I N V E S T I C E   D O   R O Z V O J E   V Z D Ě L Á V Á N Í

Robustné PID-regulátory s obmedzeniami
Robust Constrained PID Control
DC0: Robust Predictive I_0 (PrI_0) Controller Design

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Tato prezentace je spolufinancována Evropským sociálním fondem a státním rozpočtem České republiky.

Introduction

- Predictive I_0 (PrI_0) controller and Filtered Predictive I_0 ($FPrI_0$) represent generalization of the oldest structure for active dead time compensation
- Its simplified version was introduced in 1956 by Reswick,J.B.: Disturbance-response Feedback - a new control concept. *Trans. ASME* 1956, No.1, 153-162, so yet before the well-known Smith predictor
- Due to the omitted disturbance-observer-filter and traditional problems related to dealing with the dead time system, it was practically forgotten.

Introduction

- From newer publication this contribution fully disappeared and just the Smith predictor is mentioned, see e.g.
- Normey-Rico, J.E., Camacho, E.F.: Dead-time compensators: A survey. *Control Eng. Practice,* Vol. 16, 4, 2008, 407-428, or
- Guzmán,J.L., García,P., Hägglund,T., Dormido,S., Albertos,P., Berenguel,M.: Interactive tool for analysis of time - delay systems with dead - time compensators, *Control Engineering Practice*, Vol. 16, 7, July 2008, 824-835.

Introduction

- But still, PrI_0 controller appropriate for the **dead time dominated stable plants** represents *a* twin to the most broadly used PI controller predestinated for the **lag dominated plants**
- Both they correspond to the simplest 2-parameter loop approximations (gain+time constant, or gain+dead time) appropriate for stable plants
- With respect to the broad use of PI controllers it is to expect that similar situation will develop also with the PrI_0 controllers
- The crucial reason for not using PrI_0 controllers earlier was absence of methods for their optimal analysis & tuning

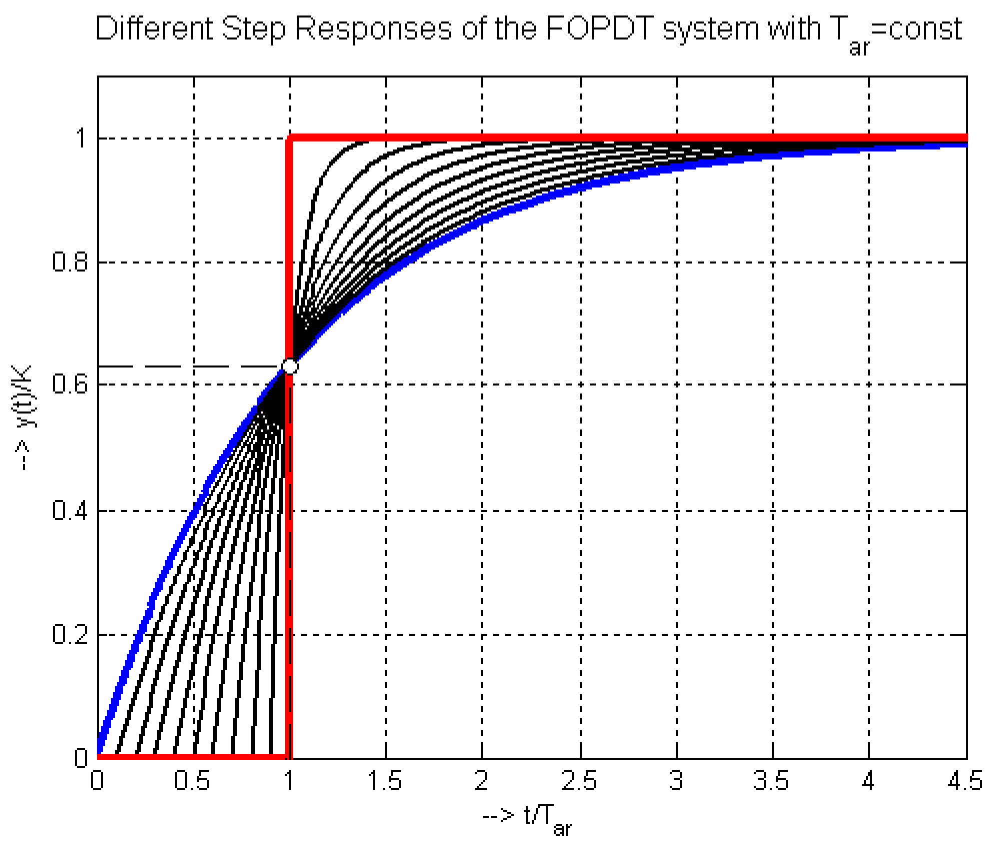
Introduction

Dead Time and **Time Constant** represent basic approximations of monotonic loop dynamics

$$\boxed{F_{nd}(s) = \frac{e^{-T_d s}}{1 + T_a s}\ ;\ T_{ar} = T_d + T_a}$$

Compensation of Time Constant => PI Control

Compensation of Dead Time => PrI Control – forgotten up to now!



Dynamical Class 0 (DC0)

- DC0 includes all controllers that ideally have monotonic setpoint step responses both at the plant and at the controller outputs
- By speeding up dynamics of these transients they converge up to rectangular steps
- PrI_0 controllers belong to the simplest controllers of DC0
- It is a fundamental controller: it means that in the nominal case (without nonmodelled dynamics) its output may be arbitrarily speeded up (up to rectangular steps at the controller, or plant outputs), i.e. it fulfills conditions:

Fundamental Controller of DC0

- For the closed loop poles

$$-\infty < \alpha_2 < \alpha_1 < 0$$

- the normalised setpoint responses corresponding to zero initial conditions and to a step *w*(*t*)

$$\bar{y}(\alpha_i, t) = y(\alpha_i, t) / w(t)$$

- satisfiy conditions

$$1 > \bar{y}(\alpha_2, t) > \bar{y}(\alpha_1, t) > 0\ ;\ \ \forall t > 0\ ;$$

$$\lim_{t \to \infty} \bar{y}(\alpha_i, t) = 1\ ;\ i = 1 \text{ or } 2$$

Fundamental Controller of DC0

- Dead time systems, setpoint response, delayed output y_1

$$\boxed{\bar{y}_1(t,\alpha_1)=\bar{y}_1(t,\alpha_2)=0,\ t\in(0,T_d)}$$

- else

$$\boxed{1>\bar{y}(\alpha_2,t)>\bar{y}(\alpha_1,t)>0\ ;\ \ \forall t>T_d}$$

Fundamental Controllers of DC0

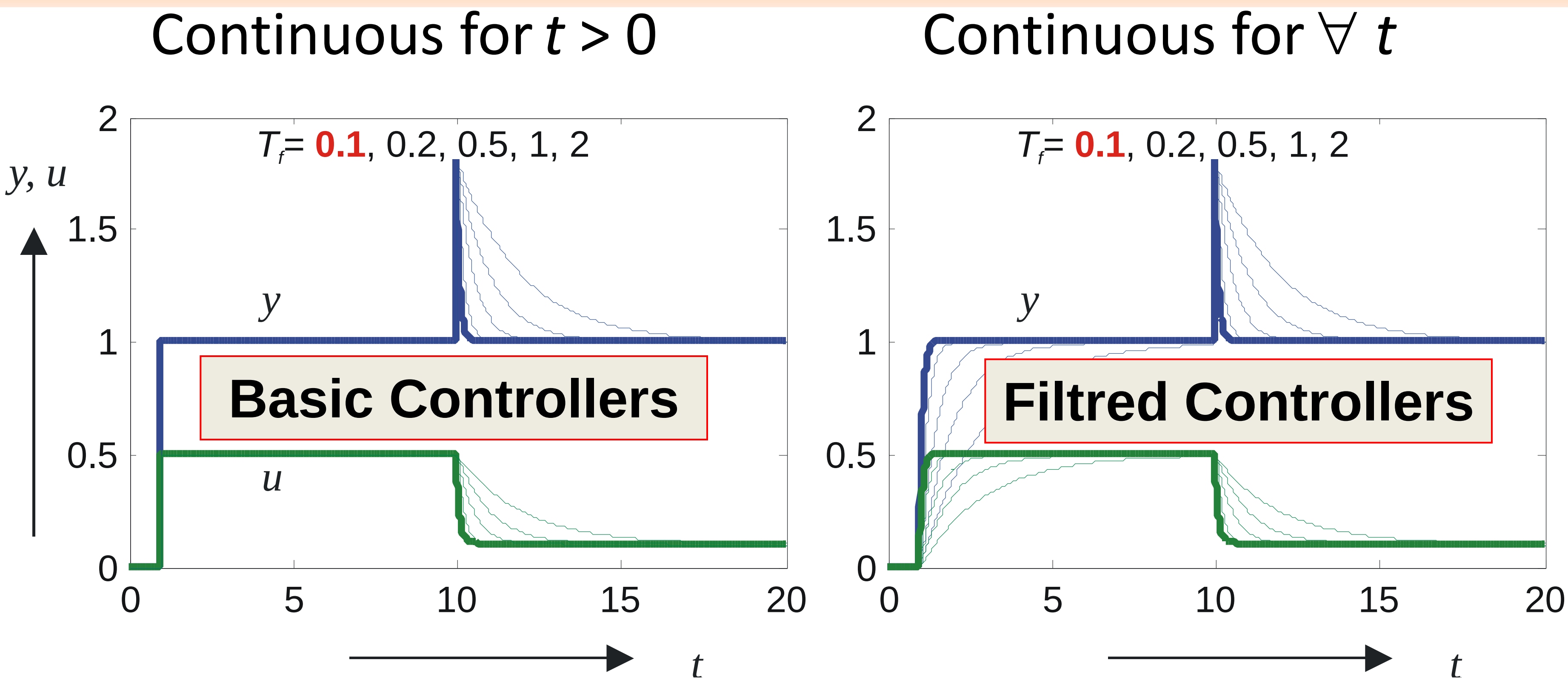
- Similar importance as the Mendelejev Periodic Table of elements in chemistry
- DC0 represents the first row of the Table of fundamental PID controllers and includes fully linear controllers

		Dominant dynamics							
Dynamic class	I-action	K	Ke^{-T_d}	$\frac{K_s}{s+a}$	$\frac{K_s e^{-T_d s}}{s+a}$	$\frac{K_{s1}}{s+a_1}+\frac{K_{s2}}{s+a_2}$	$\left[\frac{K_{s1}}{s+a_1}+\frac{K_{s2}}{s+a_2}\right]e^{-T_d s}$	$\frac{K_s}{s^2+a_1 s+a_0}$	$\frac{K_s e^{-T_d s}}{s^2+a_1 s+a_0}$
0	N	FF	FF	FF	FF	FF	FF	FF	FF
	Y	I	PrI	PI	PrPI	PID	PrPID	PID	PrPID
1	N	-	-	P	PrP	P-P	PrP-P	PD	PrPD
	Y	-	-	PI	PrPI	P-PI	PrP-PI	PID	PrPID
2	N	-	-	-	-	-	-	PD	PrPD
	Y	-	-	-	-	-	-	PID	PrPID

FF = static feedforward control

Pr = predictive (dead time) controllers

Typical Responses of the DC0

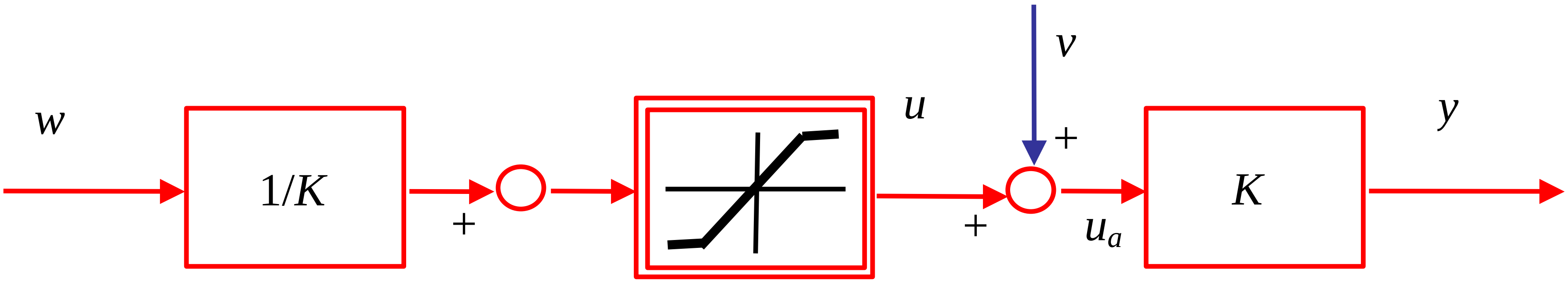


Parametrization by the closed loop time constant (T_f=-1/α, α - closed loop pole)

Possibility to speed up transients up to rectangular steps

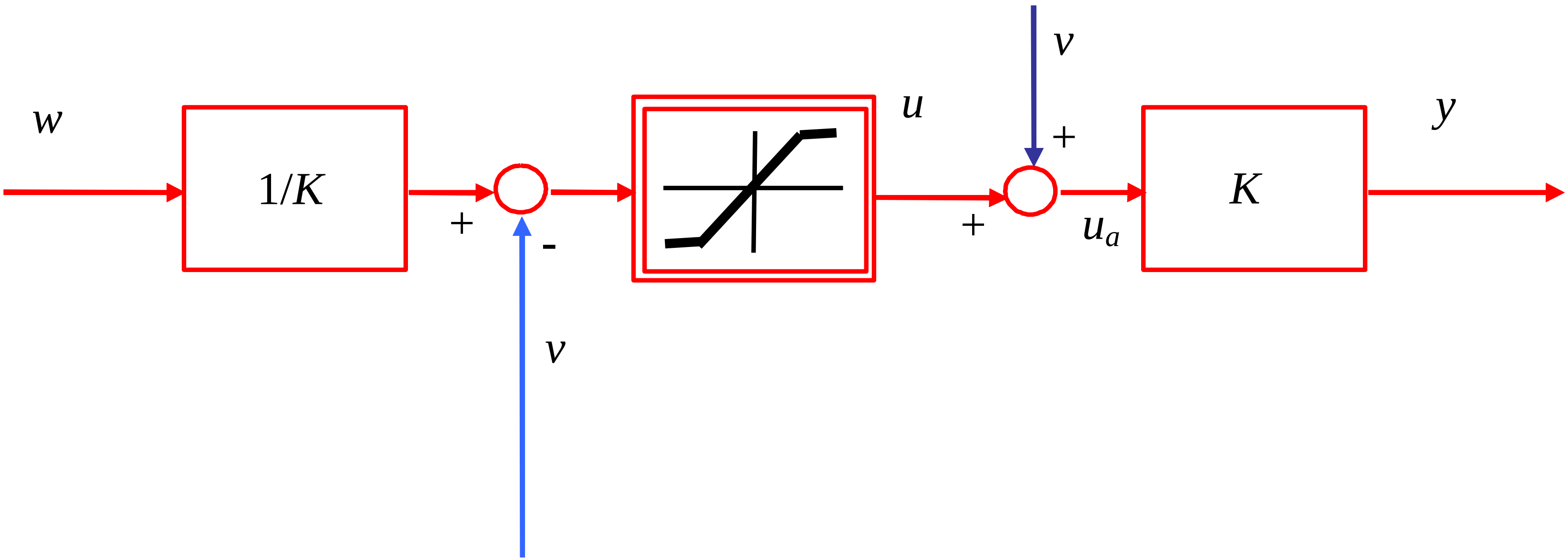
Input disturbance compensation

Static feedforward control



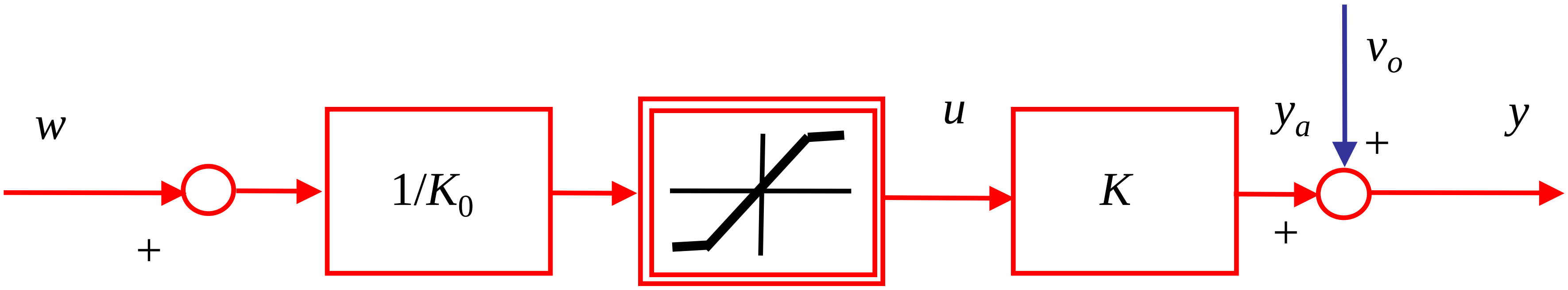
Input Disturbance (ID) Compensation

Static feedforward control with compensation of the input disturbance



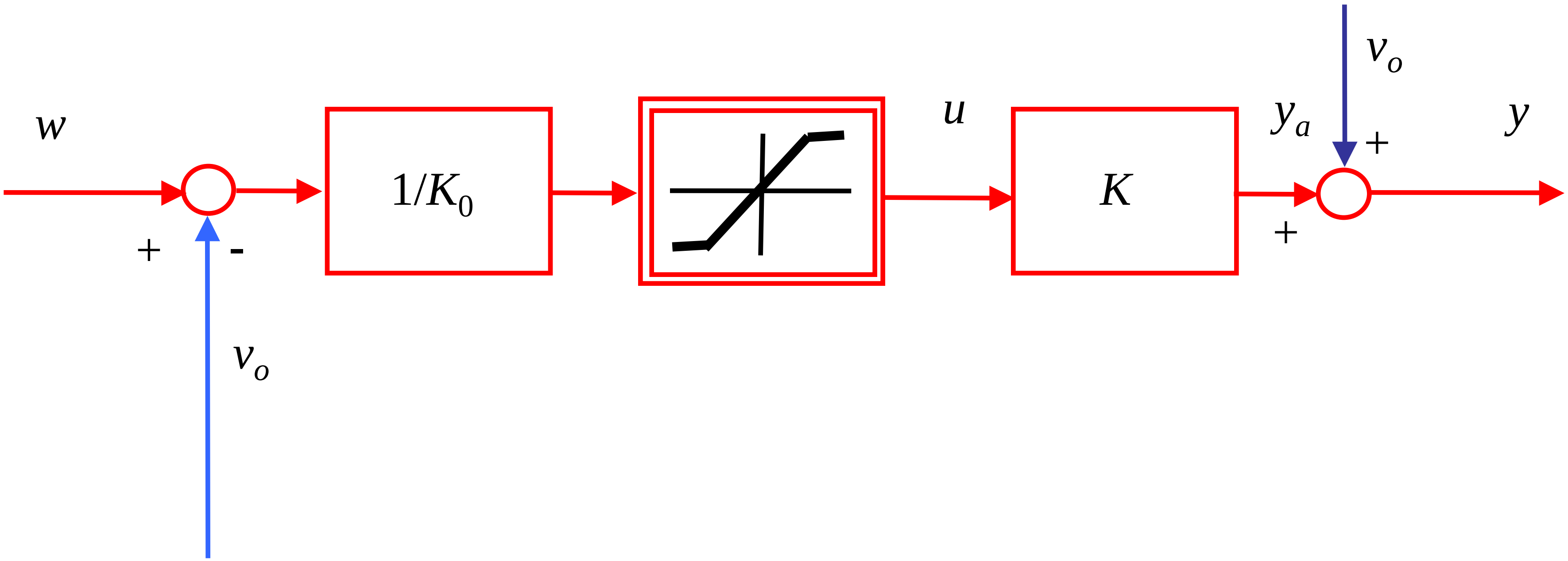
Output Disturbance (OD) Compensation

Static feedforward control



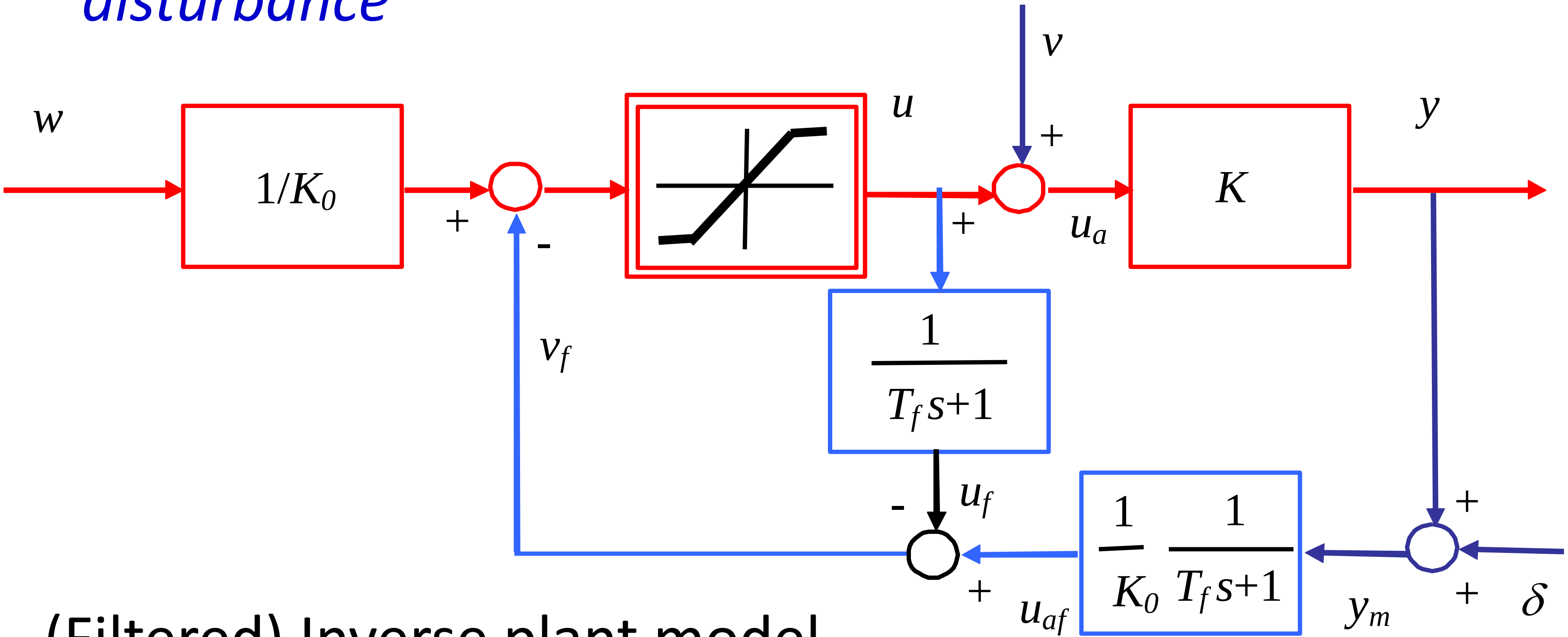
Output Disturbance Compensation

Static feedforward control with compensation of the output disturbance



I_0-ID controller – generic structure

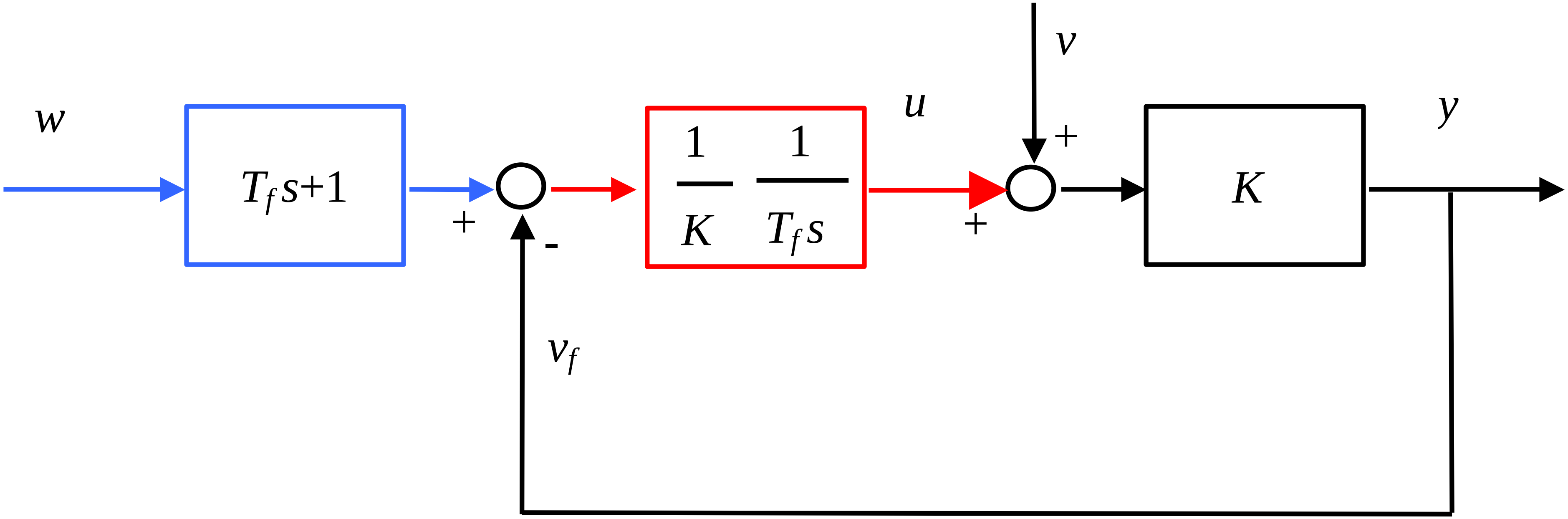
Static feedforward control with compensation of input disturbance



