INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Robustné PID-regulátory s obmedzeniami
Robust Constrained PID Control

Robust Design of Model Based PI_1 and PID_1 Controllers

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

11.3.2011

Contents

- Reconstruction & Compensation of Inptut Disturbances
- Reconstruction & Compensation of Ouptut Disturbances
- Robust Tuning by the Performance Portrait Method
- Comparing with the Parallel PI controller
- Comparing with Smith Predictor

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Contents

- Stabilization of FOPDT plants with PD controller
- Model based PID_1 controllers for the FOPDT plants
- PID_1 controllers for 2nd order plants
- Conclusions

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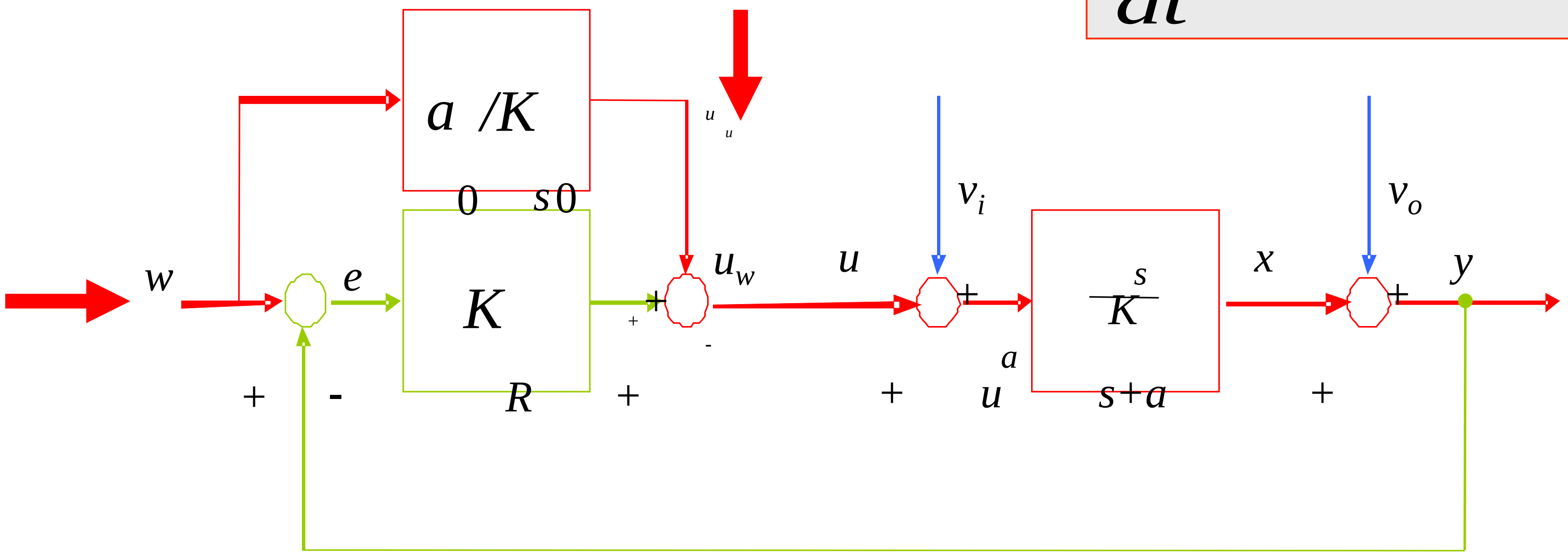
Dynamical Class “1”

