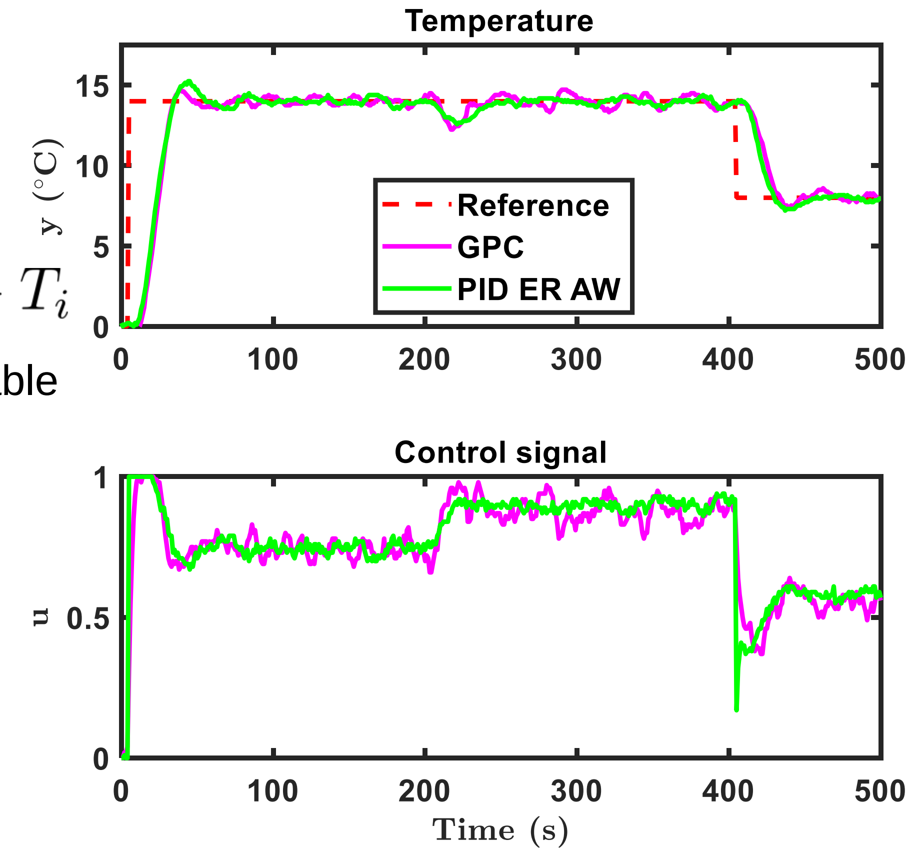
Normalized Control variable (number pulses)