(Filtered) Inverse plant model

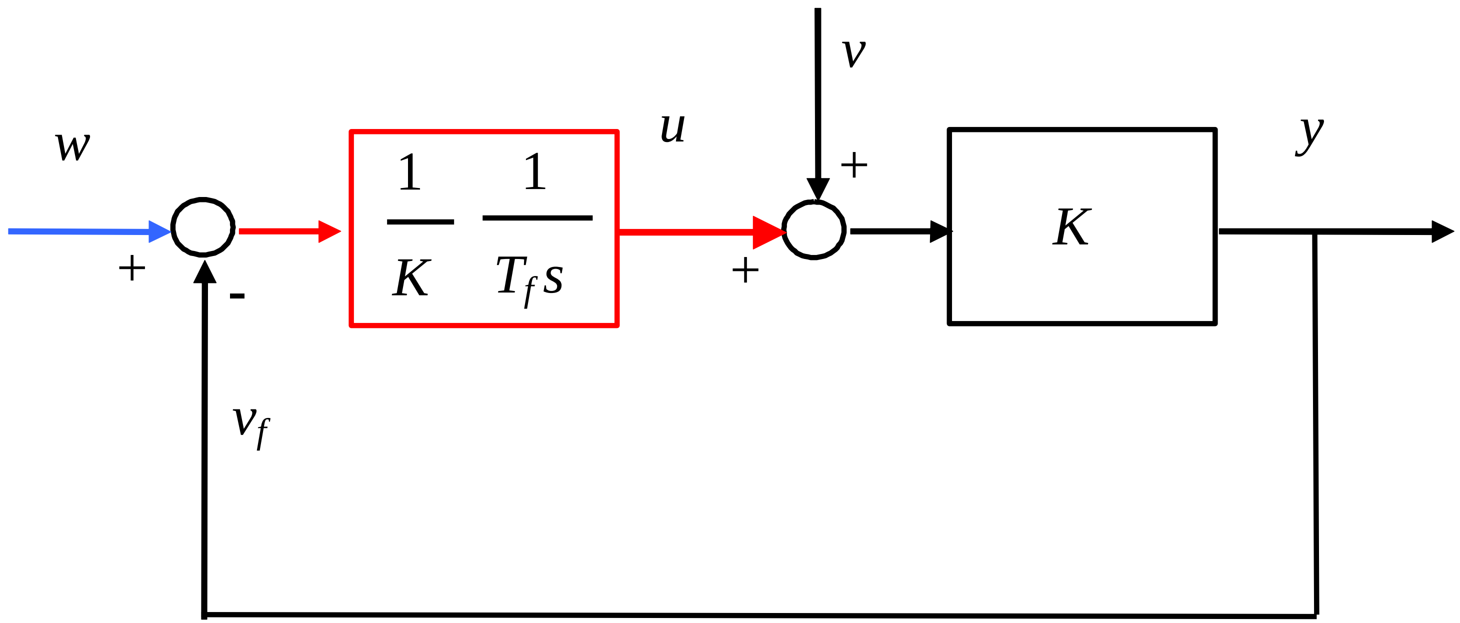
I_0-ID controller - equivalent structure

- explicit integrator
- Omitting prefilter = I-controller = FI_0 – controller



FI_0 controller = I controller

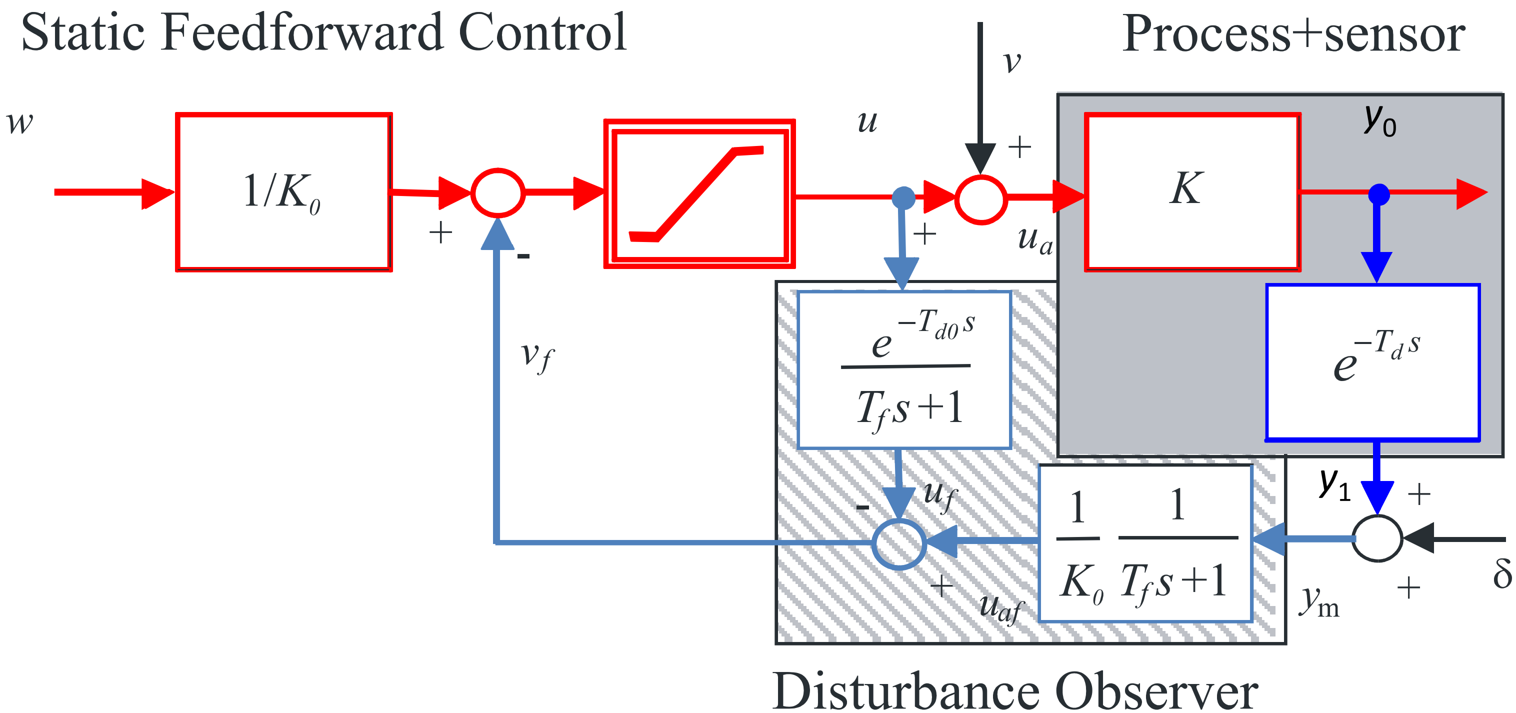
- Filtered response continuous for t = 0



PI_0 and PrI_0 Controllers

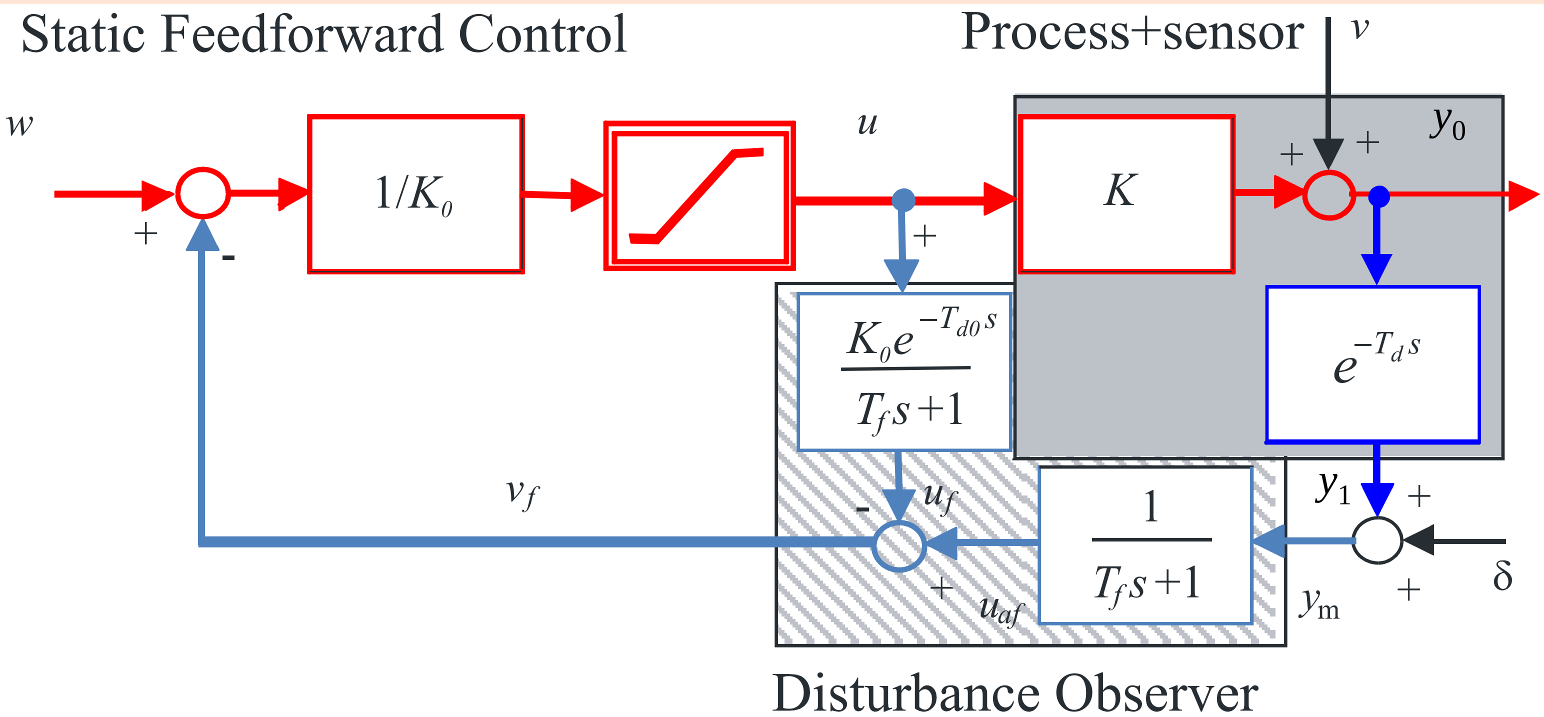
- I_0 controllers are based on the *simplest* plant approximation by a gain (memoryless plant)
- By approximating the plant dynamics by a time constant, or by a dead time it is possible to derive
- PI_0 controllers and
- Predictive I_0 (PrI_0) controllers
- Both approximations corresponds to limit situations in evaluating the *Average Residence Time* by measuring e.g. the integral area over the setpoint step response

PrI_0-Controller – input disturbance



- By adding dead time into the DOB channel from the controller output we get improved disturbance reconstruction
- Intuitively, one might expect optimal behavior for $T_{d0}=T_d$ and $K_0=K$
- *Similarities* with I_0 controller

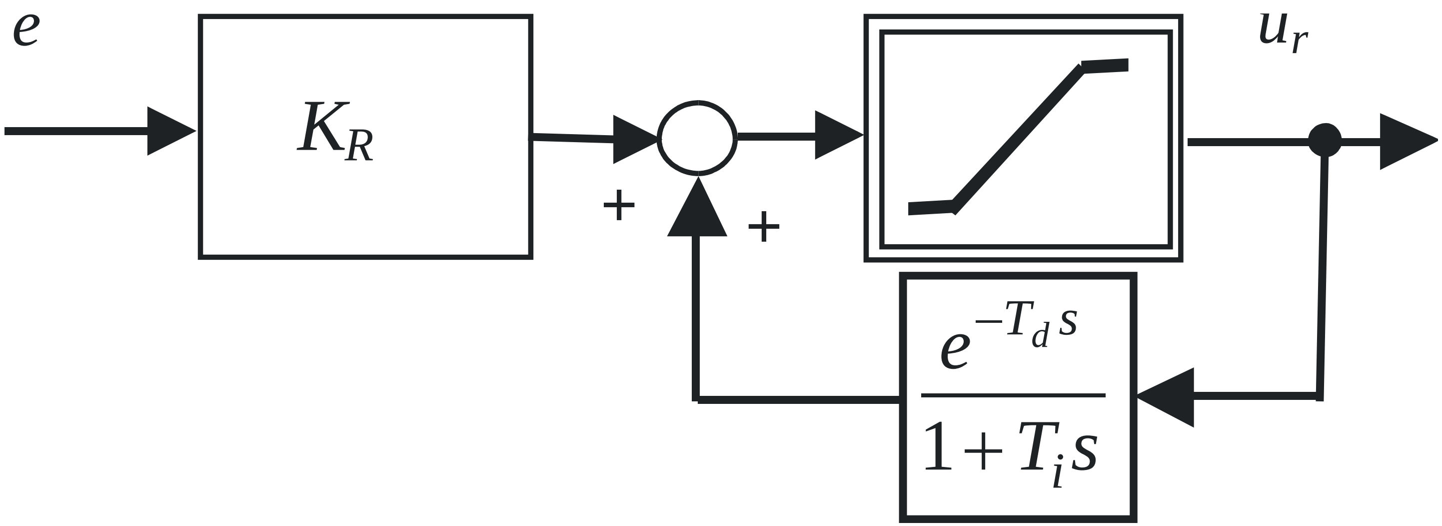
PrI_0-Controller – output disturbance



- Filtered IMC structure (parallel plant model)
- In a loop with the memoryless plant the input and output disturbances are fully equivalent
- It is enough to deal just with one structure

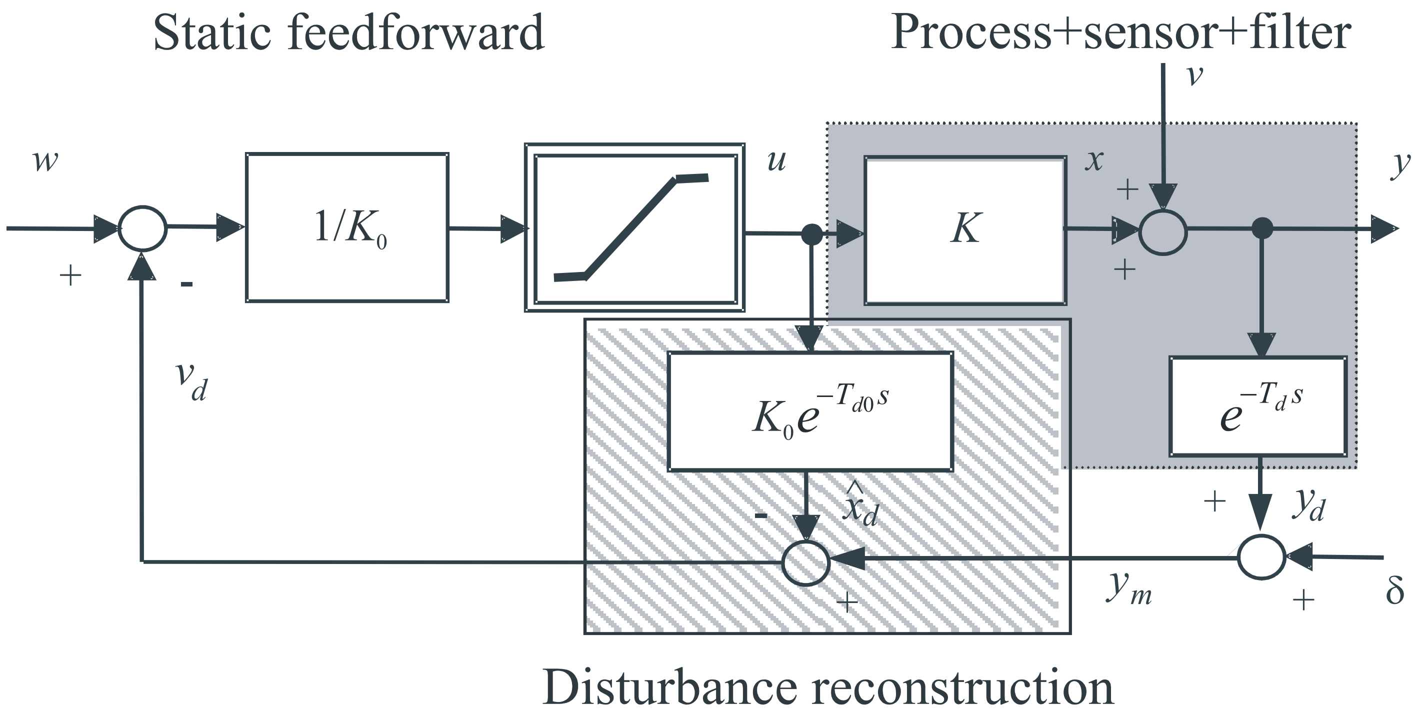
Core of the PrI_0-controller

- Similar to series implementation of the dead time compensation (feedback around the saturation at the controller output) reported e.g. by Åström & Hägglund, 1995

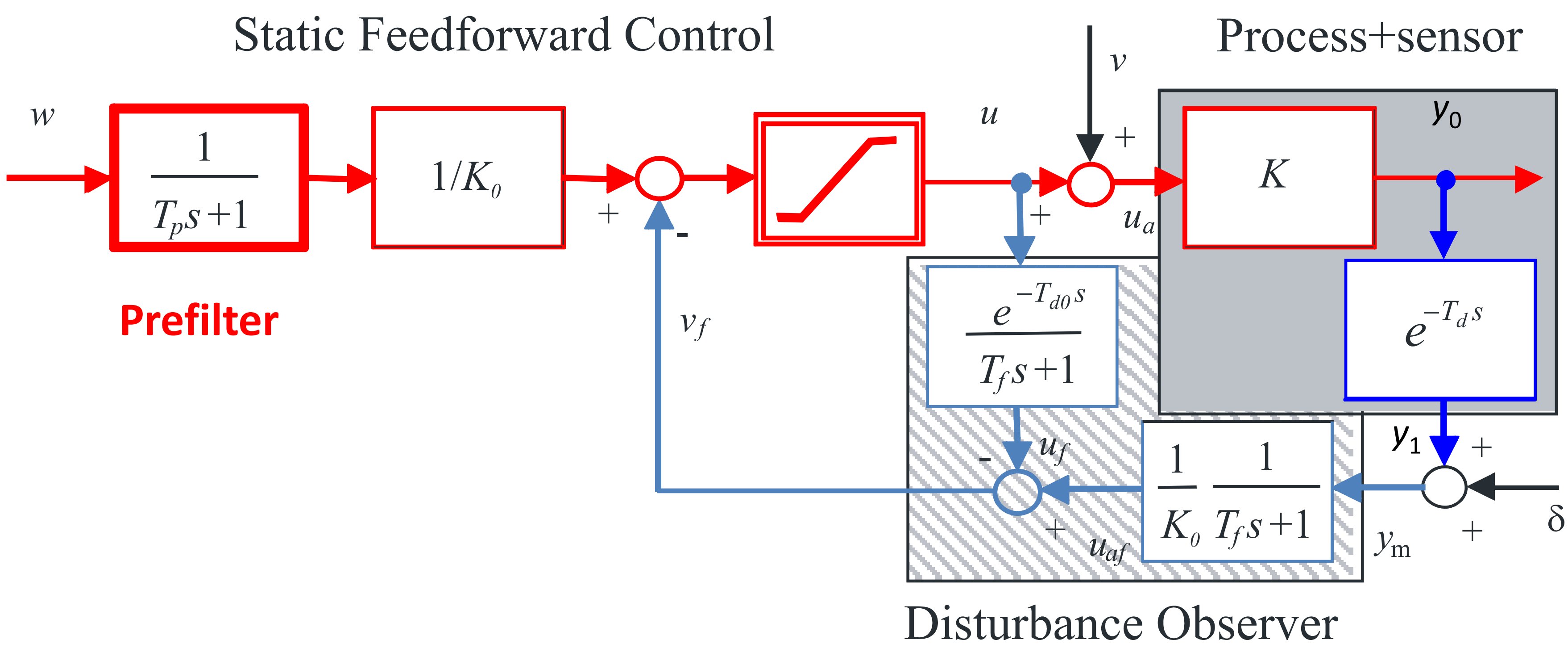


Reswick Controller (1956)

- Special Case of PrI_0 controller with T_f=0 – low robustness
- Derived for the output disturbance (K_0 in the loop from controller output & correction of the feedforward input)

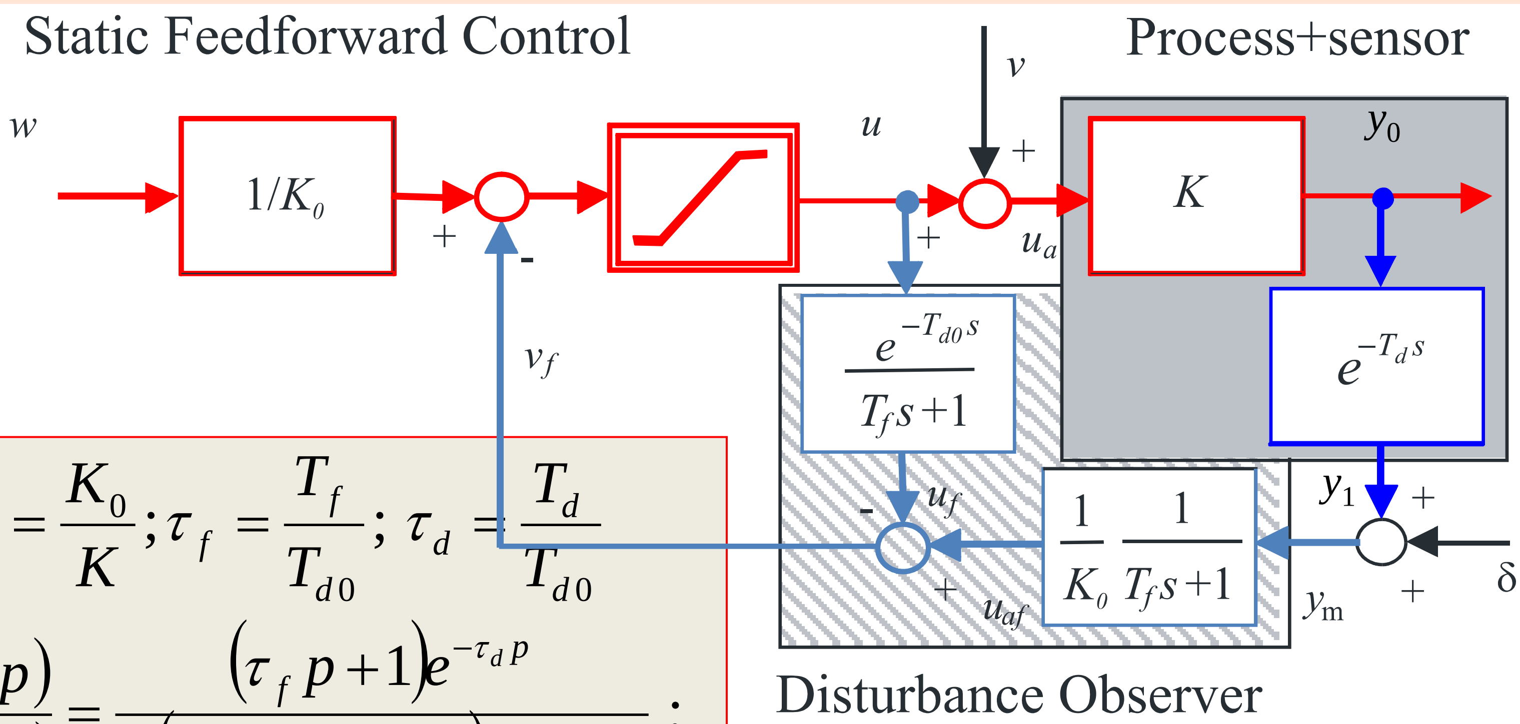


FPrI$_0$-Controller



- Smooth control signal step responses at t=0

PrI_0 Performance Portrait



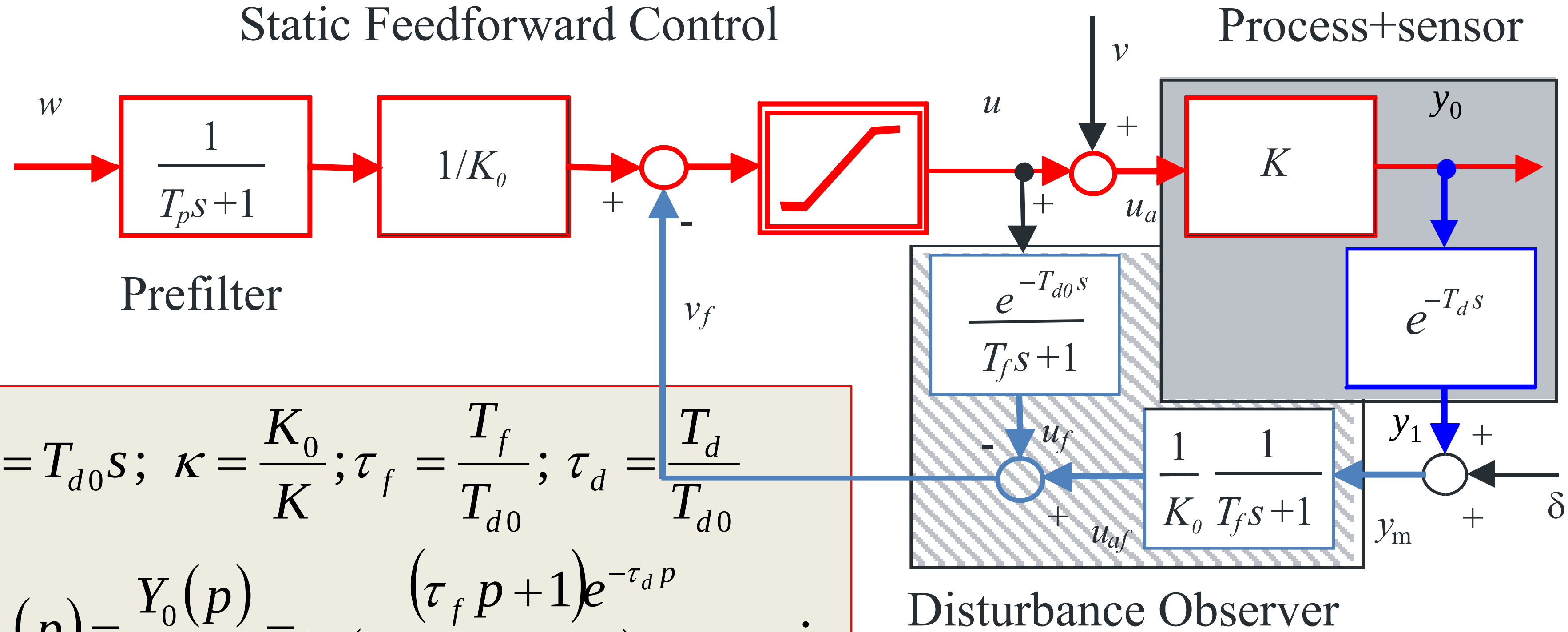
$$p = T_{d0}s;\ \kappa = \frac{K_0}{K};\ \tau_f = \frac{T_f}{T_{d0}};\ \tau_d = \frac{T_d}{T_{d0}}$$

$$F_w(p) = \frac{Y_0(p)}{W(p)} = \frac{(\tau_f p + 1)e^{-\tau_d p}}{\kappa(\tau_f p + 1 - e^{-p}) + e^{-\tau_d p}};$$

$$F_v(p) = \frac{Y_0(p)}{V(p)} = \frac{K_0 e^{-\tau_d p}(\tau_f p + 1 - e^{-p})}{\kappa(\tau_f p + 1 - e^{-p}) + e^{-\tau_d p}}$$