Linear pole assignment P-con

$$\frac{de}{dt} = \alpha e \; ; \quad \alpha < 0$$

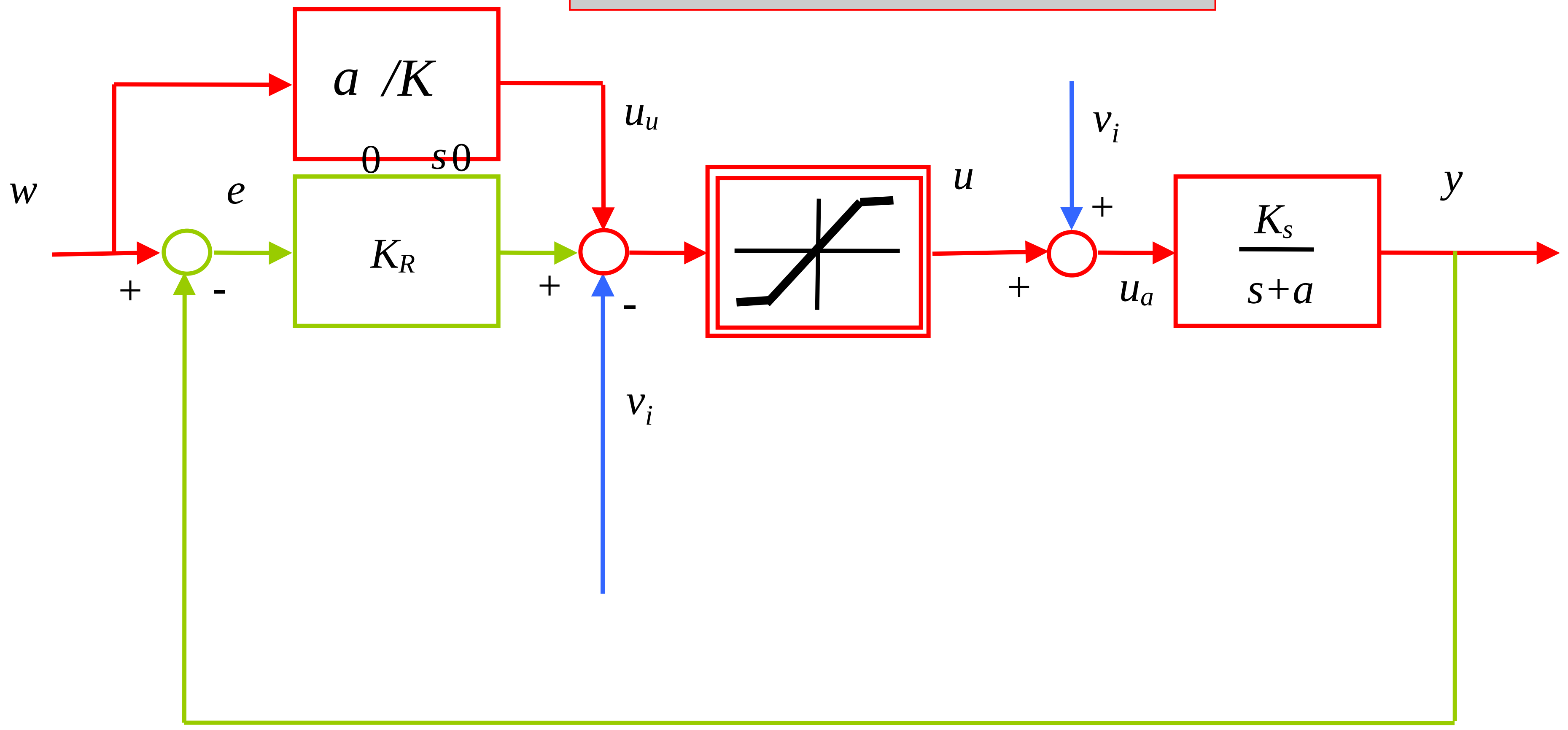


$$e = w - y$$

$$u = K_R e + u_w \; ; \;\; K_R = -\frac{\alpha + a_0}{K_{s0}} = \frac{\Omega - a_0}{K_{s0}} ; \;\; u_w = \frac{a_0}{K_{s0}} w$$