$$u_{max} = 1$$
$$u_{min} = 0$$

Model identification: step test

$$P(s) = \frac{18.7e^{-8s}}{13.1s+1}$$

$$\text{GPC} - N = 60, N_u = 10, \lambda_n = 1$$
$$\text{PID} - T_0 = 8$$



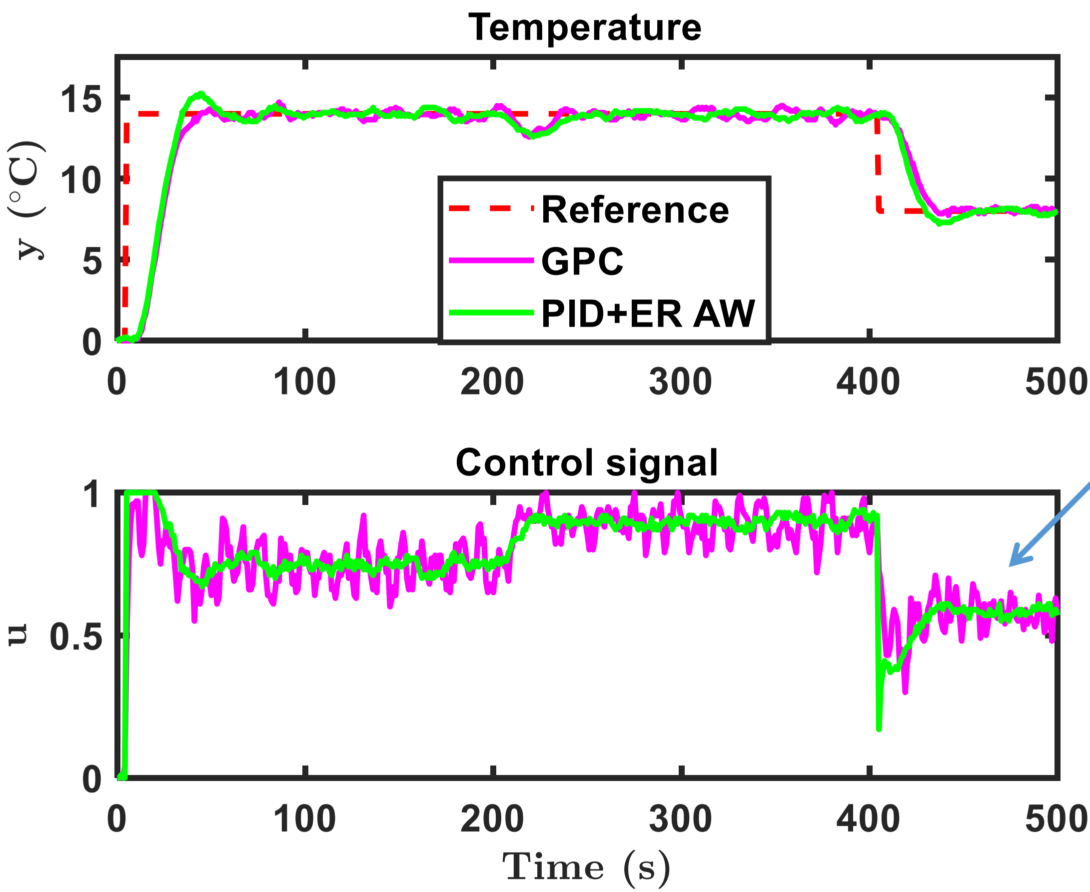
Same IAE performance
PID smother control action

Temperature control

$\mathrm{PID} - T_0 = 8$

New GPC tuning to accelerate the responses

$\mathrm{GPC} - N = 60, N_u = 10, \lambda_n = 0.3$



Problems:

- Small performance improvement
- Lower robustness
- Lower noise attenuation

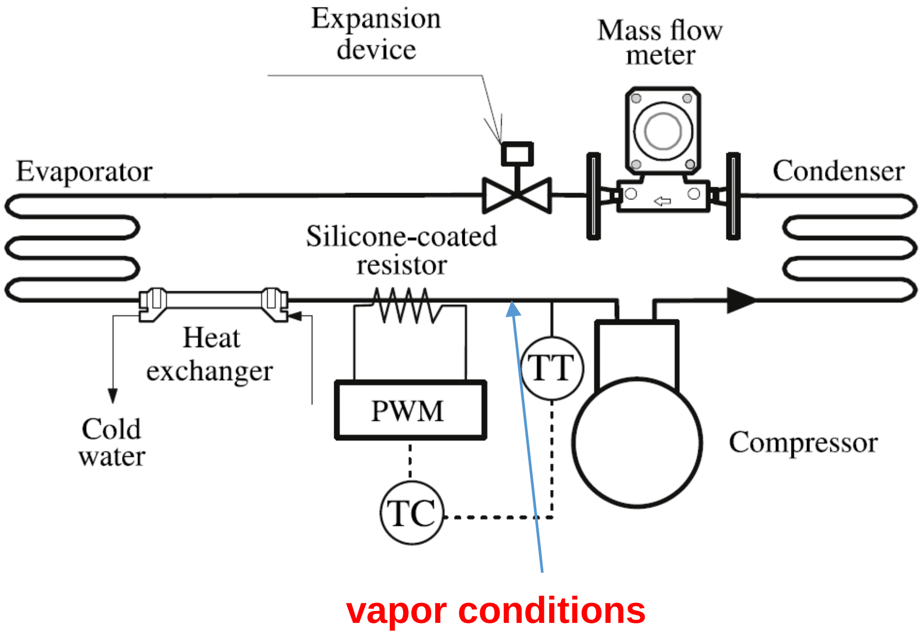
PID is simpler and better

Compressor-test system

$$\frac{T(s)}{U(s)} = \frac{0.76}{304.7s+1}e^{-108s}$$

$$u_{max} = 95\%$$

$$u_{min} = 5\%$$



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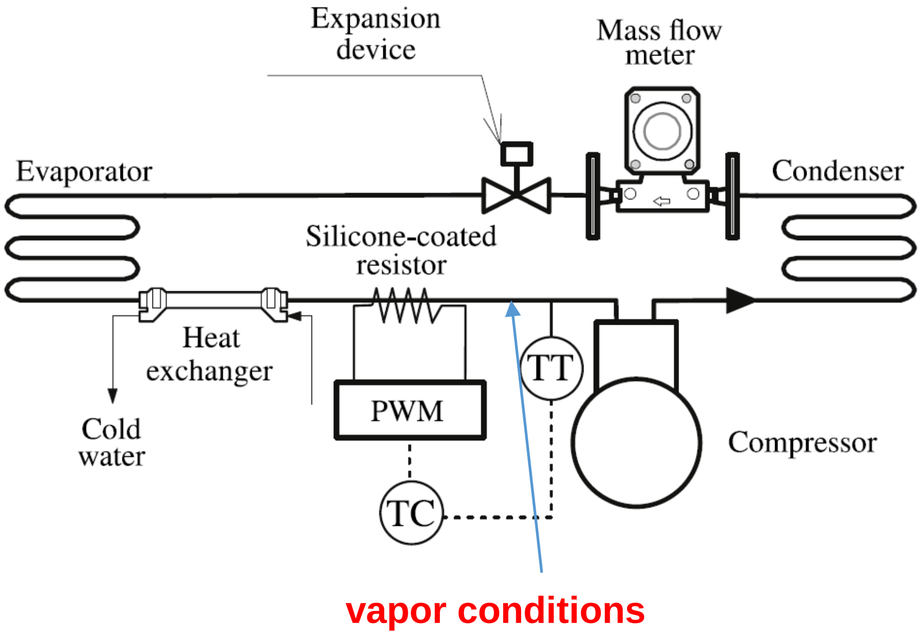

Important

- To maintain Inlet temperature
- Fast set-point response
- Fast disturbance rejection
- Delay error well estimated

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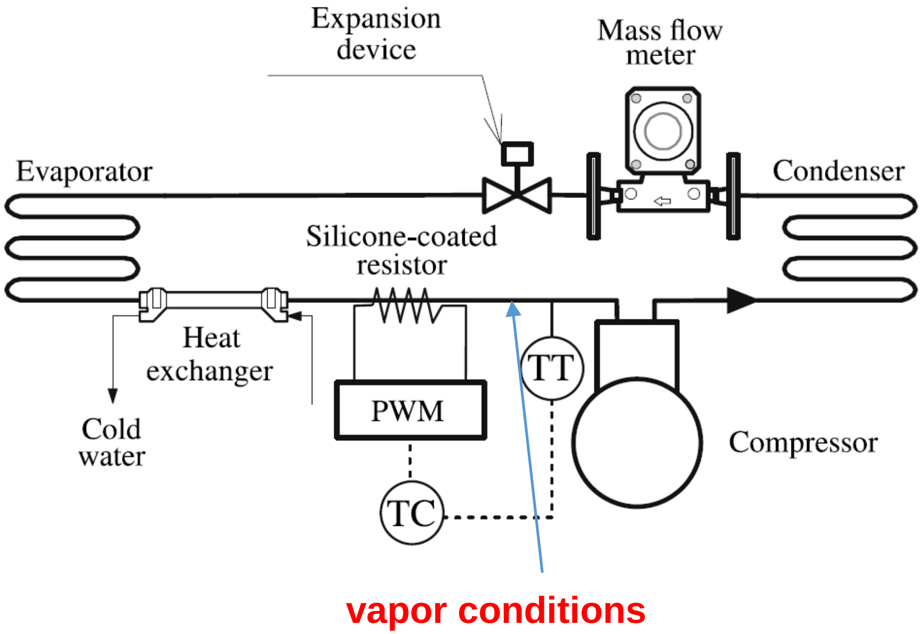