Normalized transfer functions

$FPrI_0$ Performance Portrait



$$p = T_{d0}s;\quad \kappa = \frac{K_0}{K};\ \tau_f = \frac{T_f}{T_{d0}};\ \tau_d = \frac{T_d}{T_{d0}}$$

$$F_w(p) = \frac{Y_0(p)}{W(p)} = \frac{(\tau_f p+1)e^{-\tau_d p}}{\kappa(\tau_f p+1-e^{-p})+e^{-\tau_d p}};$$

$$F_v(p) = \frac{Y_0(p)}{V(p)} = \frac{K_0 e^{-\tau_d p}(\tau_f p+1-e^{-p})}{\kappa(\tau_f p+1-e^{-p})+e^{-\tau_d p}}$$

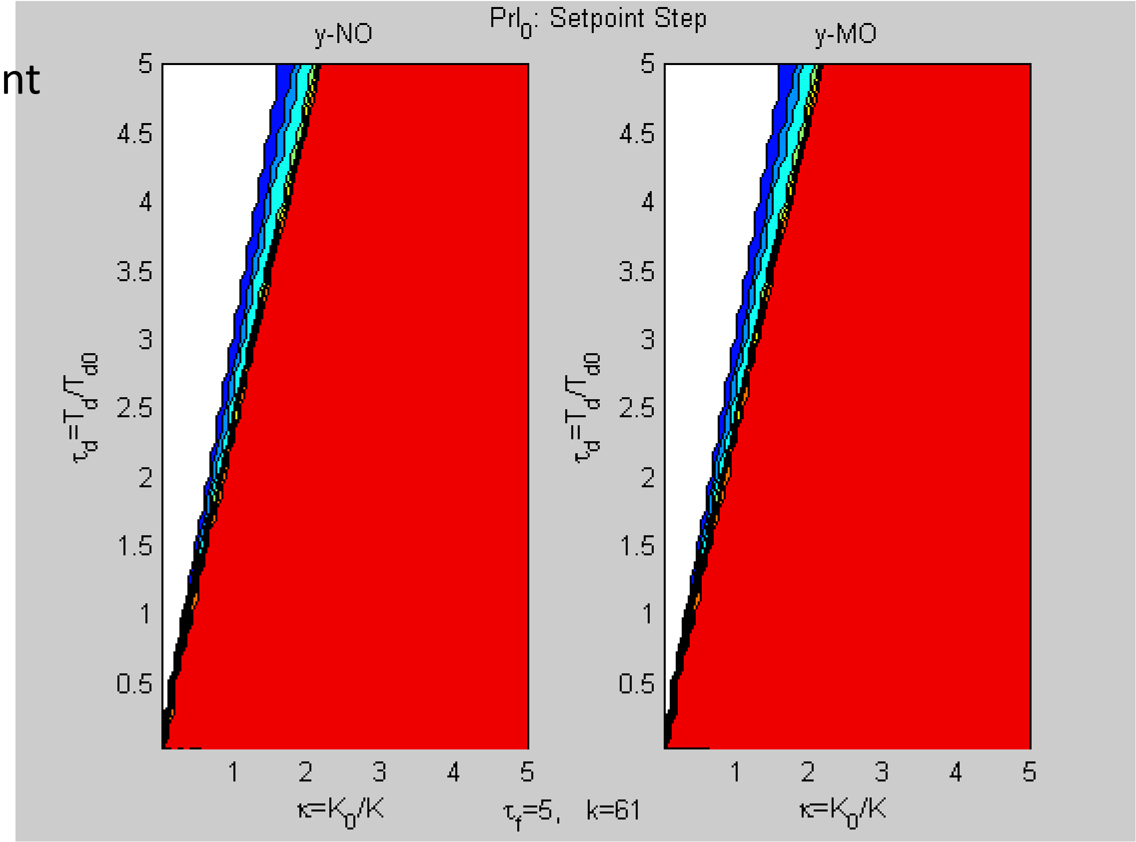
Normalized transfer functions

FPrI$_0$: 3D Performance Portrait

61 Layers for different

$$\tau_f = \frac{T_f}{T_{d0}}$$

follow numbers in the middle at the bottom of the picture

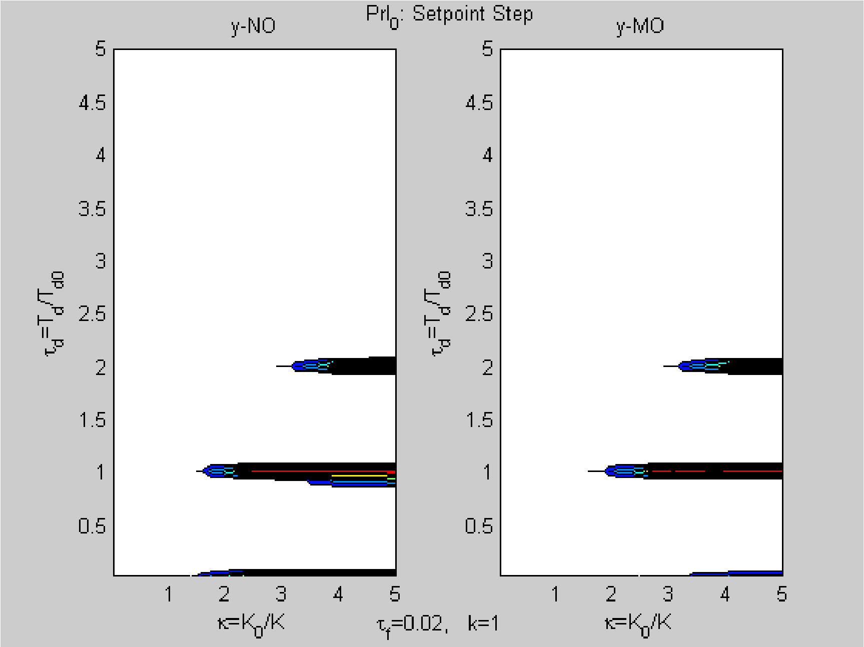


Red
ε=0.0
ε=0.00001
ε=0.0001
ε=0.001
ε=0.01
ε=0.02
ε=0.05
Dark blue

$$p = T_{d0} s\,;\ F_{w0}(p) = \frac{e^{-\tau_d p}}{\kappa\left(\tau_f p + 1 - e^{-p}\right) + e^{-\tau_d p}}$$

Collors corresponding to different ε

FPrI$_0$: Performance Portrait $T_f / T_{d0} \rightarrow 0$



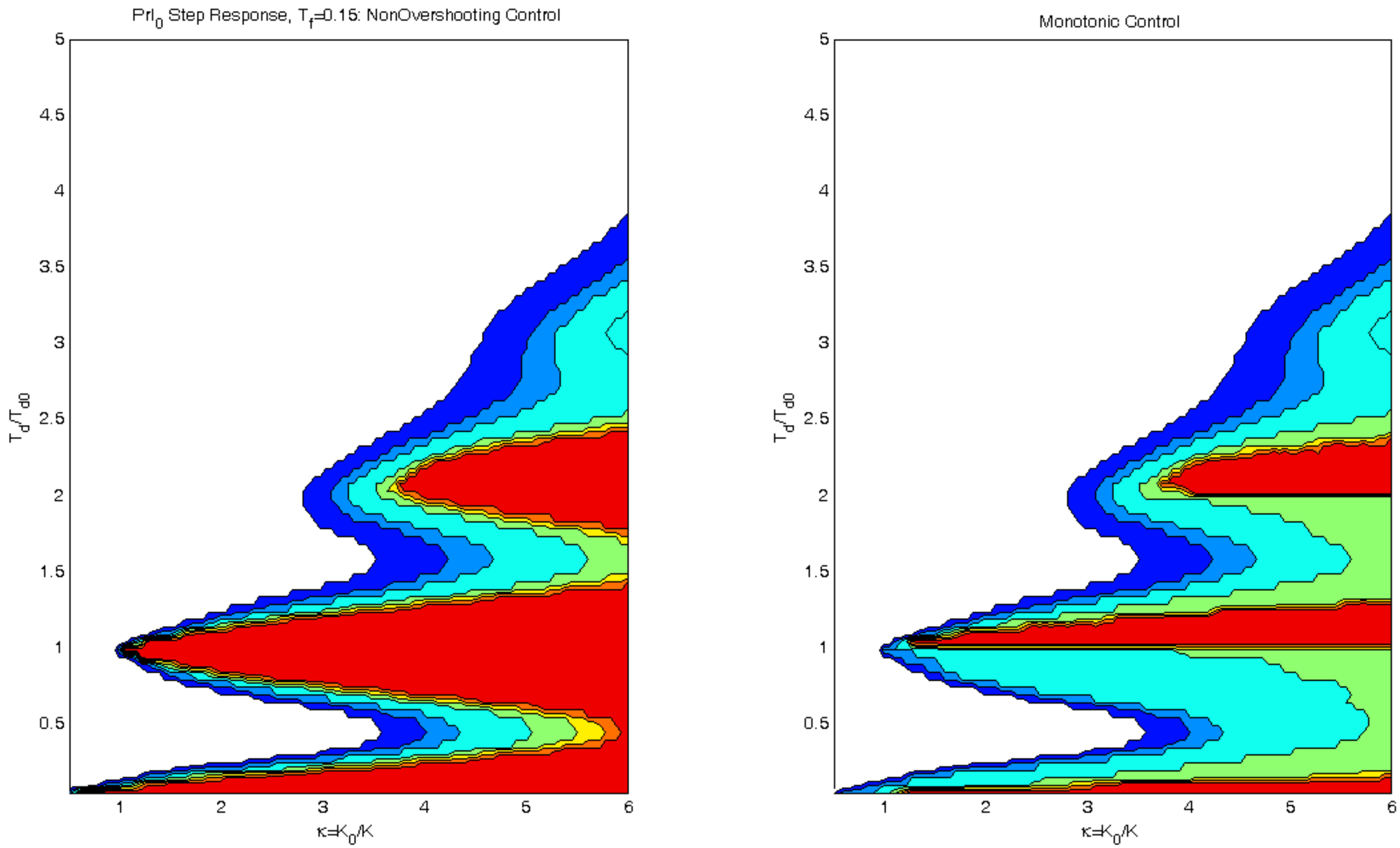
• areas of nonovershooting (NO), or monotonic (MO) control responses shrink to narrow strips that explains problems of the Reswick solution

•the intuitive expectation of optimale tuning K_0=K is missleading – under finite precission larger K_0 values must be used than K to get the operating point to a position, where the areas of NO, or MO control are wider

•Note special periodicity !!!

$FPrI_0$: Performance Portrait $T_f / T_{d0} \rightarrow 0$

Different areas of NO and MO control



Uncertainty Sets - PrI_0 Controllers

Interval parameters

$$K \in \langle K_{\min}, K_{\max} \rangle ;\; c_K = K_{\max} / K_{\min} \geq 1 ;$$
$$T_d \in \langle T_{d\min}, T_{d\max} \rangle ;\;\; c_d = T_{d\max} / T_{d\min} \geq 1 ;$$

One interval parameter – horizontal or vertical *Uncertainty Line Segment* in the plane (κ,τ_d) - section of 3D space (κ,τ_d,τ_f)

$$\begin{matrix} ULS_\kappa = [\kappa_{\min}, \tau_d \quad \kappa_{\max}, \tau_d] \\ ULS_d = [\kappa, \tau_{d\min} \quad \kappa, \tau_{d\max}] \end{matrix} ;\; \kappa = \frac{K_0}{K} ;\; \tau_d = \frac{T_d}{T_{d0}} ;\; \tau_f = \frac{T_f}{T_{d0}}$$

Two interval parameters – *Uncertainty Box* – plane of interval parameters (κ,τ_d) – subplane of 3D space (κ,τ_d,τ_f)

$$UB = \begin{bmatrix} \kappa_{\min}, \tau_{d\max} & \kappa_{\max}, \tau_{d\max} \\ \kappa_{\min}, \tau_{d\min} & \kappa_{\max} \tau_{d\min} \end{bmatrix} ;\; \kappa = \frac{K_0}{K} ;\; \tau_d = \frac{T_d}{T_{d0}} ;\; \tau_f = \frac{T_f}{T_{d0}}$$

Sweeping Optimal Uncertainty Box UB in 3D

Optimal UB => localizing UB into position with minimal mean IAE value & admissible overshooting & admissible TV0 values, etc.

Sweeping 3D parameter space (κ,τ_d,τ_f) for absolute optimum

FPrI$_0$-Controller – UB for ε=0.02

Due to the parameter quantization UB may fully lay in the area corresponding to lower value ε (ε=0)

Red ε=0.0

ε=0.00001

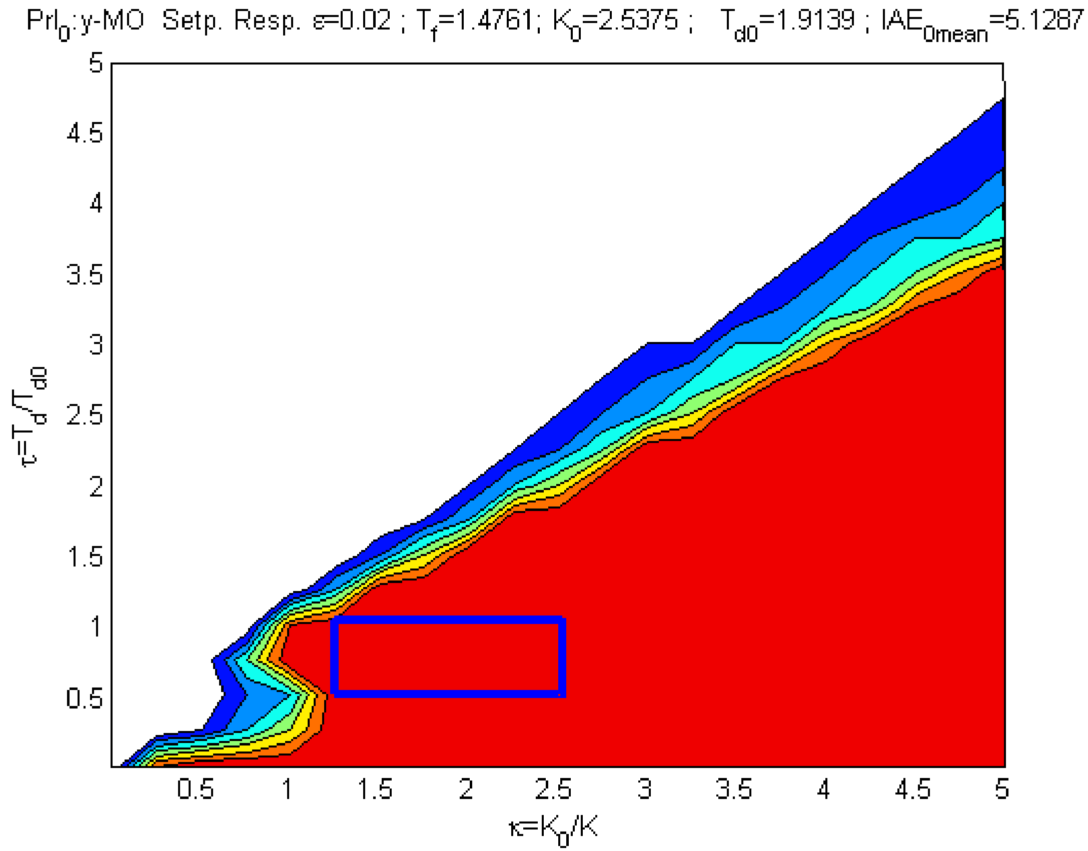
ε=0.0001

ε=0.001

ε=0.01

Light blue ε=0.02

Dark blue ε=0.05



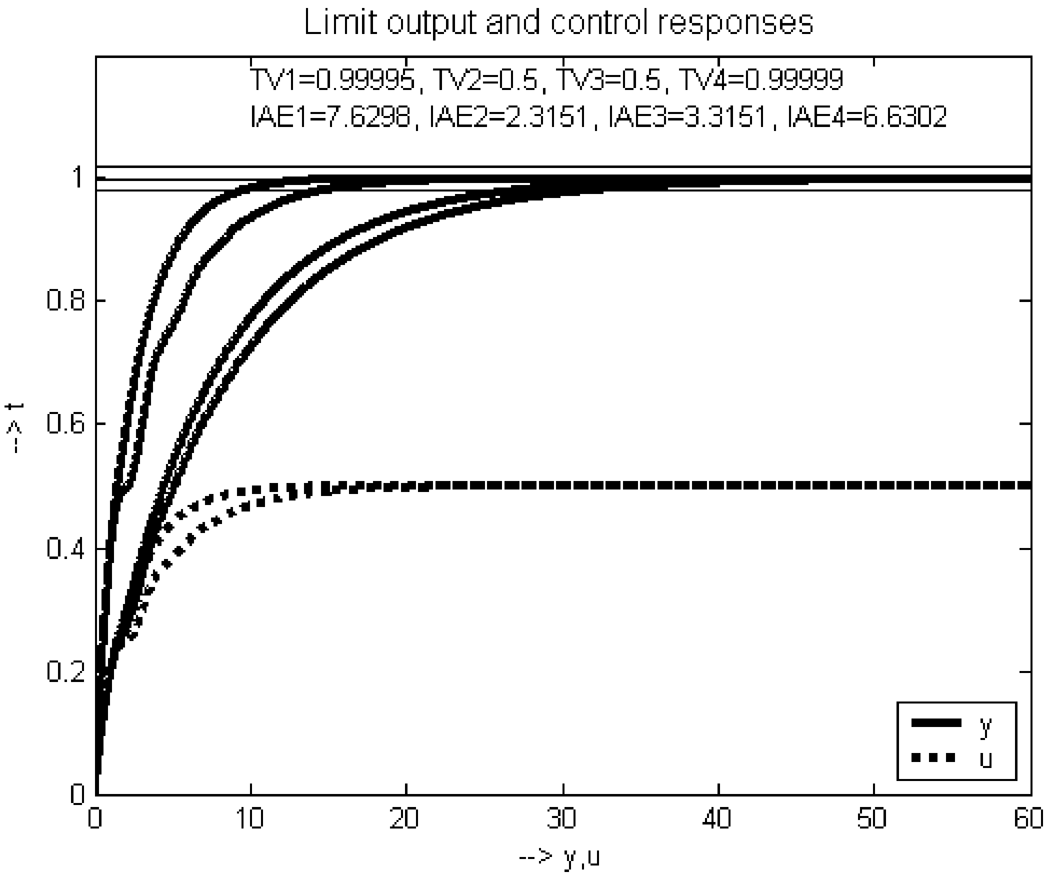
FPrI$_0$-Controller – UB for ε=0.02

Transcients corresponding to UB vertices

TV1, TV2, TV3, TV4 correspond to TV at different vertices of UB

For variable K are the absolute values of TV at different vertices not transparent ➔

More transparent is to use TV$_0$ showing just increments due to higher harmonics



FPrI$_0$-Controller – UB for ε=0.05

Due to the parameter quantization UB may lay in area corresponding to lower ε=0.02 (instead of ε=0.05)

Red ε=0.0

ε=0.00001

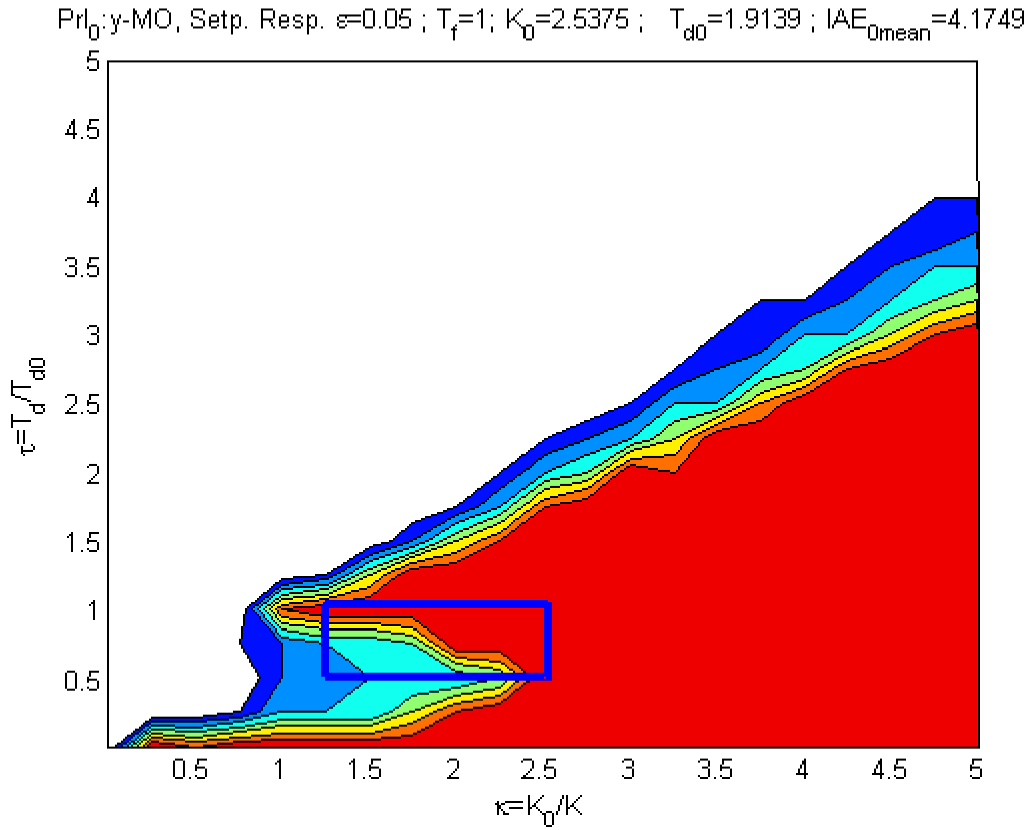
ε=0.0001

ε=0.001

ε=0.01

Light blue ε=0.02

Dark blue ε=0.05



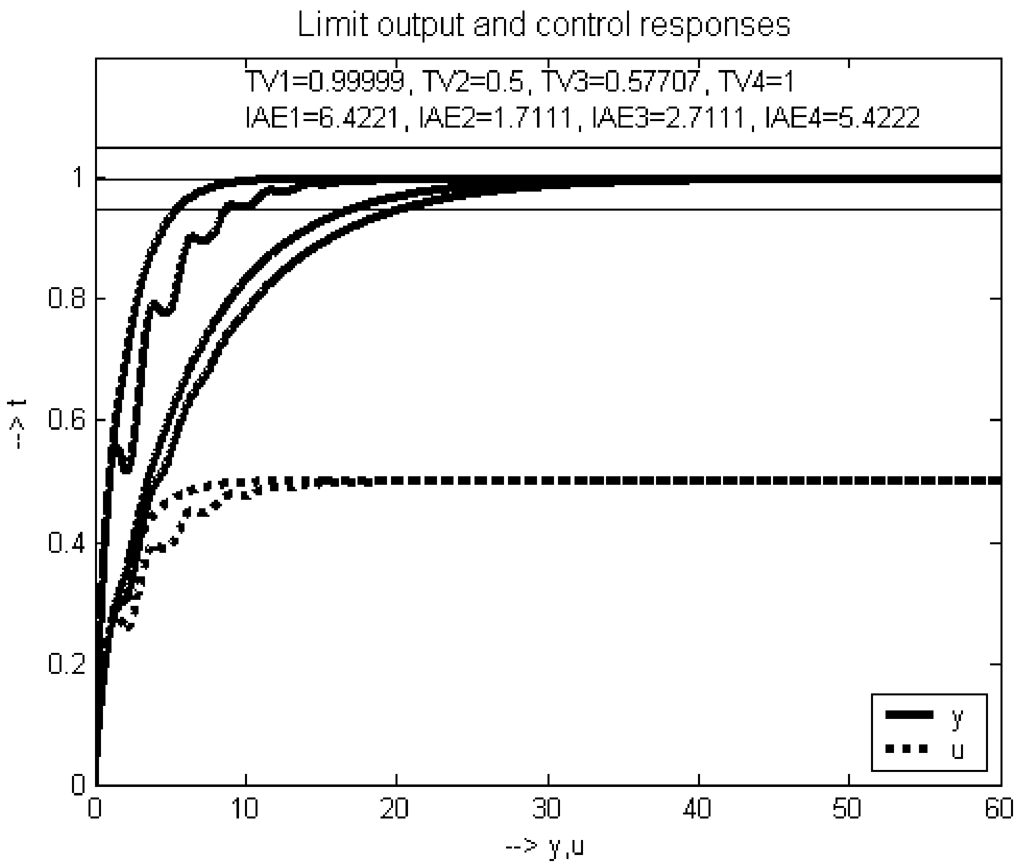
FPrI$_0$-Controller – UB for ε=0.05

Transients corresponding to UB vertices

TV3 (left down vertex) increased from 0.5 to 0.57707

IAE1 decreased from 7.6298 to 6.4221

(comparing with ε=0.02)