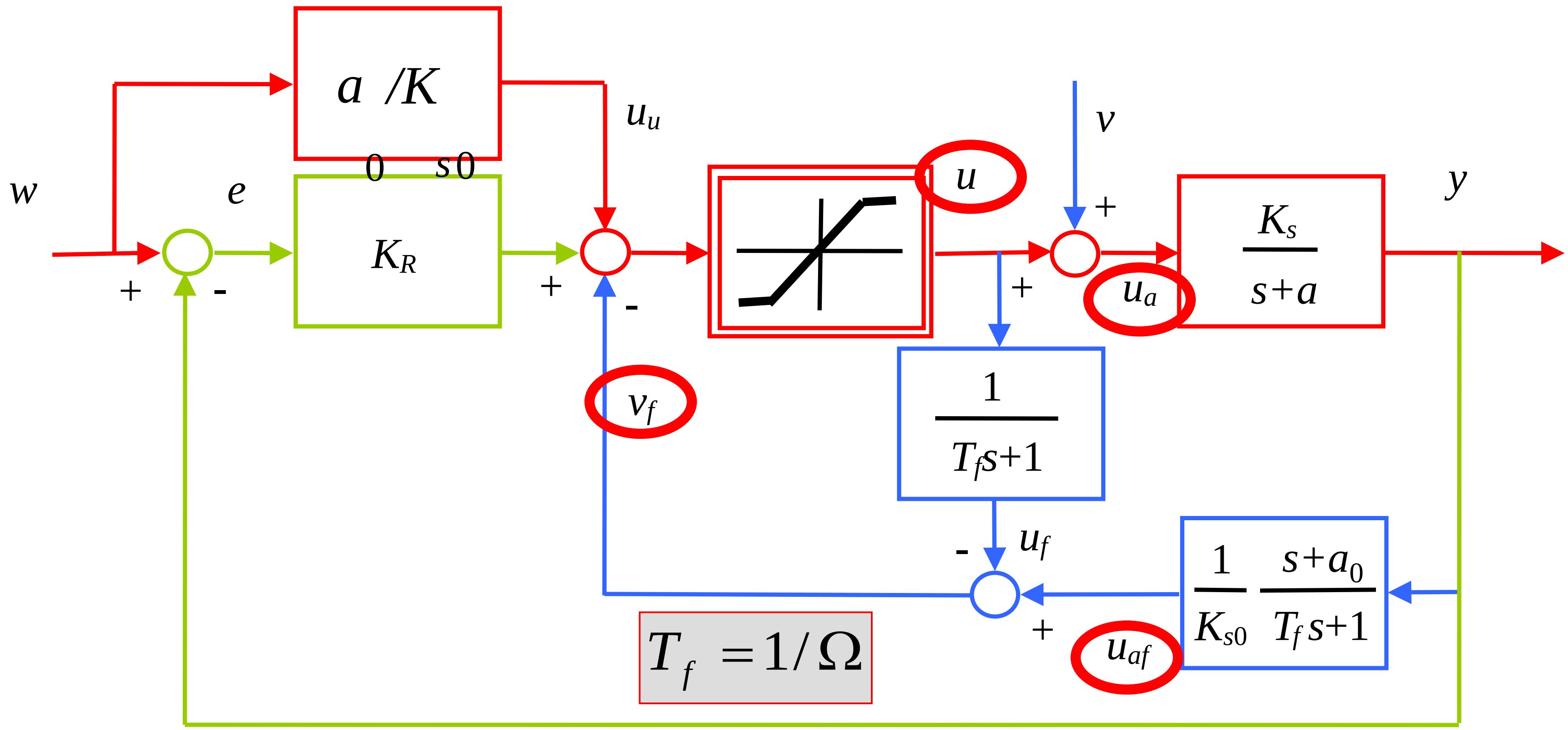
Input Disturbance Compensation

$$K_R = (\Omega - a_0) / K_{s0}$$



Input Disturbance Compensation

$$K_R = (\Omega - a_0)/K_{s0}$$



$$T_f = 1/\Omega$$

Input Disturbance Compensation

- PI_1-IM Transfer functions

$$a_0 = a\ ;\ \ K_{s0} = K_s$$

$$F_w(s) = \frac{K_s K_R + a}{s + K_s K_R + a} = \frac{1}{1 + T_w s}\ ;\ T_w = \frac{1}{K_s K_R + a} = \frac{1}{\Omega};$$

$$F_{vo}(s) = \frac{s(s+a)T_f T_w}{(1+T_w s)(1+T_f s)}\ ;\ F_{vi}(s) = \frac{K_s}{s+a} F_{vo} = \frac{s T_f T_w K_s}{(1+T_w s)(1+T_f s)}$$

$$F_{vo}(0) = 0\ ;\ F_{vi}(0) = 0$$

- Nominal stability condition $T_f>0$, $T_w>0$, $K_R K_s+a>0$
- Disturbance response has pole of the setpoint response + pole of the Disturbance Observer
- IM = Inverse Model

Output Disturbance Compensation

- PI_1-IM Transfer functions (uncertain case)

$$F_w(s)=\frac{(T_f s+1)\Omega K_s}{K_{s0}T_f s^2+\left[K_s T_f(\Omega-a_0)+K_{s0}T_f a+K_s\right]+K_s\Omega};$$

$$F_{vo}(s)=\frac{s(s+a)T_f K_{s0}}{K_{s0}T_f s^2+\left[K_s T_f(\Omega-a_0)+K_{s0}T_f a+K_s\right]+K_s\Omega};$$

$$F_{vi}(s)=\frac{sT_f K_s K_{s0}}{K_{s0}T_f s^2+\left[K_s T_f(\Omega-a_0)+K_{s0}T_f a+K_s\right]+K_s\Omega};$$

$$\boxed{F_w(0)=1;\ F_{vo}(0)=0;\ F_{vi}(0)=0}$$

- Increased robustness of the setpoint responses for prefilter with $T_p=T_f$

Output Disturbance Compensation

- PI_1-IM Transfer functions (uncertain case)

$$F_w(s)=\frac{(T_f s+1)\Omega K_s}{K_{s0}T_f s^2+\left[K_s T_f(\Omega-a_0)+K_{s0}T_f a+K_s\right]+K_s\Omega};$$