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FSP ER-AWP

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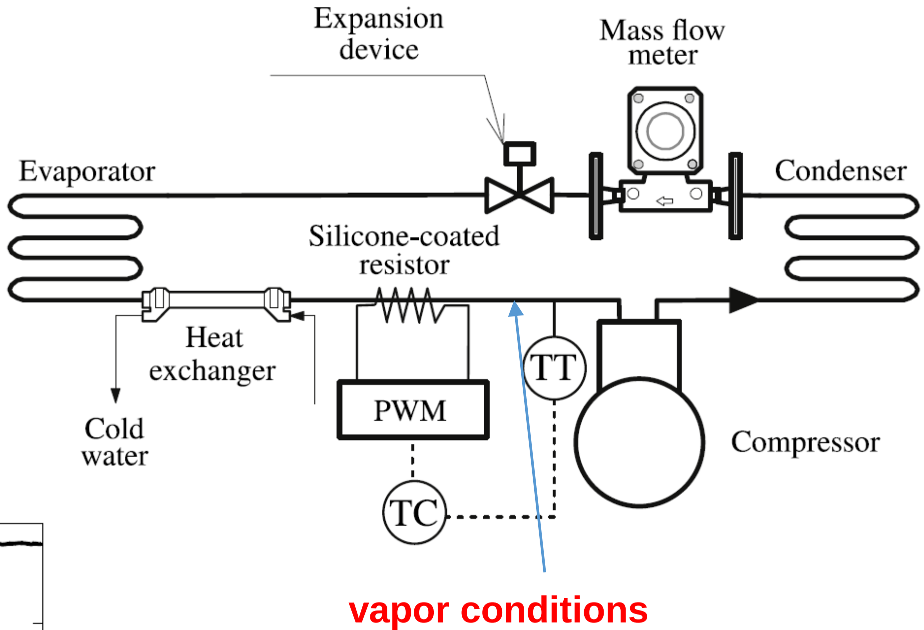