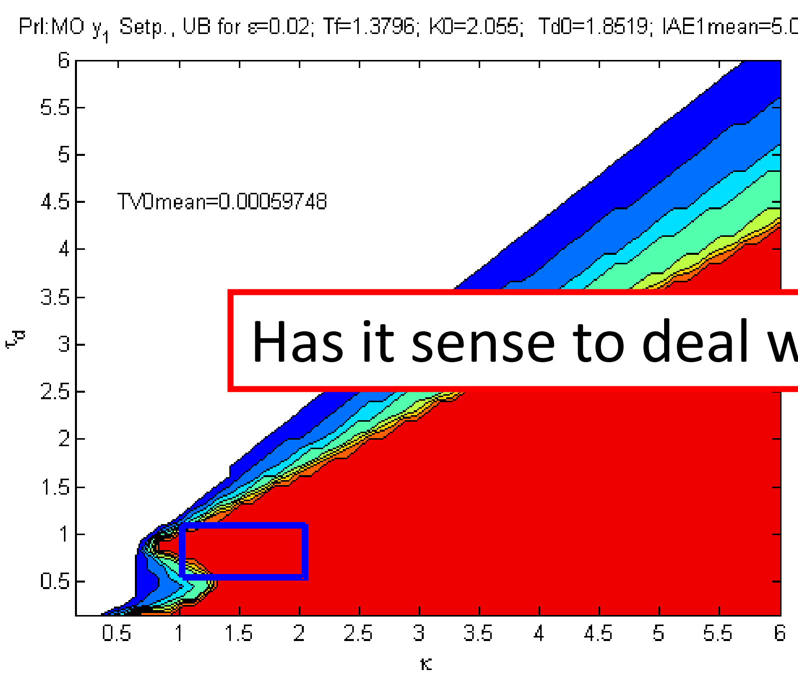


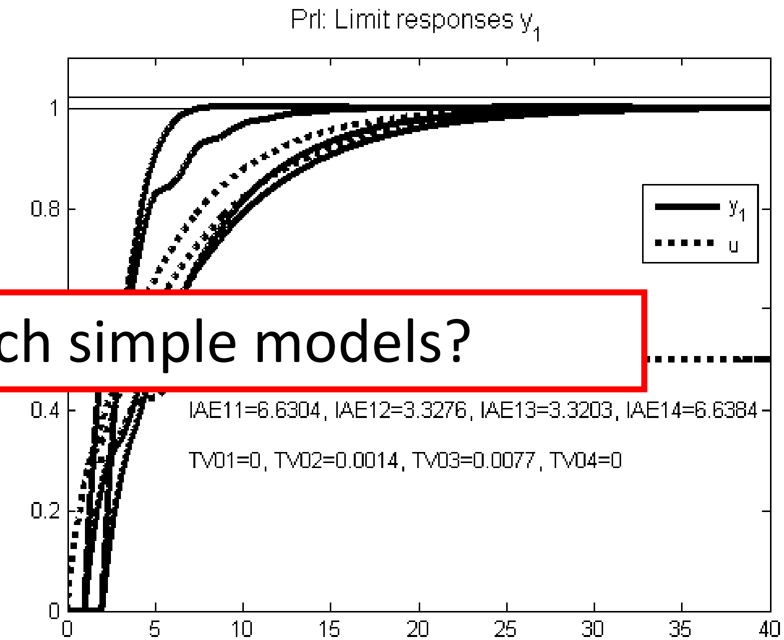
Example: Robust controller tuning

$$S(s) = Ke^{-T_d s} \;;\; K \in \langle K_{\min}, K_{\max} \rangle; \; T_d \in \langle T_{d\min}, T_{d\max} \rangle$$

- PP of FPrI$_0$ controller

$$K_{\min} = 1; K_{\max} = 2; T_{d\min} = 1; T_{d\max} = 2$$





Has it sense to deal with such simple models?

Sweeping Optimal Uncertainty Box UB in 3D

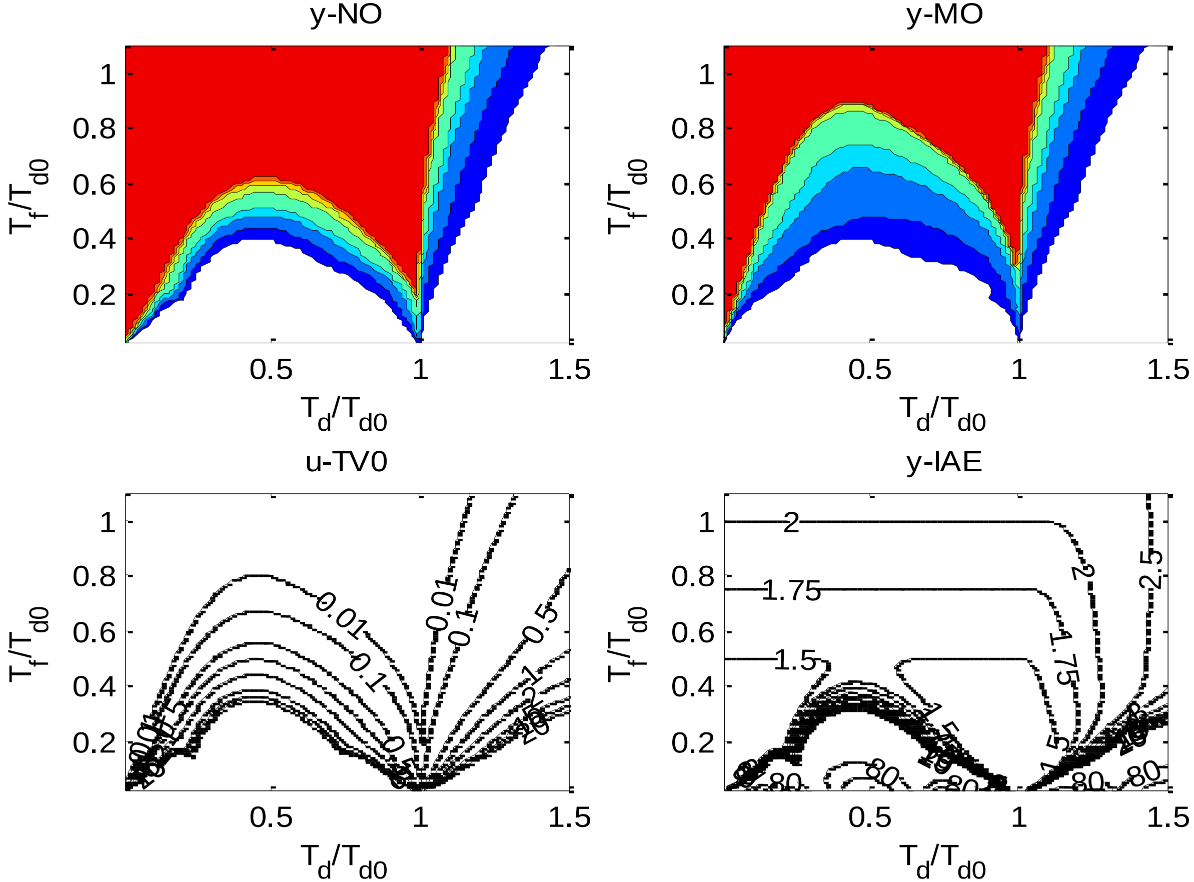
- Question – how to choose parameter grid – computation time/information size versus tuning precision, possibility to skip optimal position
- Problem – visualization of the process in 3D and higher order spaces (high number of necessary sections)
- Note – critical tuning corresponds always to $\kappa_{min}=K_0/K_{max}$
- Possibility – to make the tuning analysis in 2D

PrI_0-Controllers – Analysis in 2D

- Simplification by specifying some loop parameters to fixed values
- Decreased computation time
- Simpler visualization
- Characteristics for particular uncertainties (sensitivity to dead time uncertainty, or to gain uncertainty)
- Subsequent loop analysis

$FPrI_0$: PP in 2D

Performance Portrait (PP) in 2D - fixed $K=K_0$



Sensitivity to the Dead Time Uncertainty in 2D

Single uncertain (interval) loop parameter T_d

Fixed K_0=$K_{\max}$, or simplified situation with K_{min}=K_{max}

$$c_K = K_{\max} / K_{\min} = 1\,;$$
$$T_d \in \langle T_{d\min}, T_{d\max} \rangle\,; \quad c_d = T_{d\max} / T_{d\min} \geq 1\,;$$

Horizontal *ULS* in the plane (τ_d, τ_f) - section of 3D space (κ,τ_d,τ_f) corresponding to κ=1

FPrI$_0$ - ULS_d - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f), ε=0.00001&c_d=3

$$ULS_\kappa = \left[\tau_{d\,\min}, \tau_f \quad \tau_{d\,\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ \tau_d = \frac{T_d}{T_{d0}};\ \tau_f = \frac{T_f}{T_{d0}};\ c_d = \frac{T_{d\,\max}}{T_{d\,\min}} = 3$$

Red

ε=0.00001

ε=0.0001

ε=0.001

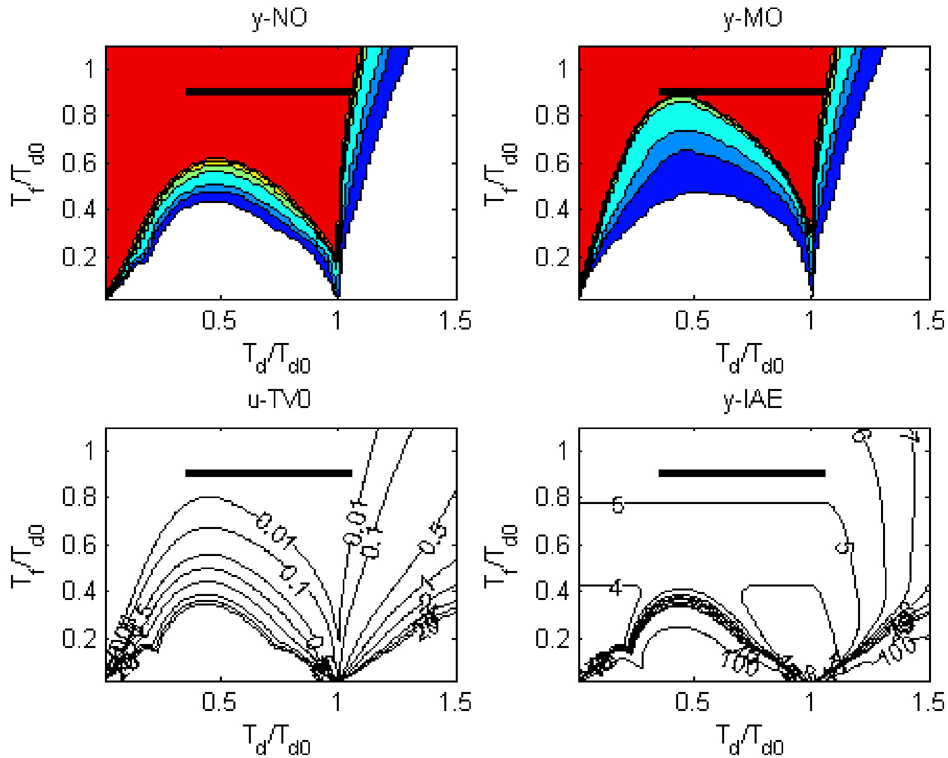
ε=0.01

ε=0.02

ε=0.05

ε=0.1

Dark blue

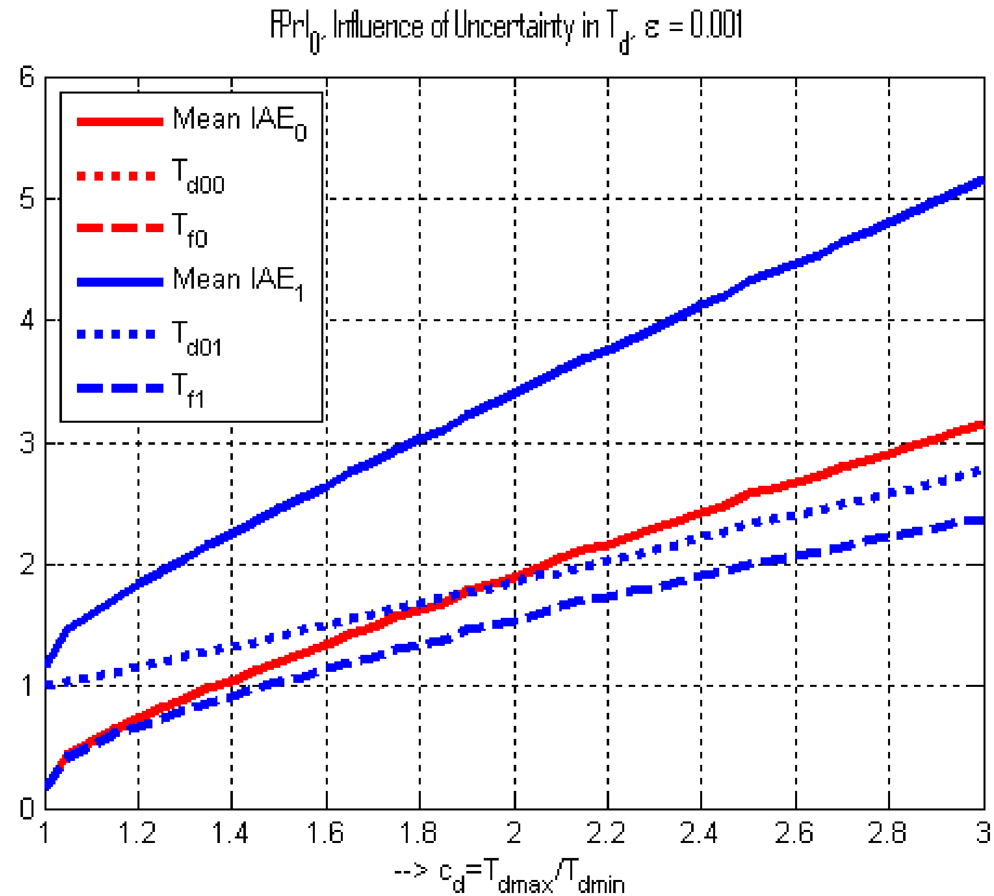


Sensitivity to the Dead Time Uncertainty in 2D

Identified from the Performance Portrait in 2D, 200x200 points

Ideally, IAE_0 should start at 0 and IAE_1 at 1.

This, however, requires to compute the PP over grid of points ∞x∞



PrI$_0$ - ULS_d - Uncertainty in T_d

Nominal tuning for T_f/T_{d0}=11.88 & c_d=1 & ε=0.001

Red

ε=0.00001

ε=0.0001

ε=0.001

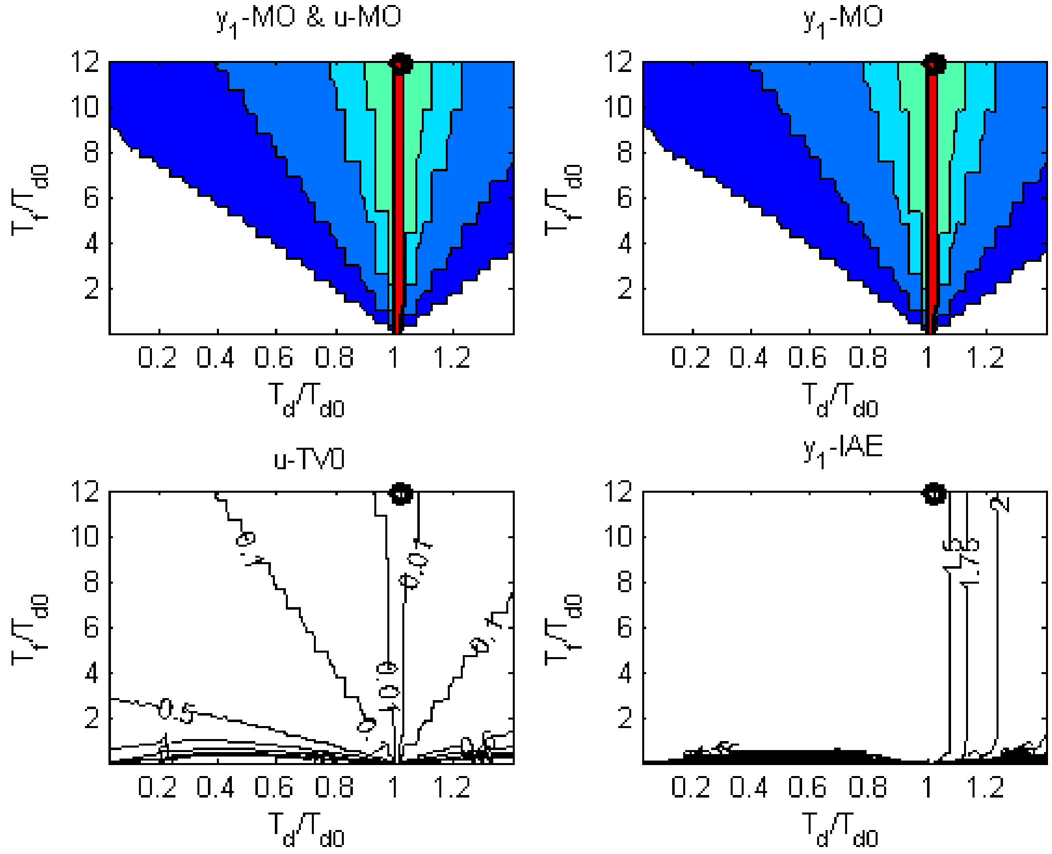
ε=0.01

ε=0.02

ε=0.05

ε=0.1

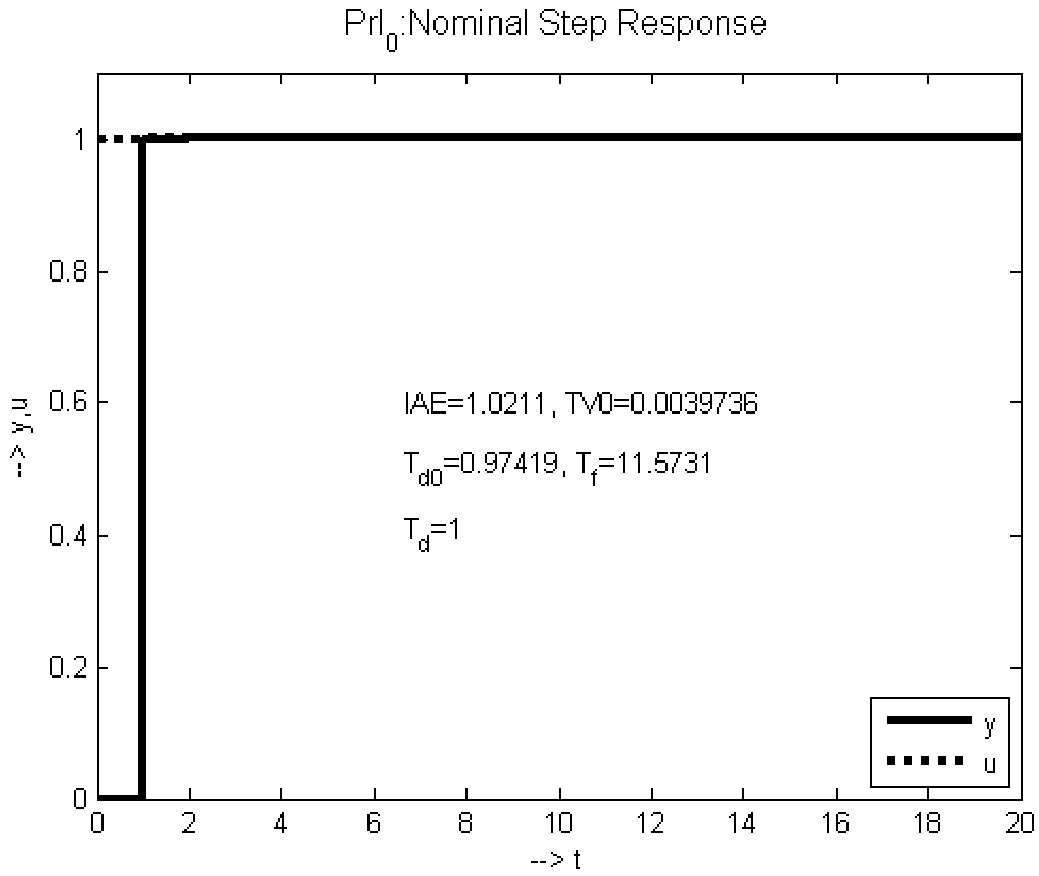
Dark blue



PrI_0 - ULS_d - Uncertainty in T_d

Nominal step response corresponding to T_f/T_{d0}=11.88 & c_d=1

PrI$_0$ is a fundamental solution, i.e. without considering nonmodelled dynamics the transients may approach step responses both at the plant input and output



PrI_0 - ULS_d - Uncertainty in T_d

ULS corresponding to $T_f/T_{d0}=11.88$ & $c_d=3$ & $\varepsilon=0.05$

Red

ε=0.00001

ε=0.0001

ε=0.001

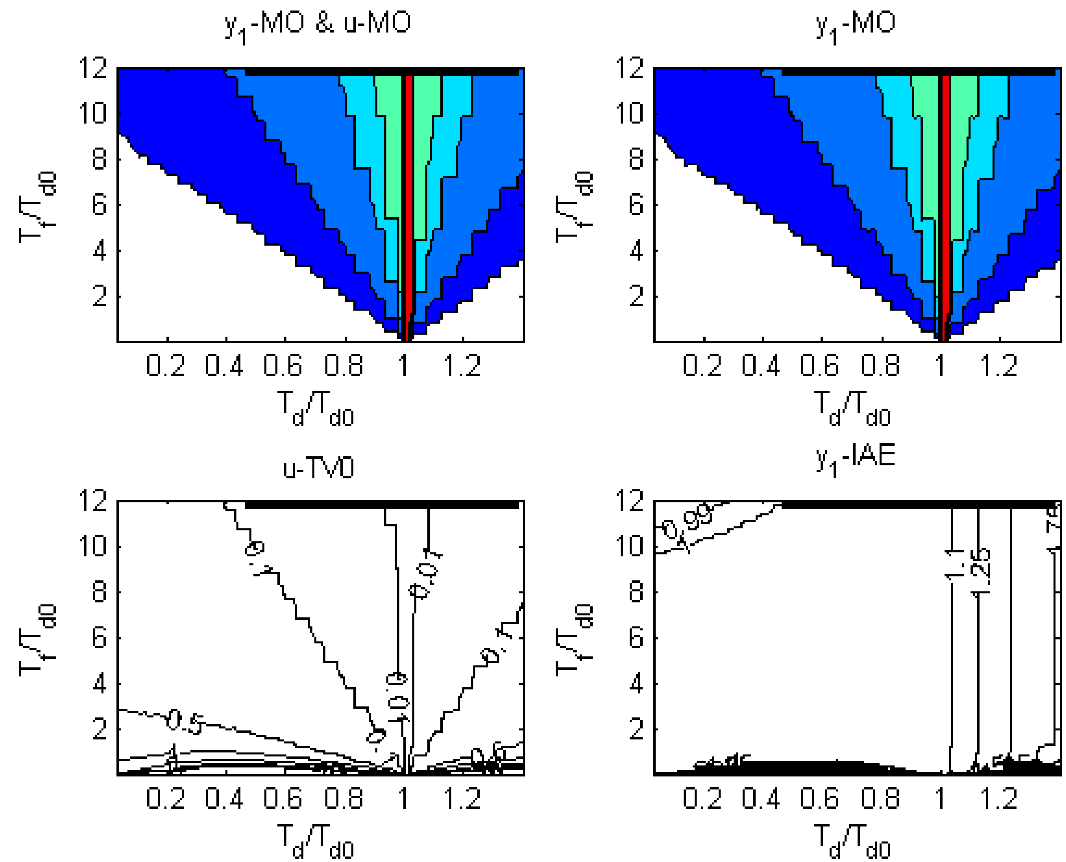
ε=0.01

ε=0.02

ε=0.05

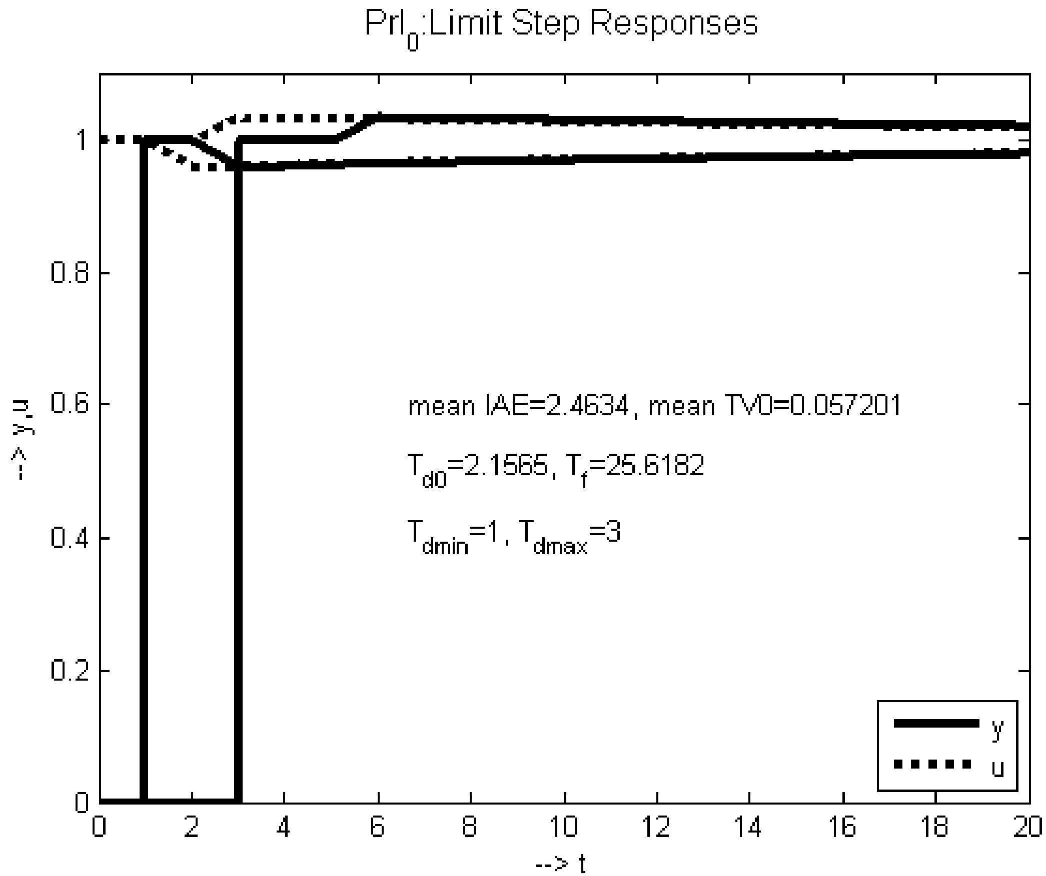
ε=0.1

Dark blue



Limit step responses corresponding to T_f/T_{d0}=11.88 & c_d=3

By choosing sufficiently large T_f/T_{d0} it is possible to achieve arbitrarily low TV0 values, however, on cost of a sluggish disturbance response



PrI0 - ULSd - Uncertainty in Td

Nominal tuning corresponding to T_f/T_{d0}=5.2 & c_d=1

Red

ε=0.00001

ε=0.0001

ε=0.001

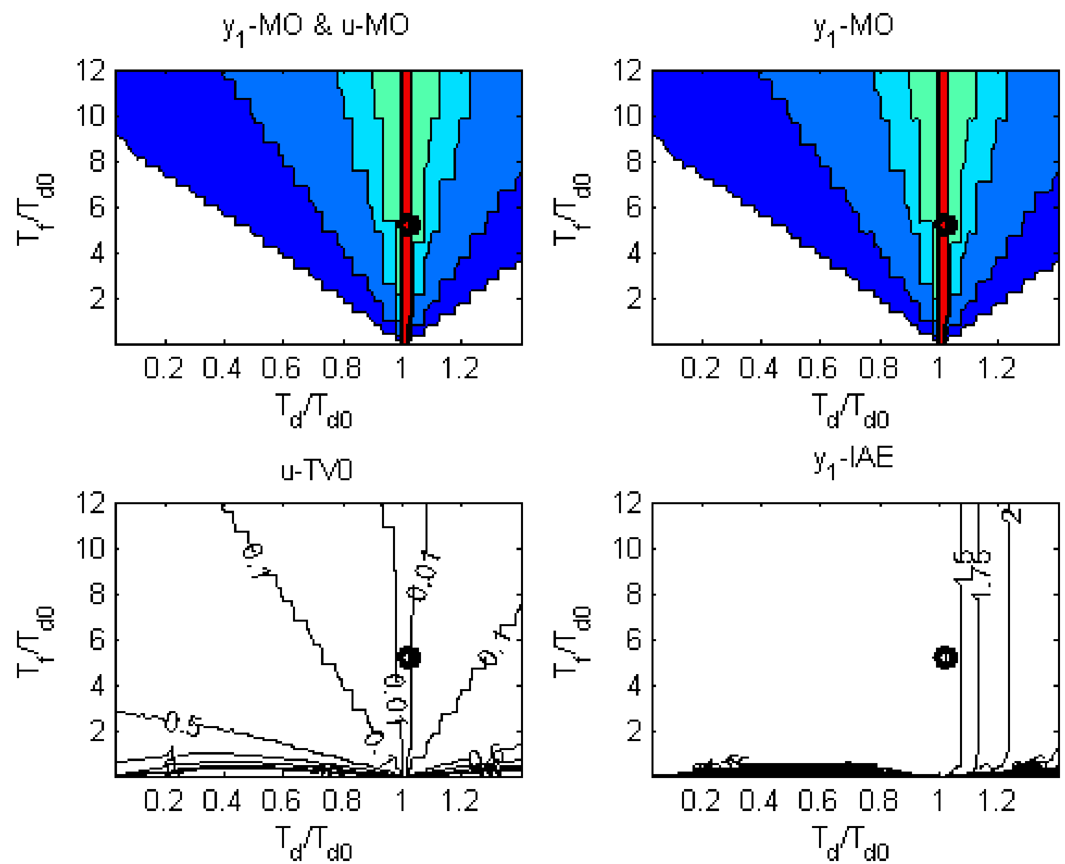
ε=0.01

ε=0.02

ε=0.05

ε=0.1

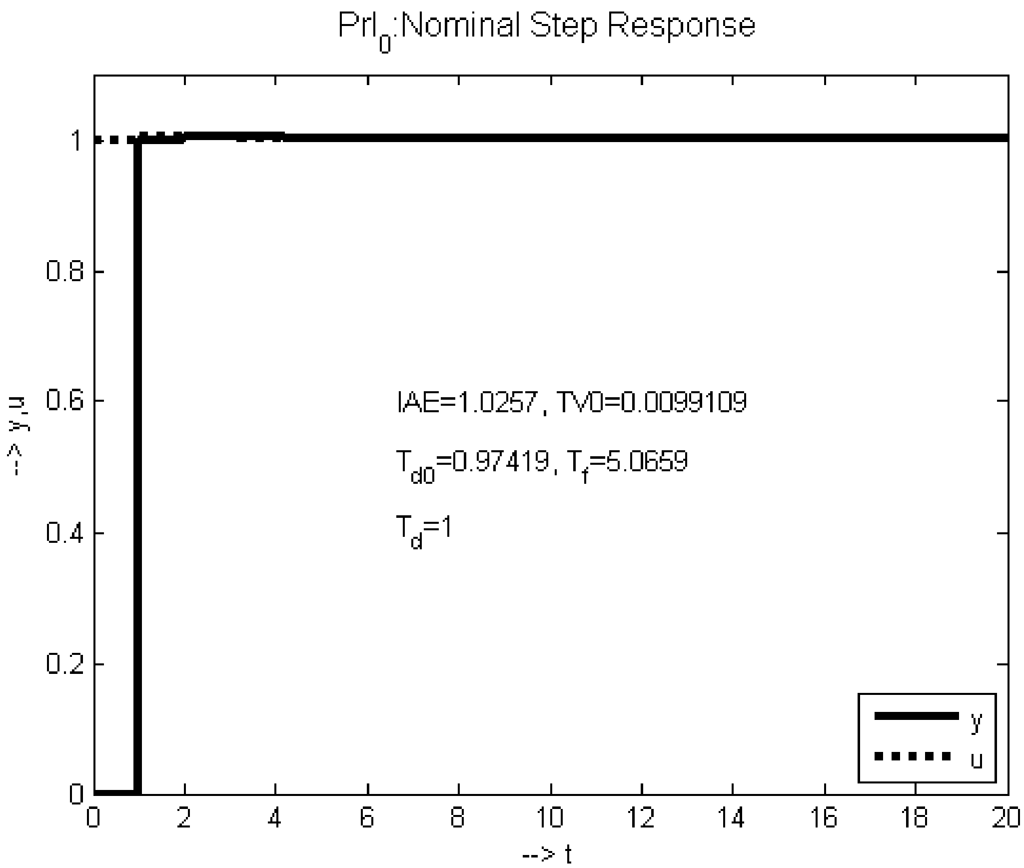
Dark blue



PrI_0 - ULS_d - Uncertainty in T_d

Nominal step response corresponding to $T_f/T_{d0}=5.2$ & $c_d=1$

PrI_0 is a fundamental solution, i.e. without considering nonmodelled dynamics the transients may approach step responses both at the plant input and output



PrI_0 - ULS_d - Uncertainty in T_d

ULS corresponding to $T_f/T_{d0}=5.2$ & $c_d=3$ & $\varepsilon=0.1$

Red

ε=0.00001

ε=0.0001

ε=0.001

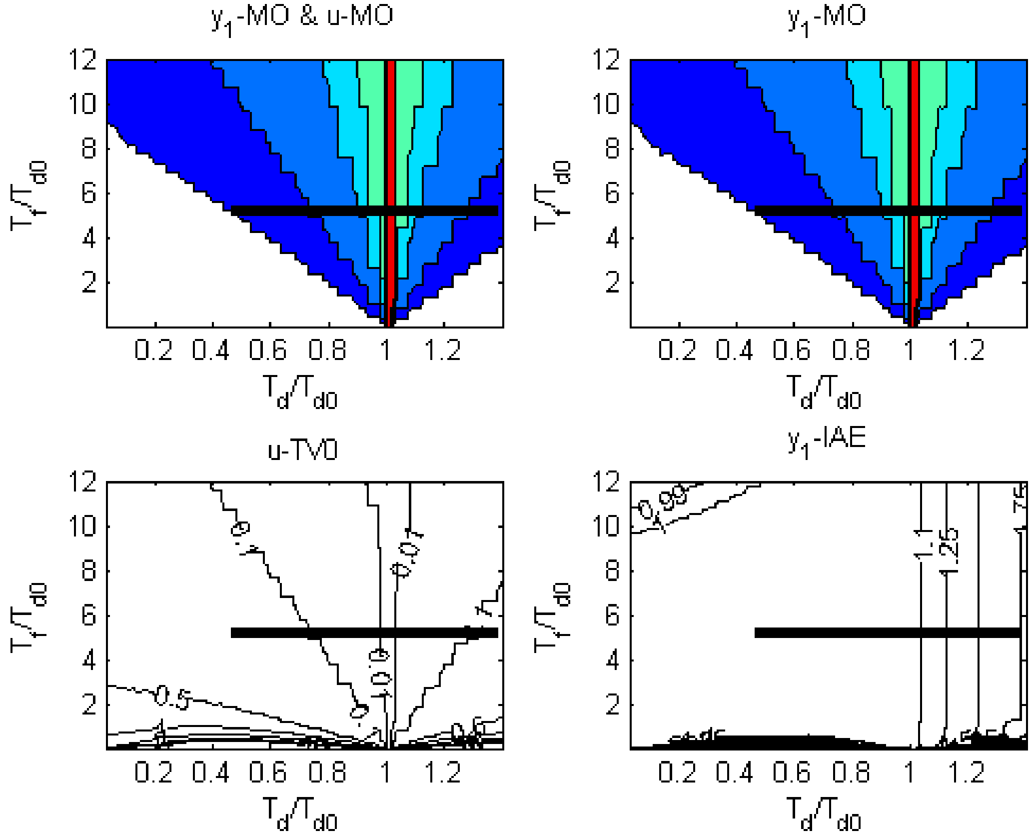
ε=0.01

ε=0.02

ε=0.05

ε=0.1

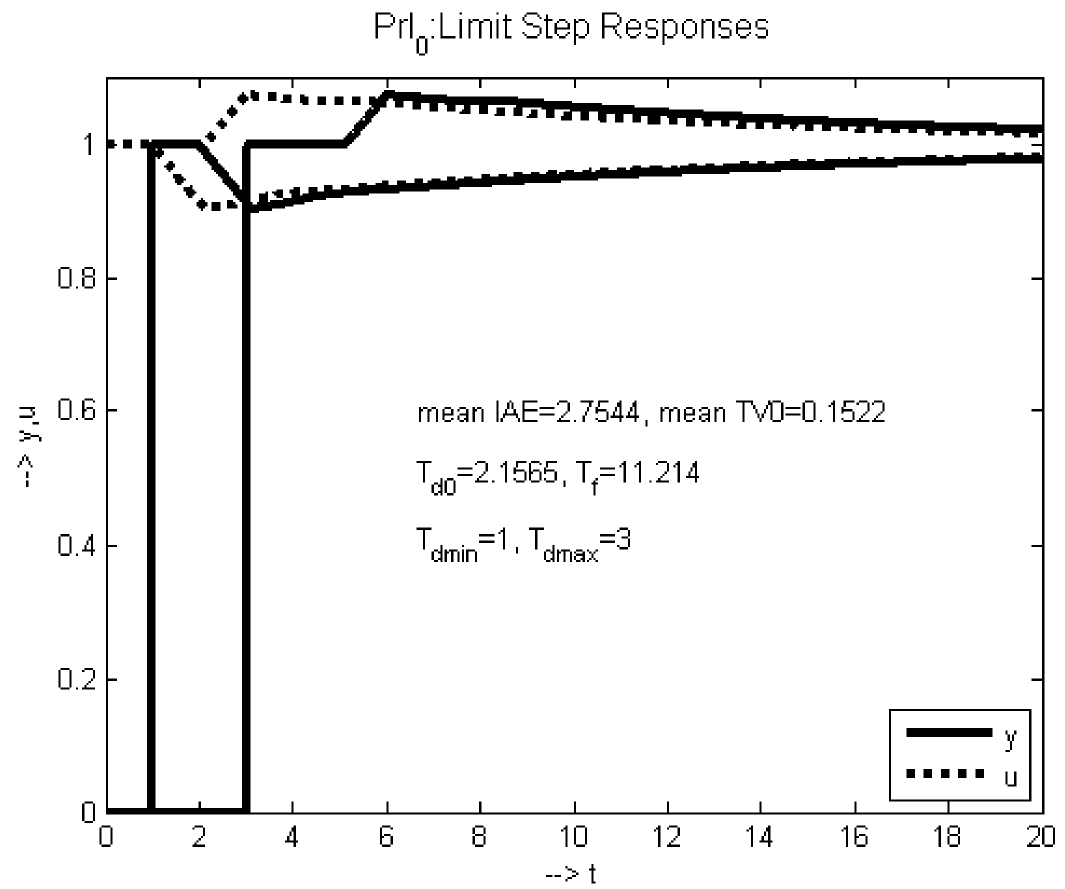
Dark blue



PrI_0 - ULS_d - Uncertainty in T_d

Limit step responses corresponding to $T_f/T_{d0}=5.2$ & $c_d=3$

By choosing smaler T_f/T_{d0} it is possible to achieve good nominal tuning and relatively fast disturbance response, however, the robustness will be poorer



Example SP - Uncertainty in T_d

Normey-Rico, J.E., Camacho, E.F.: Control of Dead-time Processes. Springer, London, 2007, Example 5.6, pp.144-145

Smith Predictor for plant approximated by FOPDT model

$$S(s)=\frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)}=\frac{e^{-Ls}}{A(s)}$$

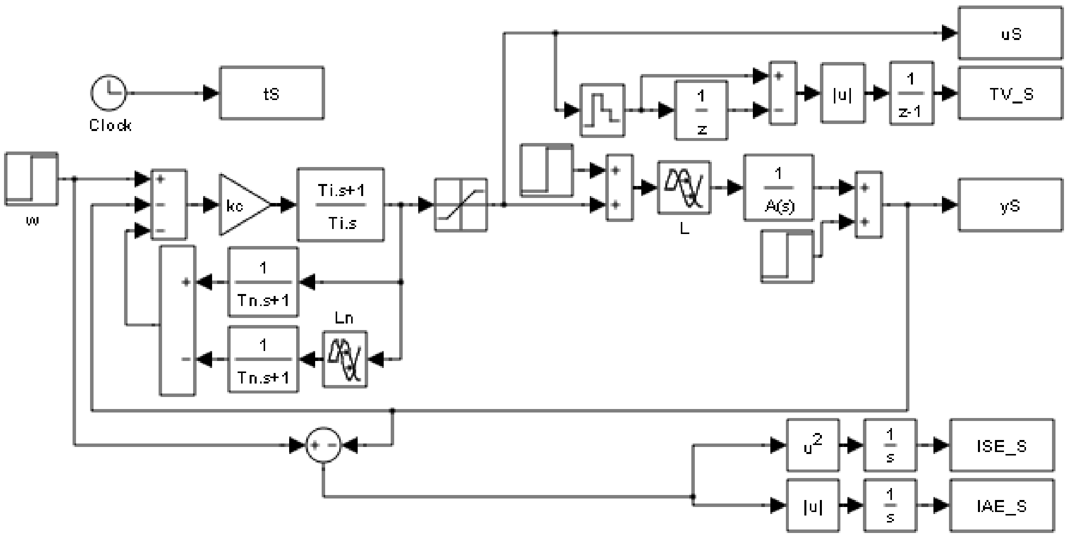
$$T_1=1;\ T_2=0.5;\ T_3=0.25;\ T_4=0.125;\ \ L\in\langle 8,12\rangle\ ;\ \ L_0=10$$

Ad-hoc tuning

$$T_n=T_1+T_2=1.5;$$

$$T_i=T_n;\ k_c=1;$$

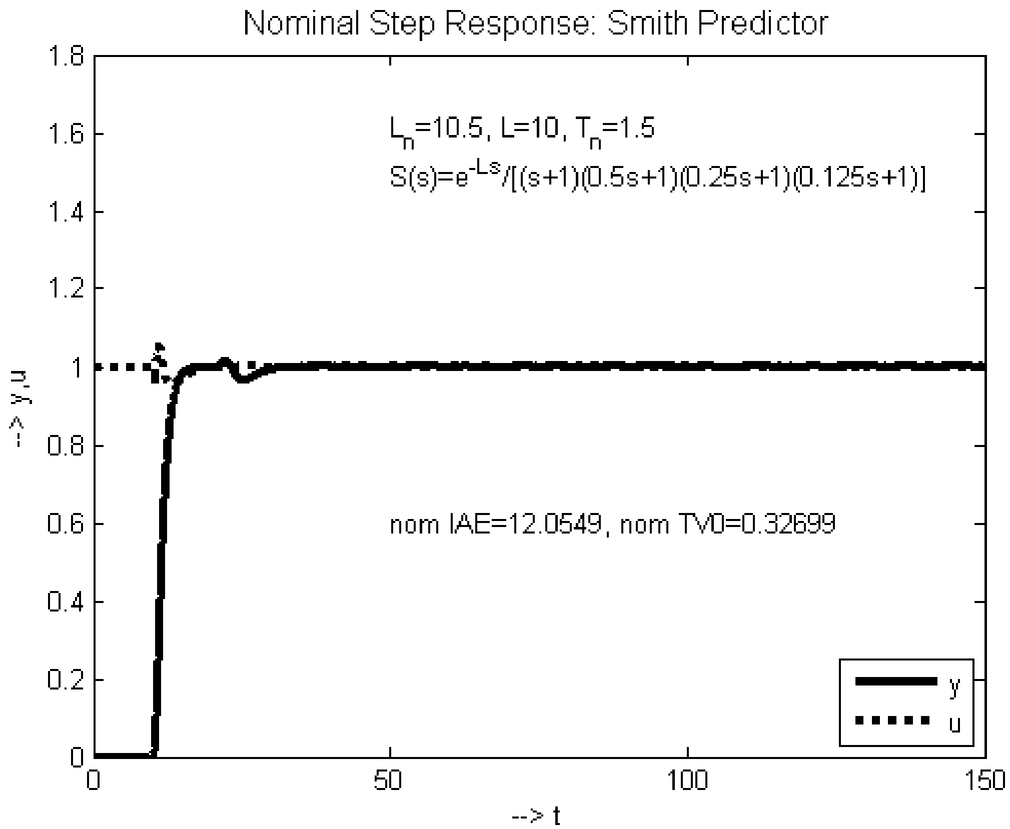
$$L_n=10.5>L_0+T_3+T_4$$



Example SP - Uncertainty in T_d

NR & Camacho, 2007, Example 5.6, pp.144-145

Nominal Responses of DC0



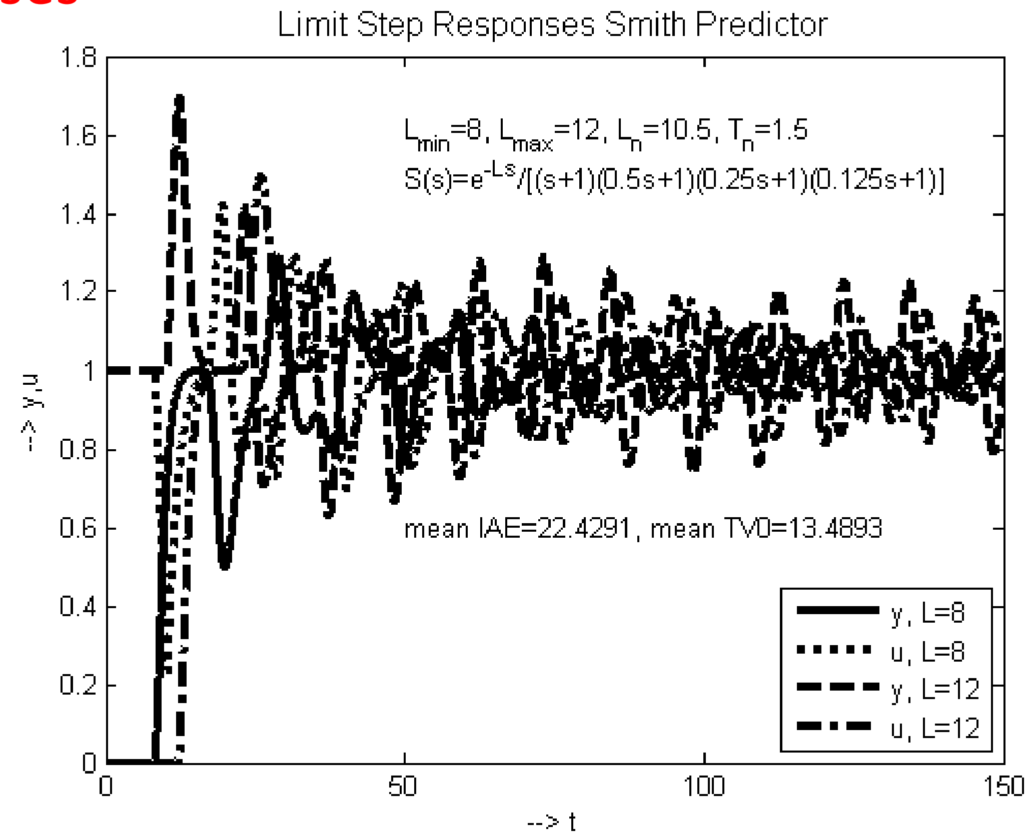
Example SP - Uncertainty in T_d

NR & Camacho, 2007, Example 5.6, pp.144-145

Badly damped Limit Responses

Reasonably large
TV0=13,48

Both IAE and TV
still increasing



Example SP - Uncertainty in T_d

- As it is obvious from above simulations, SP is very sensitive to the dead time uncertainty
- Filtered Smith Predictor (NR-Camacho, 2007) basic possibility to decrease the loop sensitivity
- Results achieved by NR-Camacho will be compared with those achieved with the PrI_0 controllers tuned using the Performance Portrait (PP)