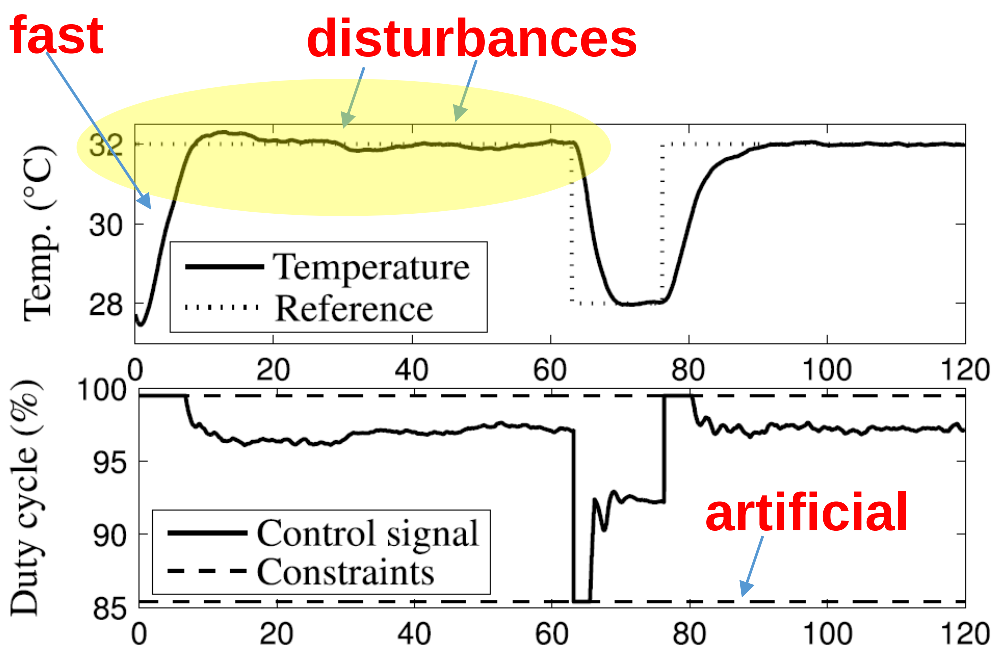

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FSP ER-AWP

Conclusions

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  - Constrained case: ER AW FSP can be equivalent to MPC
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  - Performance improvement is limited in complex cases
  - For high robust solutions PID is equivalent to FSP (even for high L)
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Low-order-process models
Large modelling error
Noise environment
Typical constraints

Well tuned robust PID with AW is the best option

Conclusions

- PID still has an important figure in process industry
- DTC strategies with PI or PID primary controllers can be considered as extensions of simple PID control and used in particular cases
- Improved AW PID algorithms (or FSP AW) can be the solution in modern real-time distributed control systems for simple constrained systems
- MPC solutions are important in complex well modeled systems and at second level control

Thanks!

For your attention

PID18 organizers

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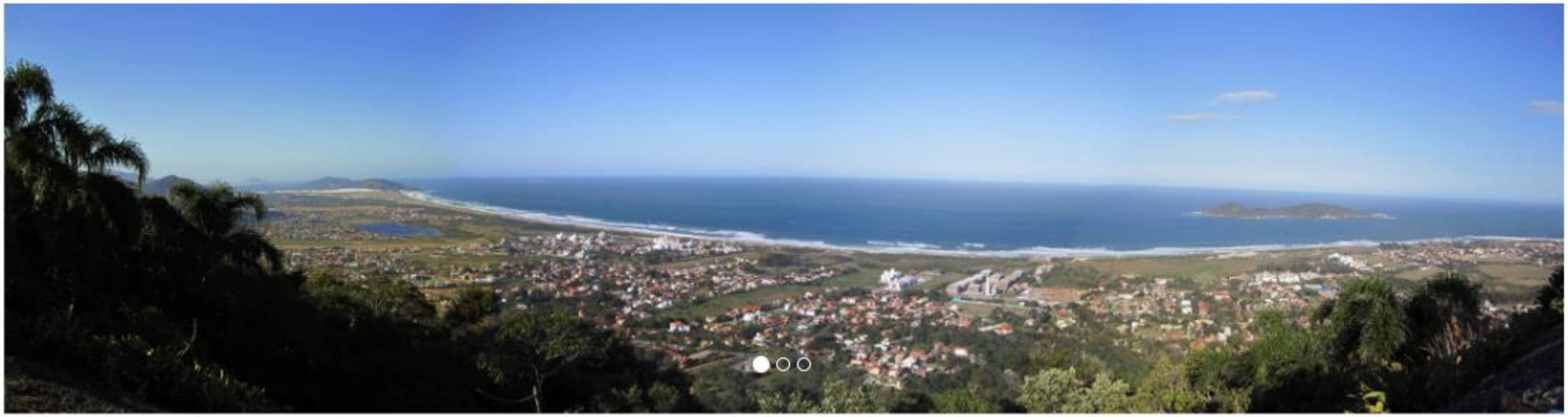

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