Example FSP - Uncertainty in T_d

Normey-Rico, Camacho, 2007, Example 6.1, pp.166-169

Filtered Smith Predictor + PI controller - slower disturbance response due to the filter

$$S(s) = \frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)} = \frac{e^{-Ls}}{A(s)}$$

$$T_1 = 1;\ T_2 = 0.5;\ T_3 = 0.25;\ T_4 = 0.125;\ \ L \in \langle 8, 12 \rangle\ ;\ \ L_0 = 10$$

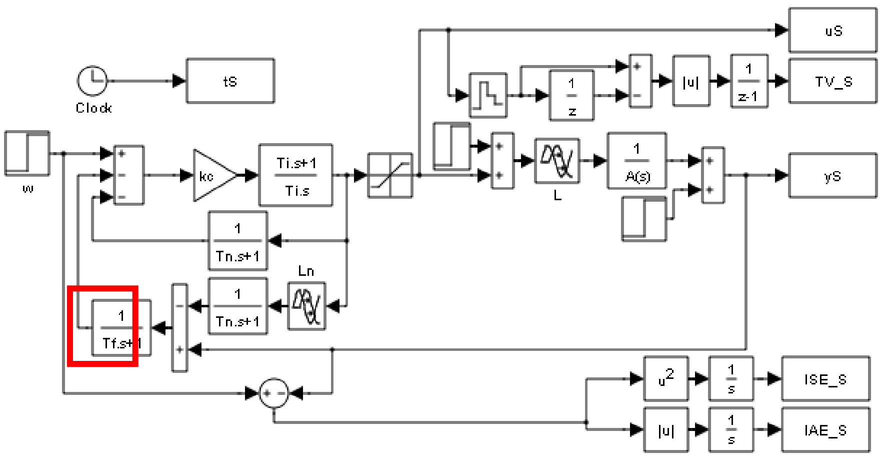
Ad-hoc tuning

$$T_n = T_1 + T_2 = 1.5;$$

$$T_i = T_n;\ k_c = 1;$$

$$L_n = 10.5 > L_0 + T_3 + T_4$$

$$T_f = L_n / 2$$

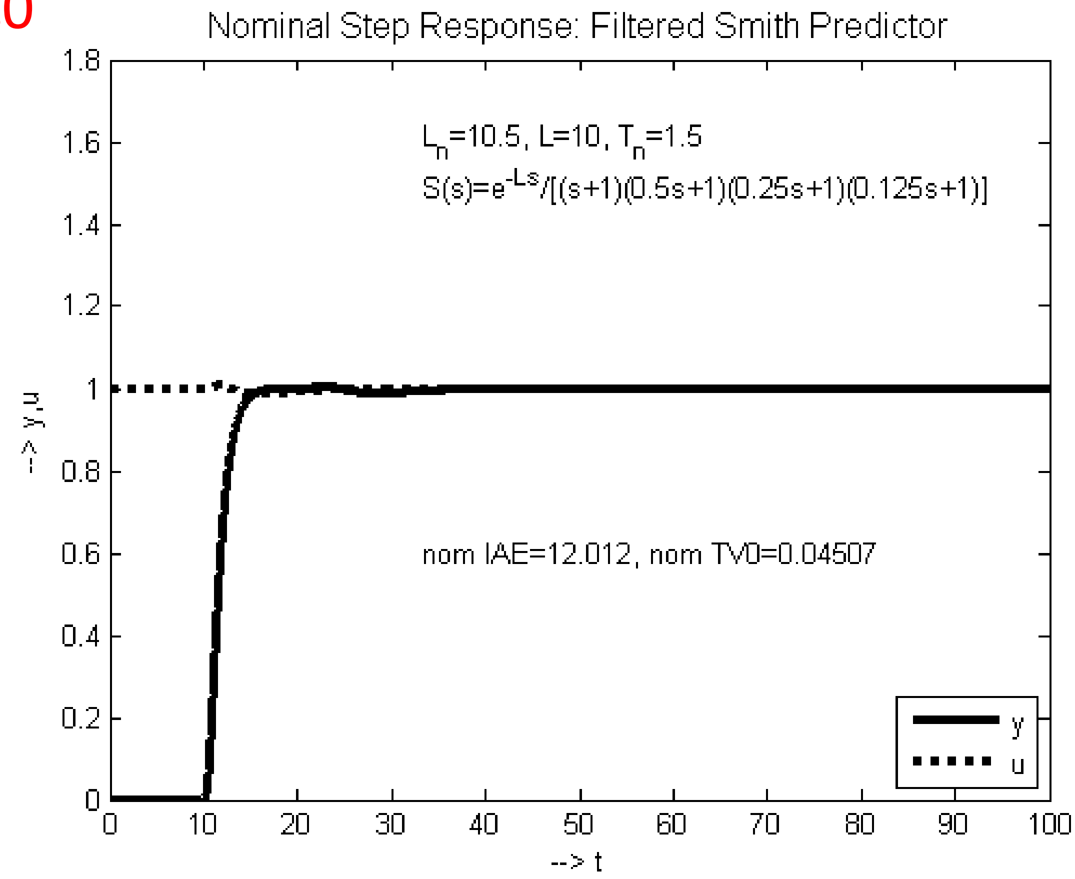


Example FSP - Uncertainty in T_d

Normey-Rico, Camacho, 2007, Example 6.1, pp.166-169

Nominal Responses of DC0

Scheme may be shown to be equivalent to the static feedforward control with disturbance reconstruction & compensation based on the parallel model (IMC like structure)



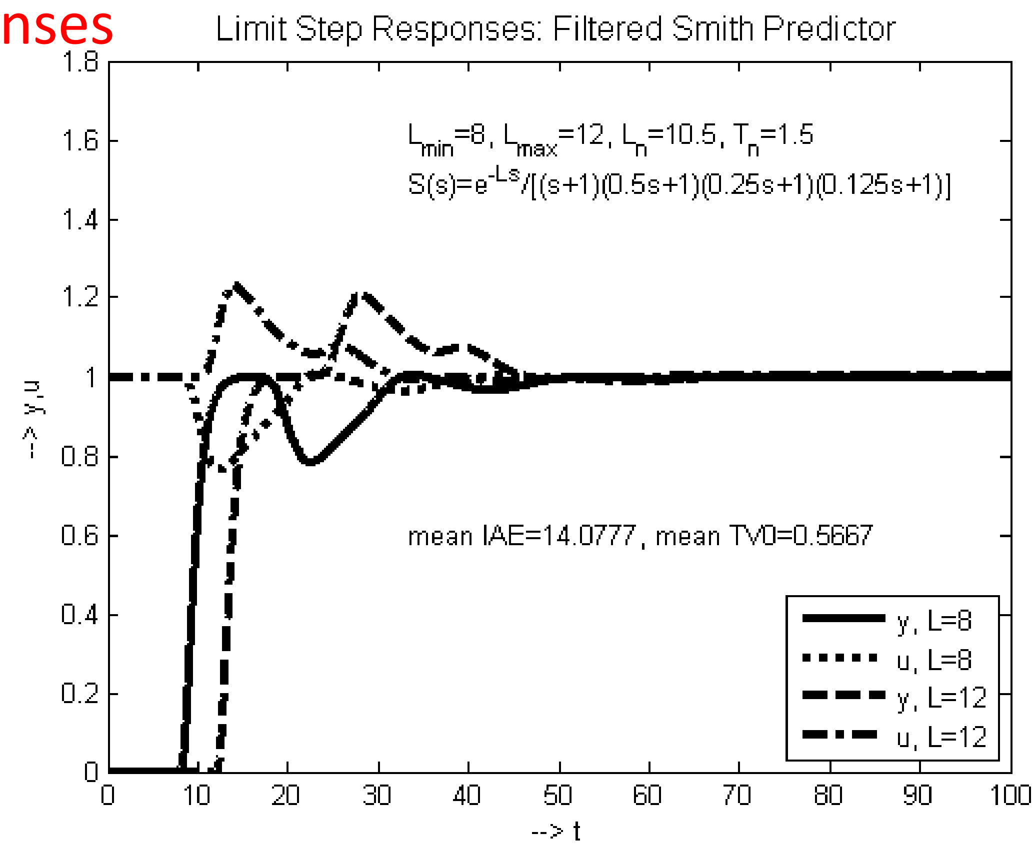
Example FSP - Uncertainty in T_d

Normey-Rico, Camacho, 2007, Example 6.1, pp.166-169

Well damped Limit Responses

More than 20% overshooting

Both IAE and TV are close to the nominal values



Example FPPI - Uncertainty in T_d

Normey-Rico, Camacho, 2007, Example 6.1, pp.166-169

Filtered Predictive PI Controller - plant approximated by FOPDT model – filters for setpoint and disturbance responses

$$S(s) = \frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)} = \frac{e^{-Ls}}{A(s)}$$

$$T_1 = 1;\ T_2 = 0.5;\ T_3 = 0.25;\ T_4 = 0.125;\ \ L \in \langle 8,12 \rangle\ ;\ \ L_0 = 10$$

Ad-hoc tuning

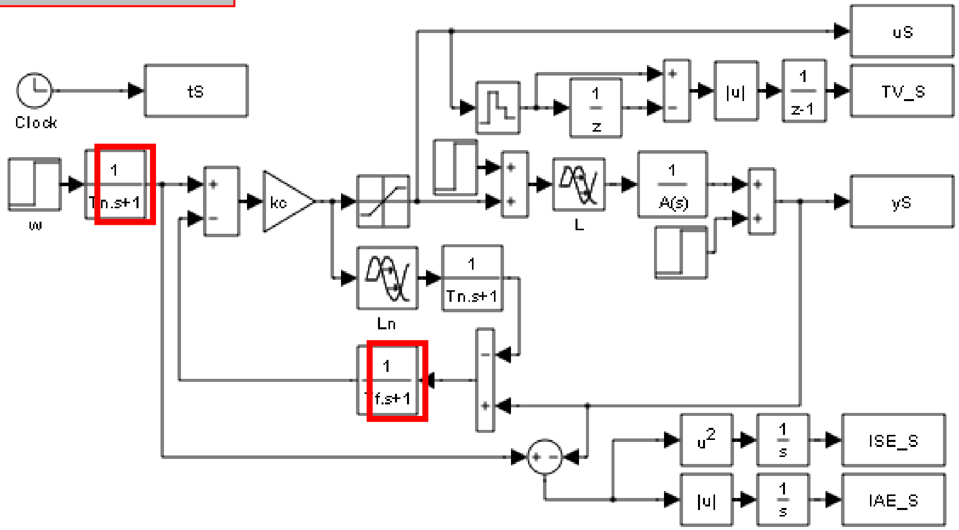
$$T_n = T_1 + T_2 = 1.5;$$

$$T_i = T_n;\ k_c = 1;$$

$$L_n = 10.5 > L_0 + T_3 + T_4$$

$$T_f = L_n / 2$$

$$T_p = T_n$$



Example FPPI - Uncertainty in T_d

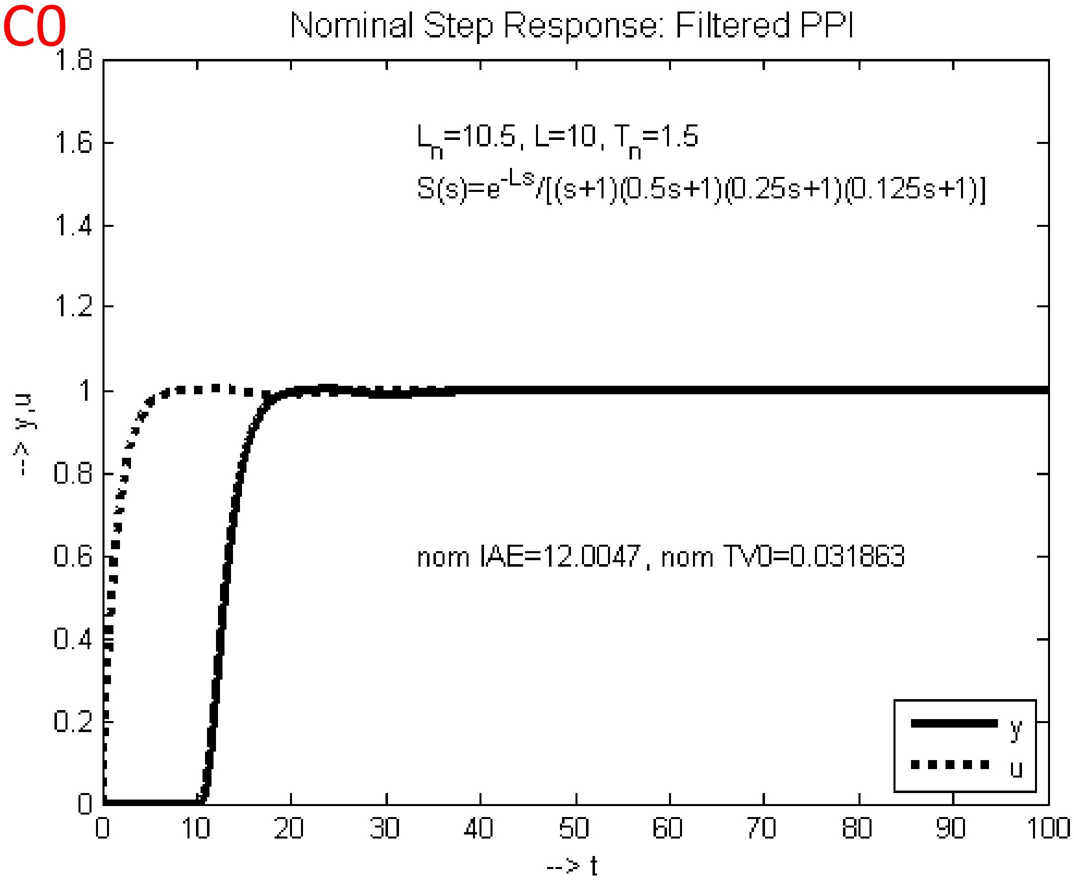
Normey-Rico, Camacho, 2007, Example 6.1, pp.166-169

Nominal Responses of DC0

Improved TV0=0,03

and

IAE=12.00



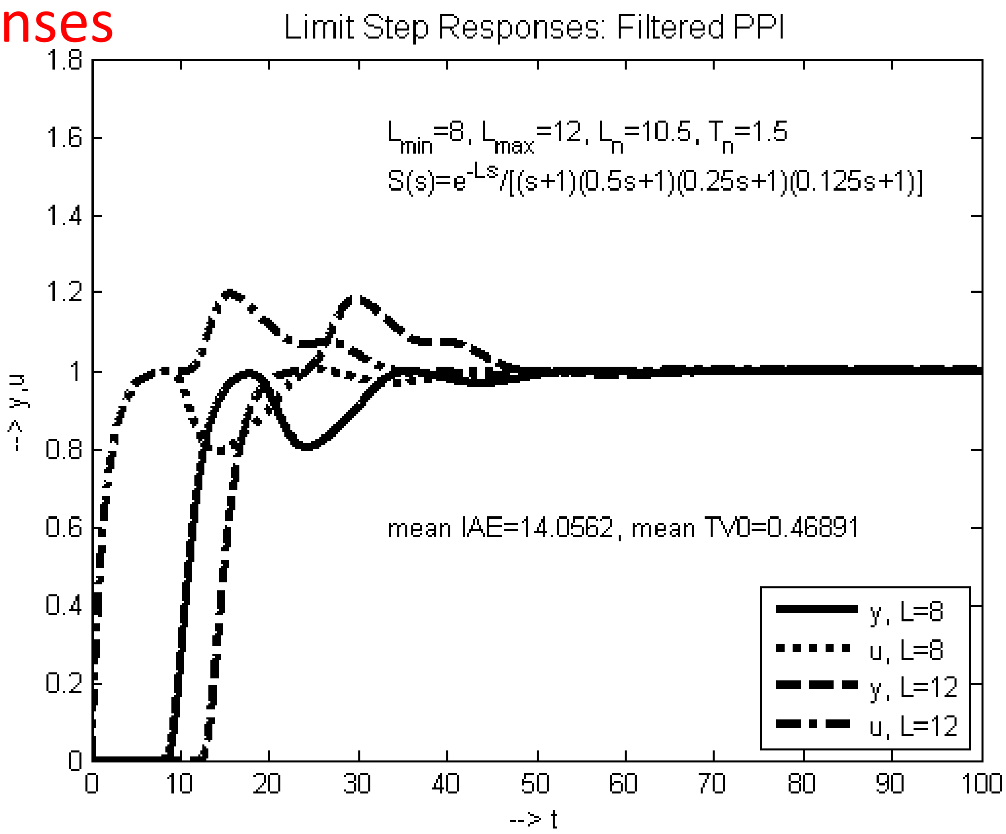
Example FPPI - Uncertainty in T_d

Normey-Rico, Camacho, 2007, Example 6.1, pp.166-169

Well damped Limit Responses

More than 20% overshooting

Slightly improved IAE and TV values



Conclusions - Uncertainty in T_d

SP, FSP, PPI and FPPI give good nominal responses, but

- Limit Responses for uncertainty in T_d have also after introducing filters over/undershooting over 20%
- Structures of these controllers may be OK, but we should have some tools to find controller tuning satisfying given requirements – and this gives the method based on Performance Portrait
- Next we will show, how this method can be used in tuning PrI_0 and $FPrI_0$ controller

Example FPrI$_0$ - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f) – ε=0.00001

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ \tau_d = \frac{T_d}{T_{d0}} = \frac{L+1.875}{L_0+1.875};\ \tau_f = \frac{T_f}{T_{d0}}$$

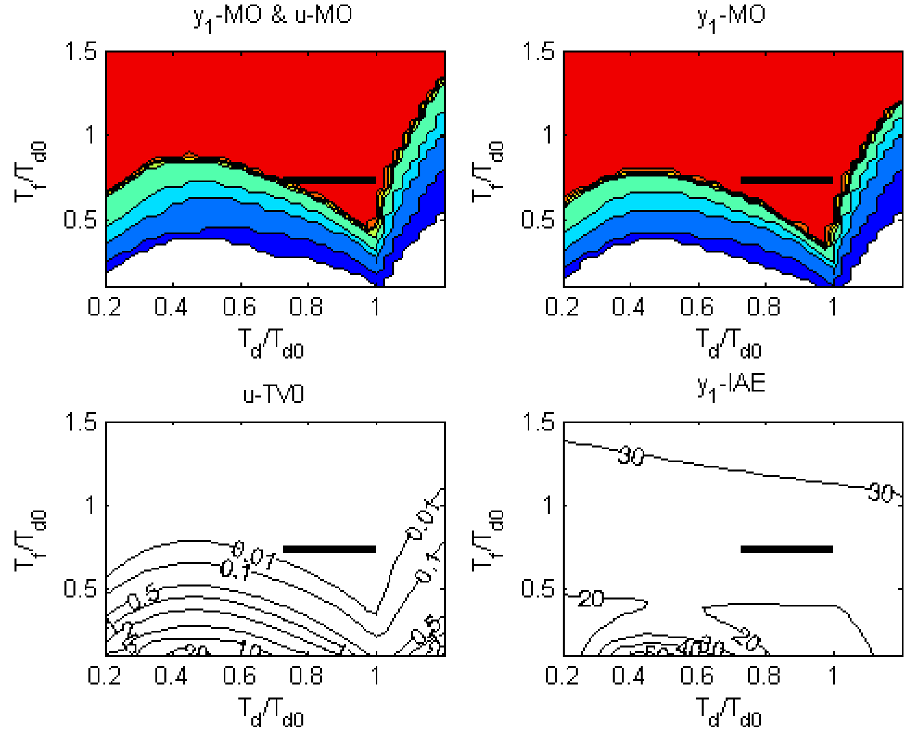
4th order + dead time system

$$S(s) = \frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)}$$

$$T_1 = 1;\ T_2 = 0.5;\ T_3 = 0.25;\ T_4 = 0.125$$

$$\sum T_i = 1.875$$

$$L \in \langle 8, 12 \rangle$$



Example FPrI$_0$ - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f) – ε=0.00001

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right]; \;\; \kappa = \frac{K_0}{K} = 1; \;\; \tau_d = \frac{T_d}{T_{d0}} = \frac{L+1.875}{L_0+1.875}\,; \;\; \tau_f = \frac{T_f}{T_{d0}}$$

Red

ε=0.00001

ε=0.0001

ε=0.001

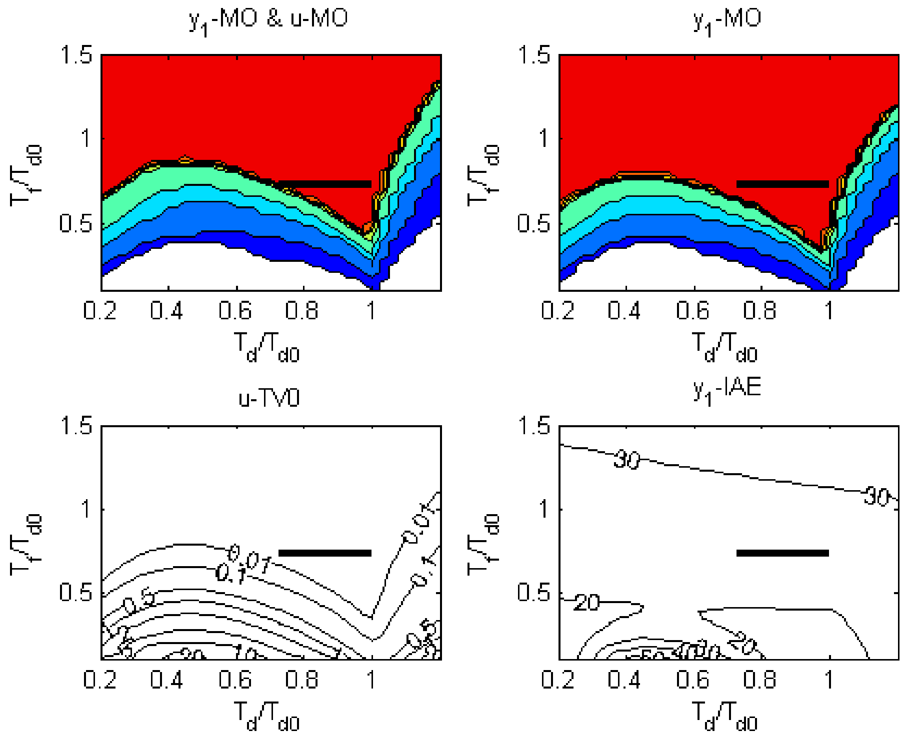
ε=0.01

ε=0.02

ε=0.05

ε=0.1

Dark blue



Example FPrI$_0$ - Uncertainty in T_d

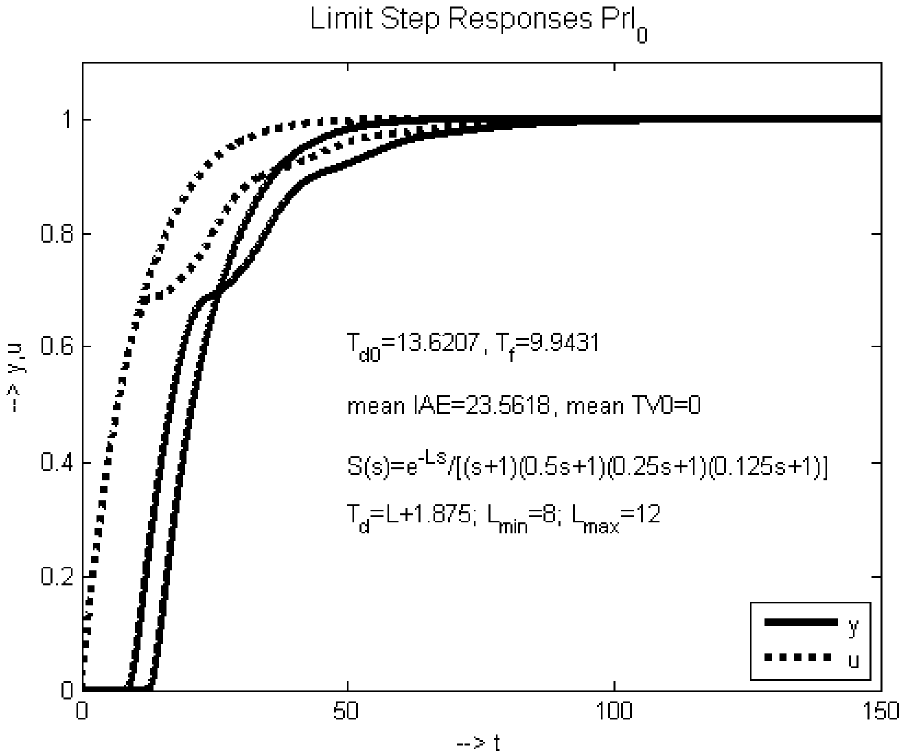
Uncertainty Line Segment in the plane (τ_d,τ_f) – ε=0.00001

$$ULS_d = [\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f]; \ \kappa = \frac{K_0}{K} = 1; \ L \in \langle 8{,}12 \rangle \ ; \ \tau_d = \frac{L + 1.875}{L_0 + 1.875} \ ; \ \tau_f = \frac{T_f}{T_{d0}}$$

IAE=23.56

TV0=0

Low overshooting and TV0 paid by high IAE value



Example FPrI$_0$ - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f) – ε=0.05

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ \tau_d = \frac{T_d}{T_{d0}} = \frac{L+1.875}{L_0+1.875};\ \tau_f = \frac{T_f}{T_{d0}}$$

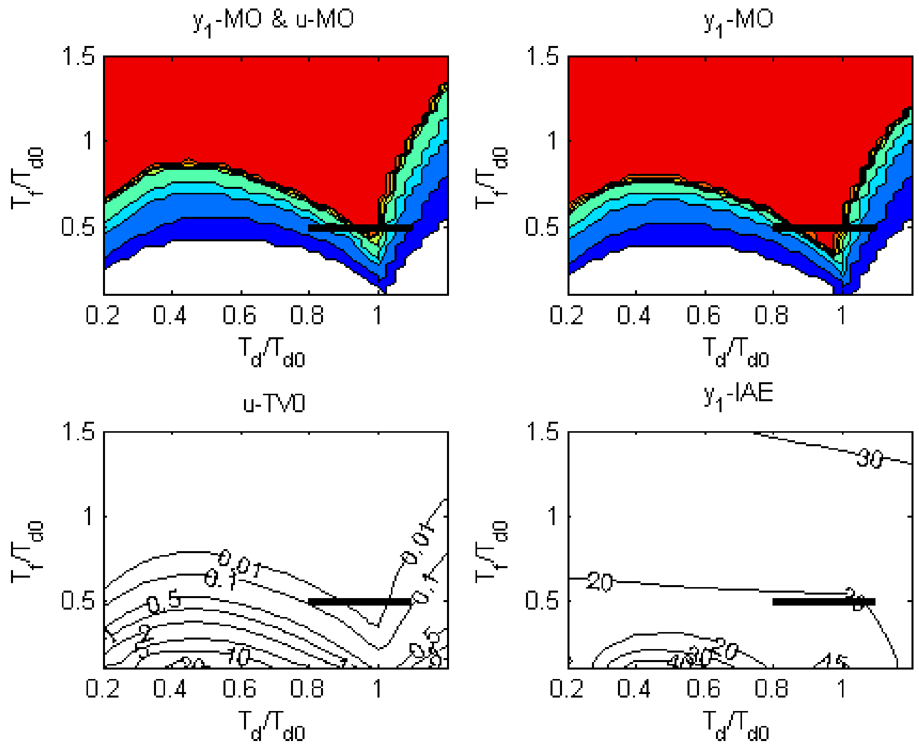
4th order + dead time system

$$S(s) = \frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)}$$

$$T_1 = 1;\ T_2 = 0.5;\ T_3 = 0.25;\ T_4 = 0.125$$

$$\sum T_i = 1.875$$

$$L \in \langle 8,12 \rangle$$



Example FPrI$_0$ - Uncertainty in T_d

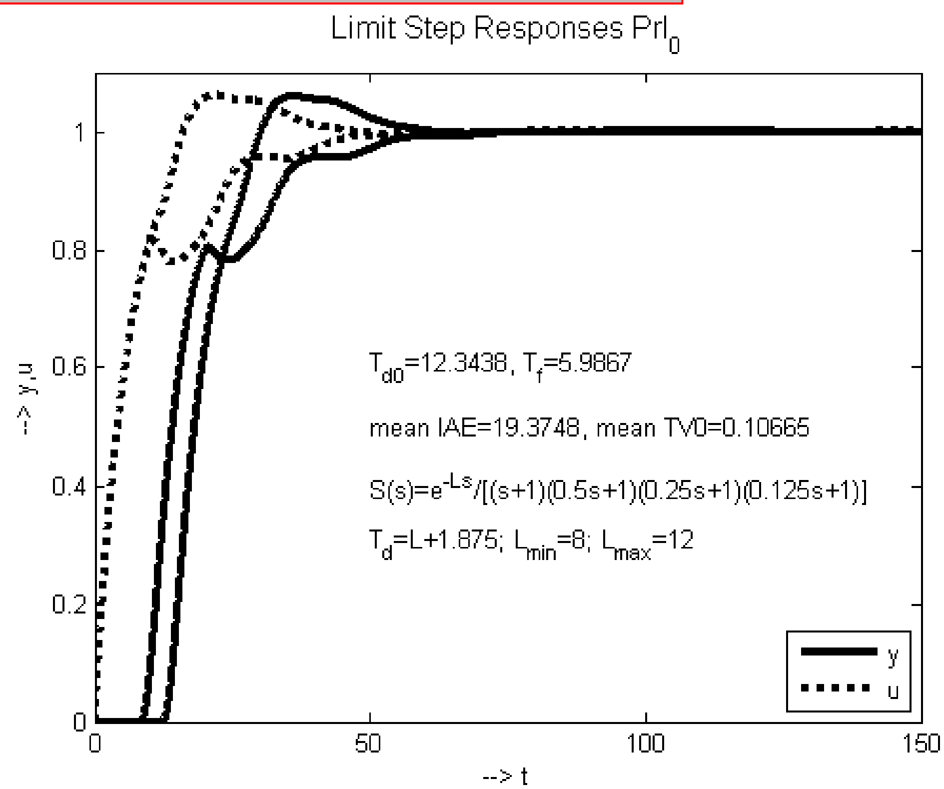
Uncertainty Line Segment in the plane (τ_d,τ_f) – ε=0.05

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ L \in \langle 8{,}12 \rangle\ ;\ \tau_d = \frac{L + 1.875}{L_0 + 1.875}\ ;\ \tau_f = \frac{T_f}{T_{d0}}$$

IAE=19.37

TV0=0.11

Lower T_f=5.99 ***value instead of T_f=9.94 guarantees also faster disturbance response***



Example PrI$_0$ - Uncertainty in T_d

Nominal tuning in the plane (τ_d,τ_f) – L=10, T_f/T_{d0}=1.13

$$ULS_d=\left[\tau_{d\,\min},\tau_f \quad \tau_{d\,\max},\tau_f\right];\ \kappa=\frac{K_0}{K}=1;\ \tau_d=\frac{T_d}{T_{d0}}=\frac{L+1.875}{L_0+1.875};\ \tau_f=\frac{T_f}{T_{d0}}=1.13$$

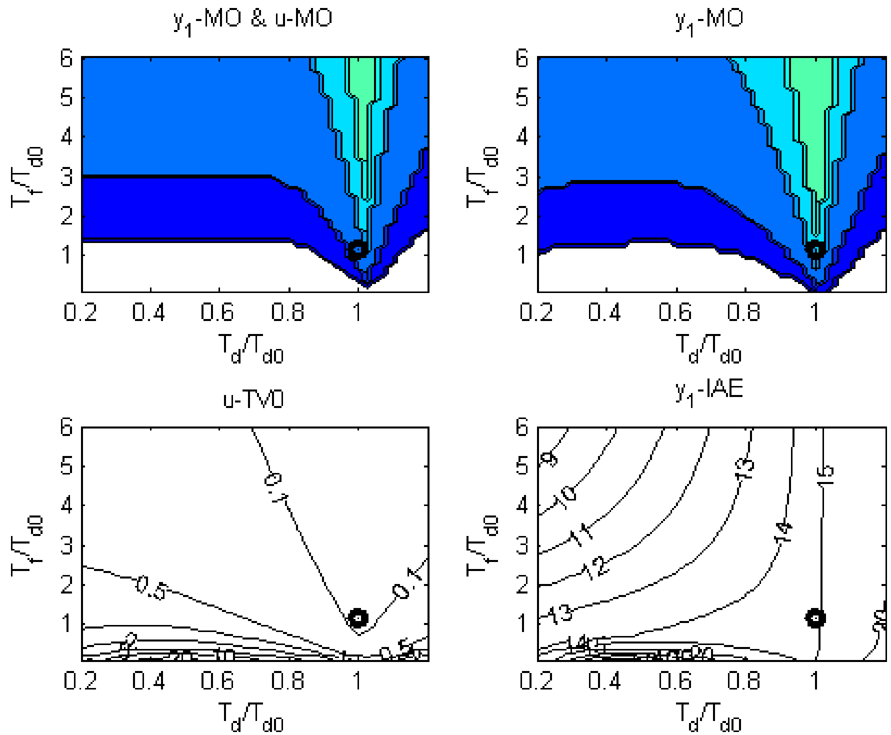
4th order + dead time system

$$S(s)=\frac{e^{-Ls}}{(T_1s+1)(T_2s+1)(T_3s+1)(T_4s+1)}$$

$$T_1=1;\ T_2=0.5;\ T_3=0.25;\ T_4=0.125$$

$$\sum T_i=1.875$$

$$L\in\langle 8,12\rangle$$



Example PrI$_0$ - Uncertainty in T_d

Nominal tuning in the plane (τ_d,τ_f) – L=10, T_f / T_{d0}=1.13

$$ULS_d = \left[\tau_{d\,\min}, \tau_f \quad \tau_{d\,\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ \tau_d = \frac{T_d}{T_{d0}} = \frac{L + 1.875}{L_0 + 1.875};\ \tau_f = \frac{T_f}{T_{d0}} = 1.13$$

Red

ε=0.00001

ε=0.0001

ε=0.001

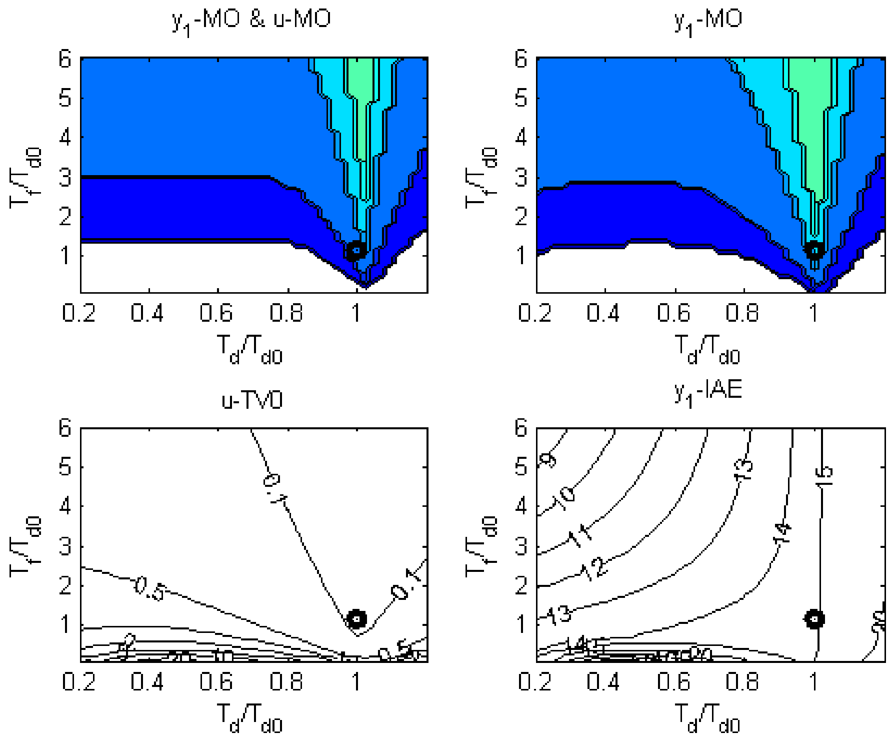
ε=0.01

ε=0.02

ε=0.05

ε=0.1

Dark blue



Example PrI_0 - Uncertainty in T_d

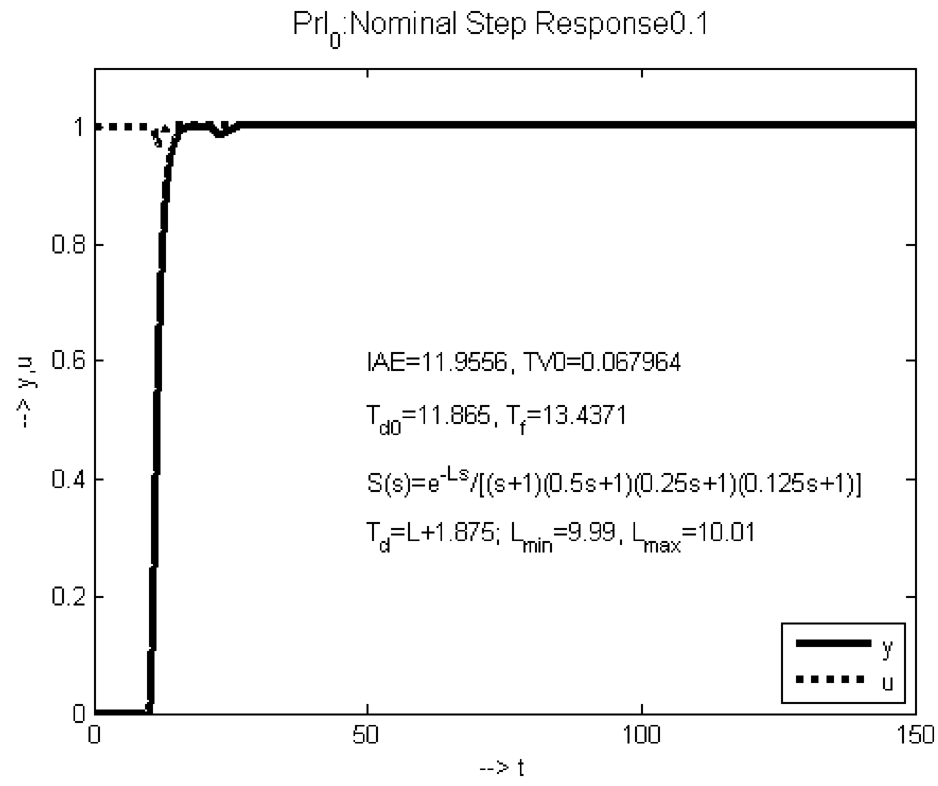
Nominal tuning in the plane (τ_d,τ_f) – L=10, T_f / T_{d0}=1.13

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ L \in \langle 8{,}12 \rangle\ ;\ \tau_d = \frac{L+1.875}{L_0+1.875}\ ;\ \tau_f = \frac{T_f}{T_{d0}} = 1.13$$

IAE=11.96

TV0=0.07

Lowest overshooting, TV0 and IAE values



Uncertainty Line Segment in the plane (τ_d,τ_f) – T_f / T_{d0}=1.28

$$ULS_d = [\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f];\ \kappa = \frac{K_0}{K} = 1;\ \tau_d = \frac{T_d}{T_{d0}} = \frac{L + 1.875}{L_0 + 1.875};\ \tau_f = \frac{T_f}{T_{d0}} = 1.28$$

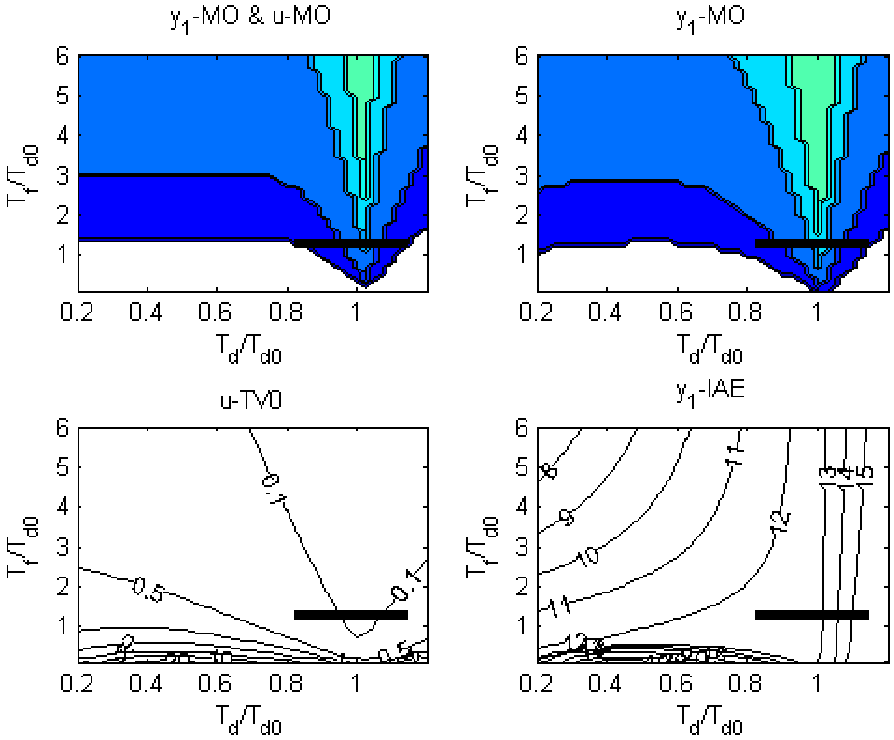
4th order + dead time system

$$S(s) = \frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)}$$

$$T_1 = 1;\ T_2 = 0.5;\ T_3 = 0.25;\ T_4 = 0.125$$

$$\sum T_i = 1.875$$

$$L \in \langle 8, 12 \rangle$$



Example PrI$_0$ - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f) – $T_f\,/\,T_{d0}$=1.28

$$ULS_d=\left[\tau_{d\min},\tau_f \quad \tau_{d\max},\tau_f\right];\ \kappa=\frac{K_0}{K}=1;\ \tau_d=\frac{T_d}{T_{d0}}=\frac{L+1.875}{L_0+1.875}\ ;\ \tau_f=\frac{T_f}{T_{d0}}=1.28$$

Red

ε=0.00001

ε=0.0001

ε=0.001

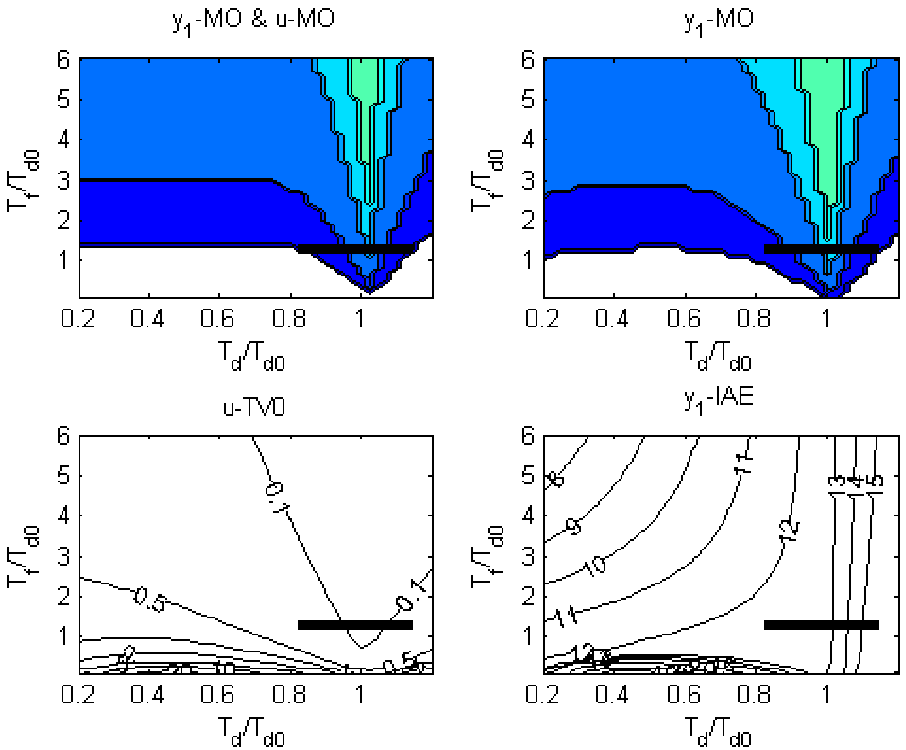
ε=0.01

ε=0.02

ε=0.05

ε=0.1

Dark blue



Example PrI$_0$ - Uncertainty in T_d

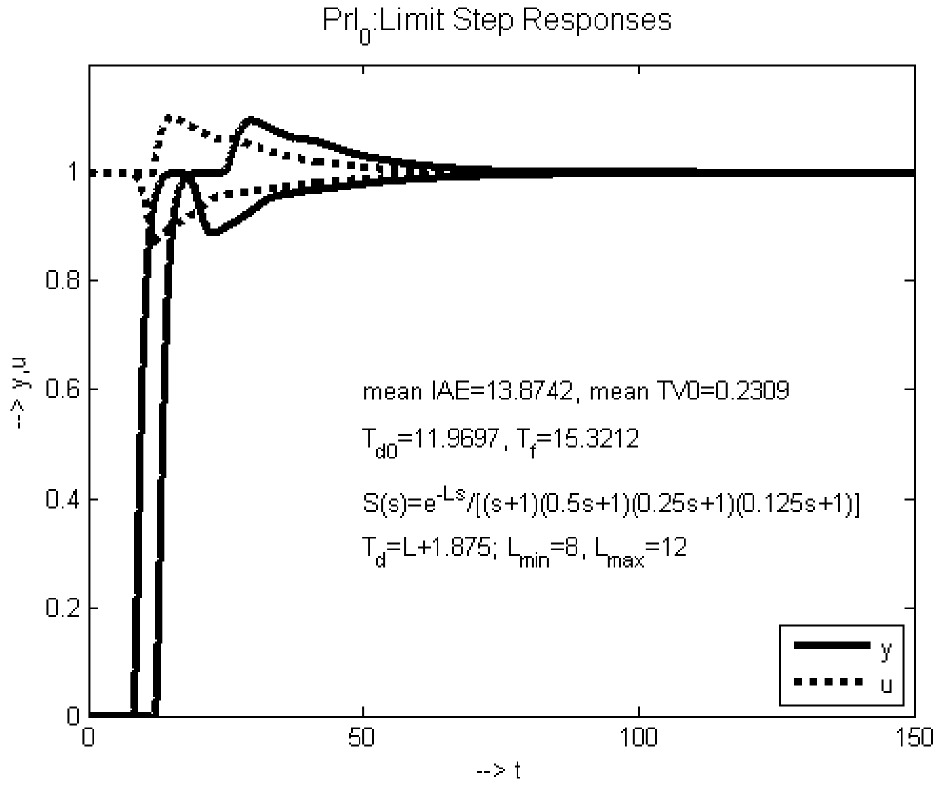
Uncertainty Line Segment in the plane (τ_d,τ_f) – T_f / T_{d0}=1.28

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right]; \; \kappa = \frac{K_0}{K} = 1; \; L \in \langle 8{,}12 \rangle \; ; \; \tau_d = \frac{L + 1.875}{L_0 + 1.875} \; ; \; \tau_f = \frac{T_f}{T_{d0}} = 1.28$$

IAE=13.87

TV0=0.23

Lowest overshooting and IAE values, low TV0



Example PrI$_0$ - Uncertainty in T_d

Nominal tuning in the plane (τ_d,τ_f) – L=10, T_f/ T_{d0}=5.85

$$ULS_d = \left[\tau_{d\,\min},\tau_f \quad \tau_{d\,\max},\tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ \tau_d = \frac{T_d}{T_{d0}} = \frac{L+1.875}{L_0+1.875};\ \tau_f = \frac{T_f}{T_{d0}} = 5.85$$

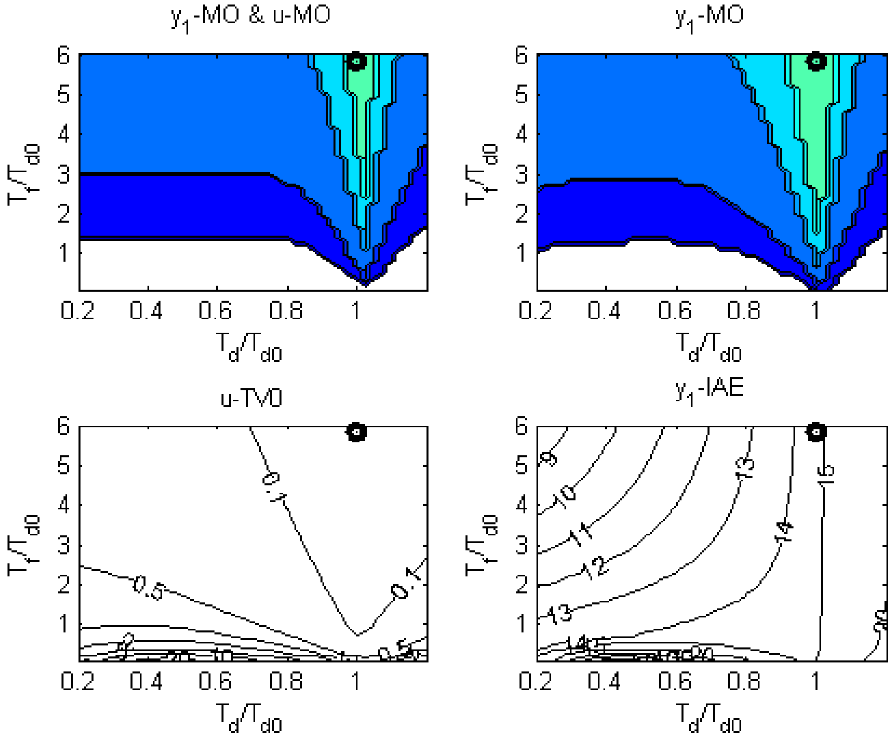
4th order + dead time system

$$S(s) = \frac{e^{-Ls}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)(T_4 s+1)}$$

$$T_1 = 1;\ T_2 = 0.5;\ T_3 = 0.25;\ T_4 = 0.125$$

$$\sum T_i = 1.875$$

$$L \in \langle 8,12 \rangle$$



Example PrI$_0$ - Uncertainty in T_d

Nominal tuning in the plane (τ_d,τ_f) – L=10, T_f / T_{d0}=5.85

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right]; \ \kappa = \frac{K_0}{K} = 1; \ \tau_d = \frac{T_d}{T_{d0}} = \frac{L+1.875}{L_0+1.875}; \ \tau_f = \frac{T_f}{T_{d0}} = 5.85$$

Red

ε=0.00001

ε=0.0001

ε=0.001

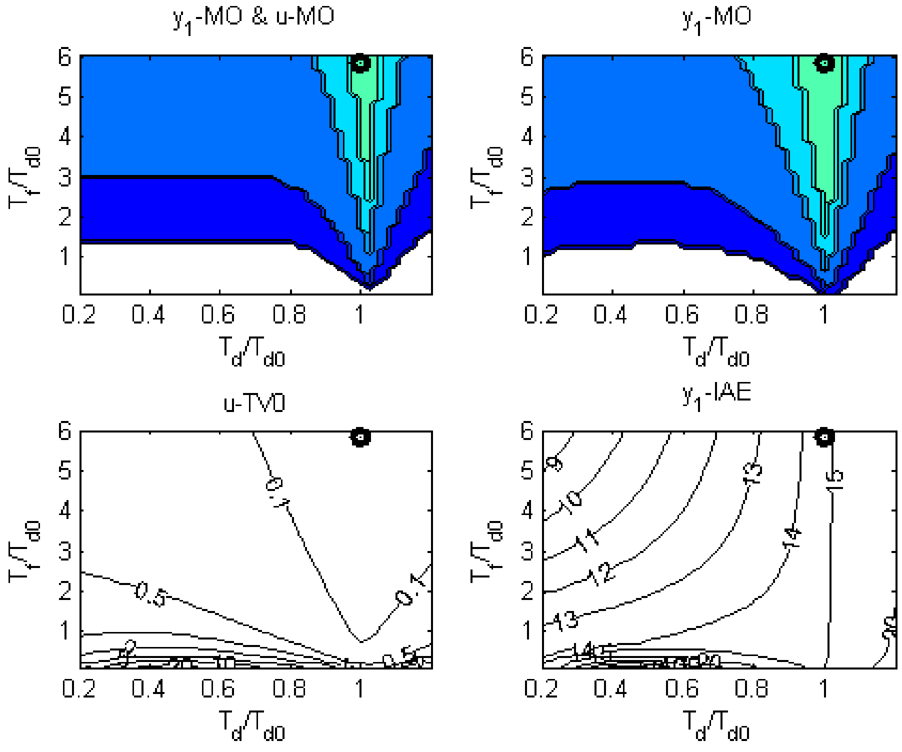
ε=0.01

ε=0.02

ε=0.05

ε=0.1

Dark blue



Example PrI_0 - Uncertainty in T_d

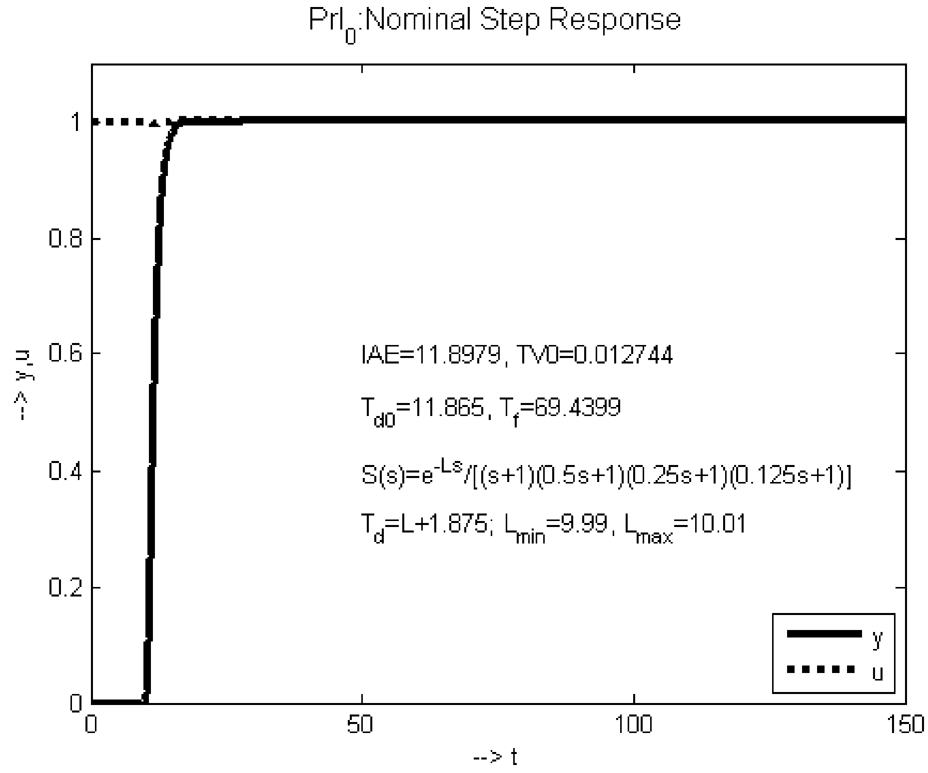
Nominal tuning in the plane (τ_d, τ_f) – L=10, T_f / T_{d0}=5.85

$$ULS_d = \left[\tau_{d\,\min}, \tau_f \quad \tau_{d\,\max}, \tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ L \in \langle 8{,}12 \rangle\ ;\ \tau_d = \frac{L + 1.875}{L_0 + 1.875}\ ;\ \tau_f = \frac{T_f}{T_{d0}} = 5.85$$

IAE=11.90

TV0=0.01

Low overshooting and TV0 paid by high T_f value => slow disturbance response



Example PrI_0 - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f) – T_f / T_{d0}=5.85

$$ULS_d = [\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f]; \ \kappa = \frac{K_0}{K} = 1; \ \tau_d = \frac{T_d}{T_{d0}} = \frac{L + 1.875}{L_0 + 1.875}; \ \tau_f = \frac{T_f}{T_{d0}} = 5.85$$

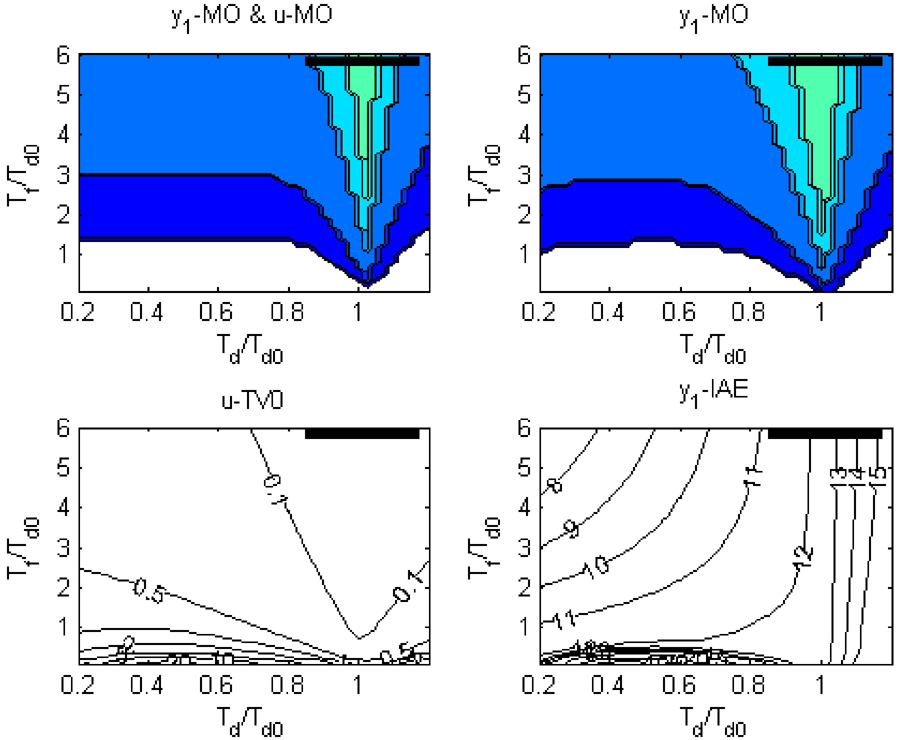
4^{th} order + dead time system

$$S(s) = \frac{e^{-Ls}}{(T_1 s + 1)(T_2 s + 1)(T_3 s + 1)(T_4 s + 1)}$$

$$T_1 = 1; \ T_2 = 0.5; \ T_3 = 0.25; \ T_4 = 0.125$$

$$\sum T_i = 1.875$$

$$L \in \langle 8, 12 \rangle$$



Example PrI$_0$ - Uncertainty in T_d

Uncertainty Line Segment in the plane (τ_d,τ_f) – T_f / T_{d0}=5.85

$$ULS_d = \left[\tau_{d\min}, \tau_f \quad \tau_{d\max}, \tau_f\right]; \ \kappa = \frac{K_0}{K} = 1; \ \tau_d = \frac{T_d}{T_{d0}} = \frac{L+1.875}{L_0+1.875}; \ \tau_f = \frac{T_f}{T_{d0}} = 5.85$$

Red

ε=0.00001

ε=0.0001

ε=0.001

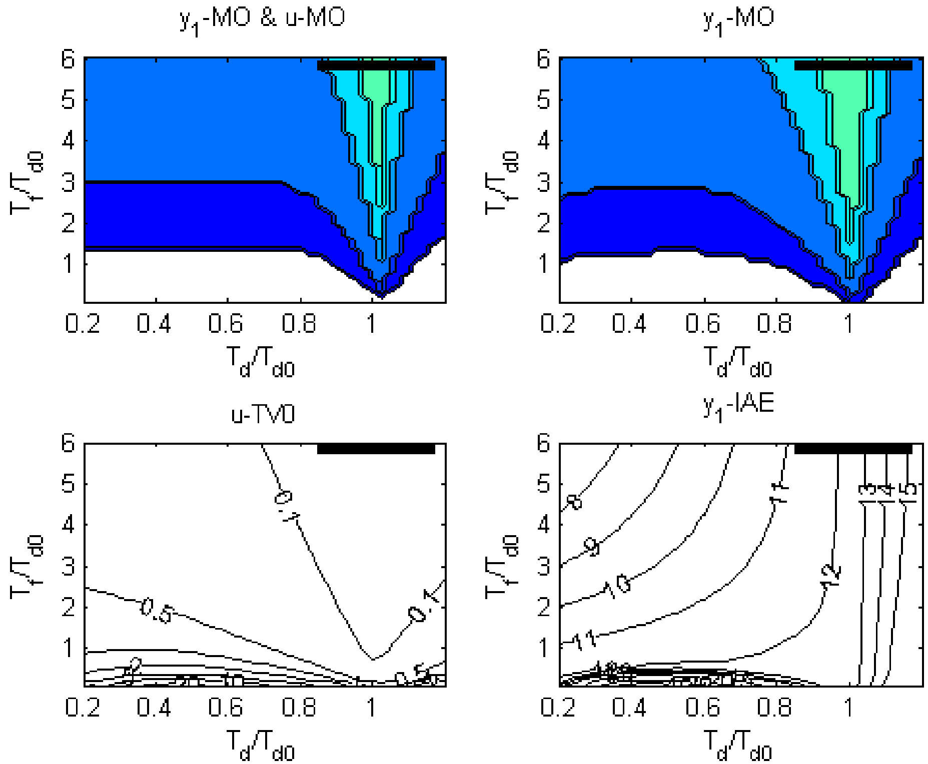
ε=0.01

ε=0.02

ε=0.05

ε=0.1

Dark blue



Example PrI$_0$ - Uncertainty in T_d

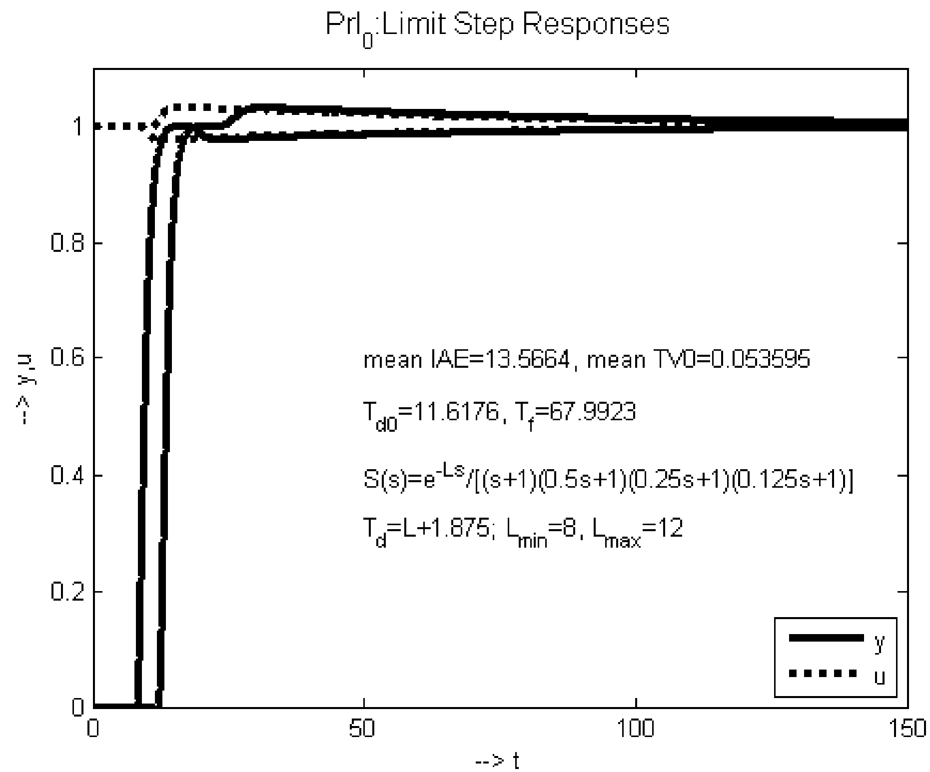
Uncertainty Line Segment in the plane (τ_d,τ_f) – T_f / T_{d0}=5.85

$$ULS_d = \left[\tau_{d\min},\tau_f \quad \tau_{d\max},\tau_f\right];\ \kappa = \frac{K_0}{K} = 1;\ L \in \langle 8{,}12\rangle\ ;\ \tau_d = \frac{L+1.875}{L_0+1.875}\ ;\ \tau_f = \frac{T_f}{T_{d0}} = 5.85$$

IAE=13.57

TV0=0.05

Low overshooting and TV$_0$ paid by high *T$_f$* value => slow disturbance response

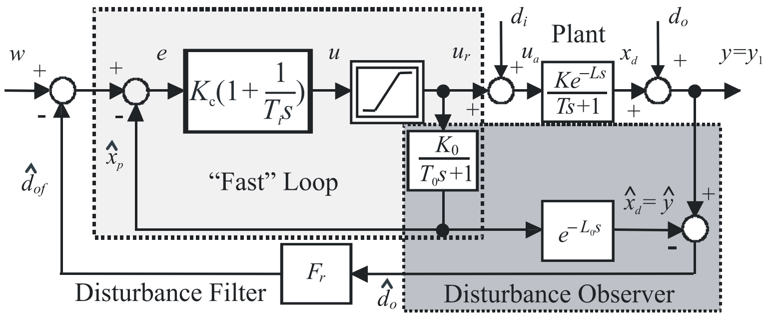


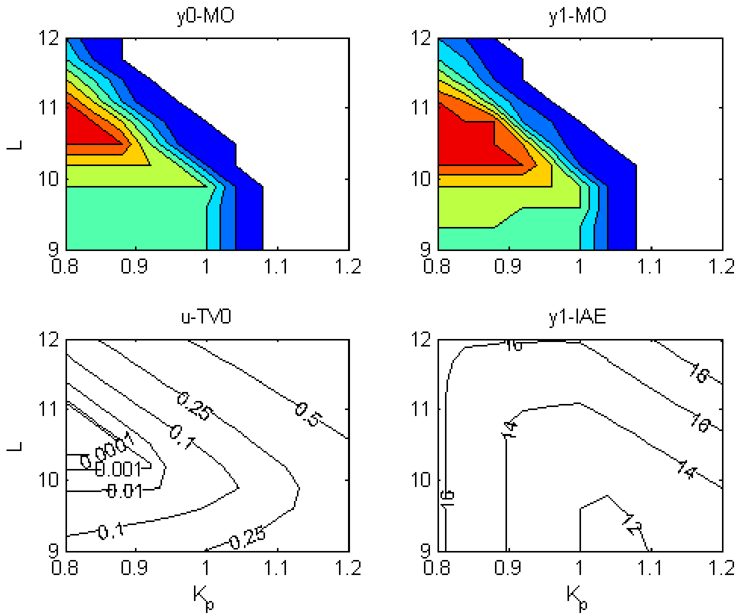
Example: PP of the FSP

- Normey-Rico and Camacho, (2007); Example 6.1

$$F(s)=\frac{K_p e^{-Ls}}{(s+1)(0.5s+1)(0.25s+1)(0.125s+1)};$$

$$K_p \in \langle 0.8, 1.2\rangle;\ L \in \langle 9, 12\rangle$$





Example: FSP Retuned for ε=0.02, T_0=1.5

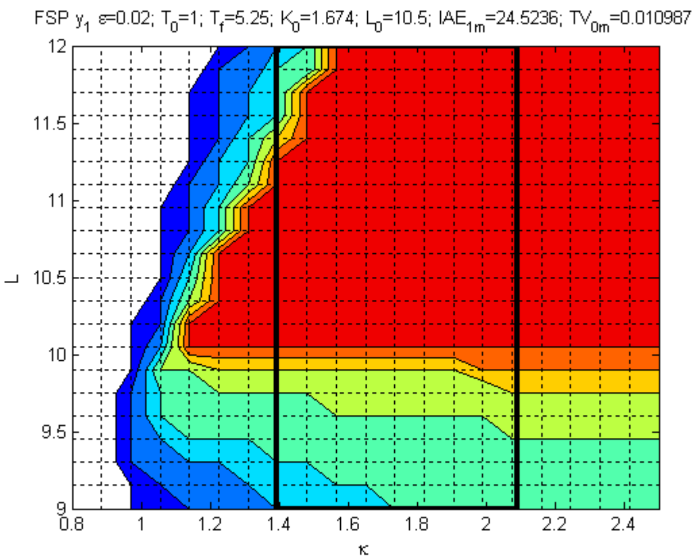
$$\varepsilon = \varepsilon_u = \varepsilon_y = \left\{0.1, 0.05, 0.02, 0.01, 10^{-3}, 10^{-4}, 10^{-5}\right\}$$

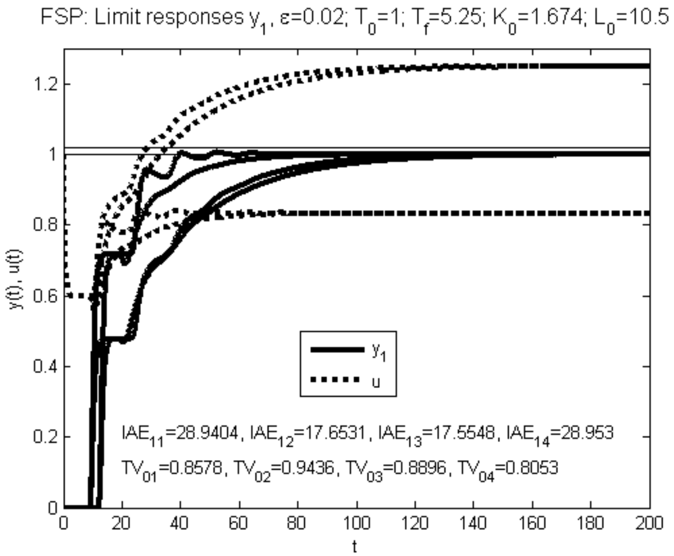
Example: FSP Retuned for ε=0.02, T_0=1.0

- FSP
  IAE=24.5; TV_0=0.01

$$F(s)=\frac{K_p e^{-Ls}}{(s+1)(0.5s+1)(0.25s+1)(0.125s+1)};$$

$$K_p \in \langle 0.8, 1.2\rangle;\ L \in \langle 9, 12\rangle$$





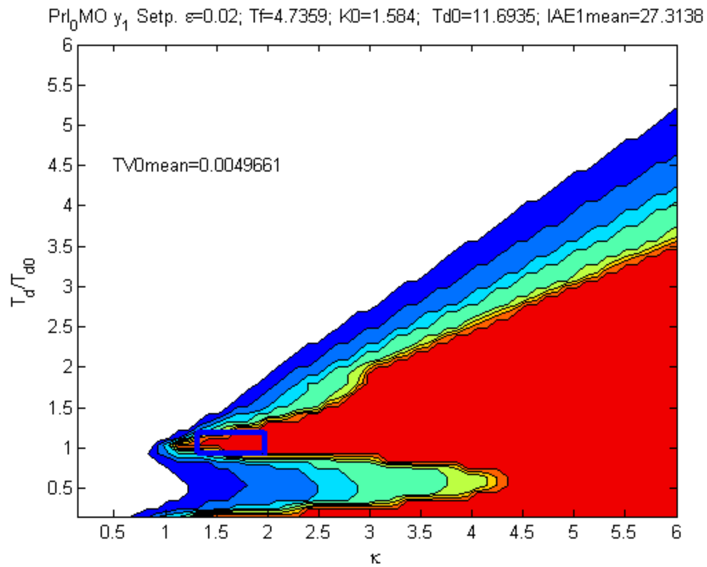
Example: Comparing with FSP

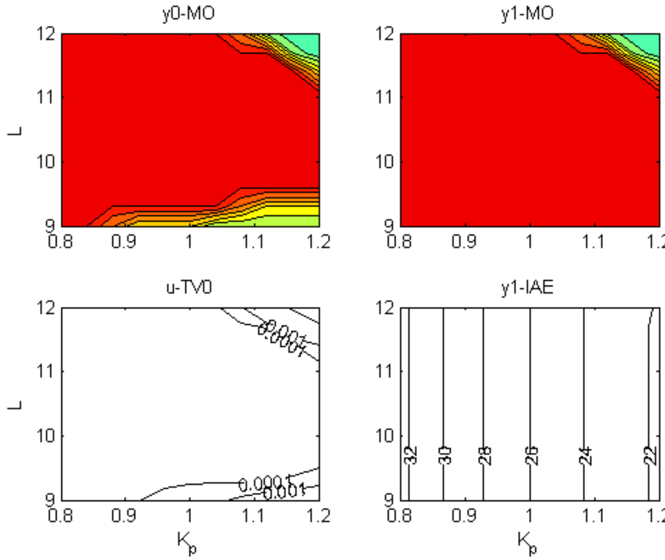
- $FPrI_0$ controller
  $IAE=27.3$; $TV_0=0.005$

$$F(s)=\frac{K_p e^{-Ls}}{(s+1)(0.5s+1)(0.25s+1)(0.125s+1)};$$

$$K_p \in \langle 0.8, 1.2 \rangle;\ L \in \langle 9, 12 \rangle$$

Recent result – simplified tuning in 2D





Conclusions

- PrI_0 and $FPrI_0$ controllers keep the modular character of RCPIDC
- Simpler PrI_0 and $FPrI_0$ controllers allow to achieve better quality by a more straightforward tuning and in a broader range of requirements than the more complex Smith Predictor and its modifications (FSP, PPI, FPPI)
- The comparison was not completely fair, because controller compensating dead time and the largest time constant (SP->Predictive PI) was compared with solution compensating just dead time (Predictive I_0).

Conclusions

- In this sense, we should compare FSP, or PPI controllers with $PrPI_0$ controllers, but, as mentioned already by Normey-Rico, Camacho, 2007, pp.174:
- "…when the dead time is dominant the contribution of the open-loop poles to the closed-loop response will be small, thus their elimination will contribute with a small increment in the speed of the transients"
- $PrPI_0$ controllers respect this fact, they compensate just dead time and the above comparison fully confirms its validity

Conclusions

- Performance Portrait based analysis and controller tuning represent flexible alternative to analytical approaches
- Apriori robust controller analysis & tuning attractive especially for the traditionally bad treatable structures with dead time like the Smith Predictor, Reswick-controller, etc.
- The traditional frequency-domain methods still represent *methods for nominal tuning* offering just restricted possibility to check robust stability
- New possibility to design transients with specified performance (overshooting, TV_0, etc.)

Conclusions

- Comparison of results will be complete just after considering also the disturbance responses
- The new tuning procedure may be used also for other controllers, e.g. for the Smith predictor
- It brings shift from Laplace transform, polynomials and frequency domain to the Computer Graphics and Computer Geometry problems.