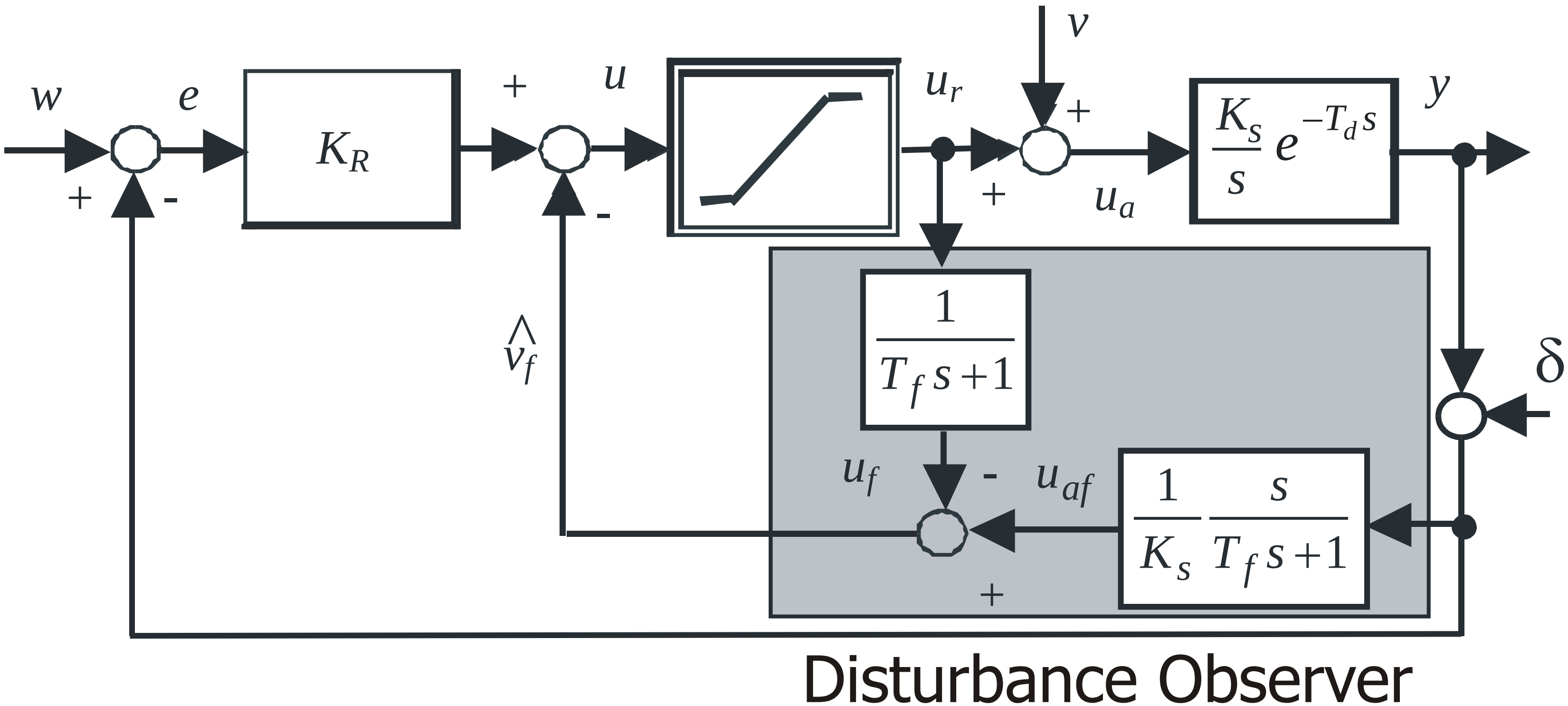
$$F_{vo}(s)=\frac{s(s+a)T_f K_{s0}}{K_{s0}T_f s^2+\left[K_s T_f(\Omega-a_0)+K_{s0}T_f a+K_s\right]+K_s\Omega};$$

$$F_{vi}(s)=\frac{sT_f K_s K_{s0}}{K_{s0}T_f s^2+\left[K_s T_f(\Omega-a_0)+K_{s0}T_f a+K_s\right]+K_s\Omega};$$

- Robust design parameters K_{s0}/K_s, a, a_0, T_f, Ω
- Positioning 2D UB corresponding to (K_{s0}/K_s, a) in 5D (remaining coordinates are a_0, T_f, Ω)

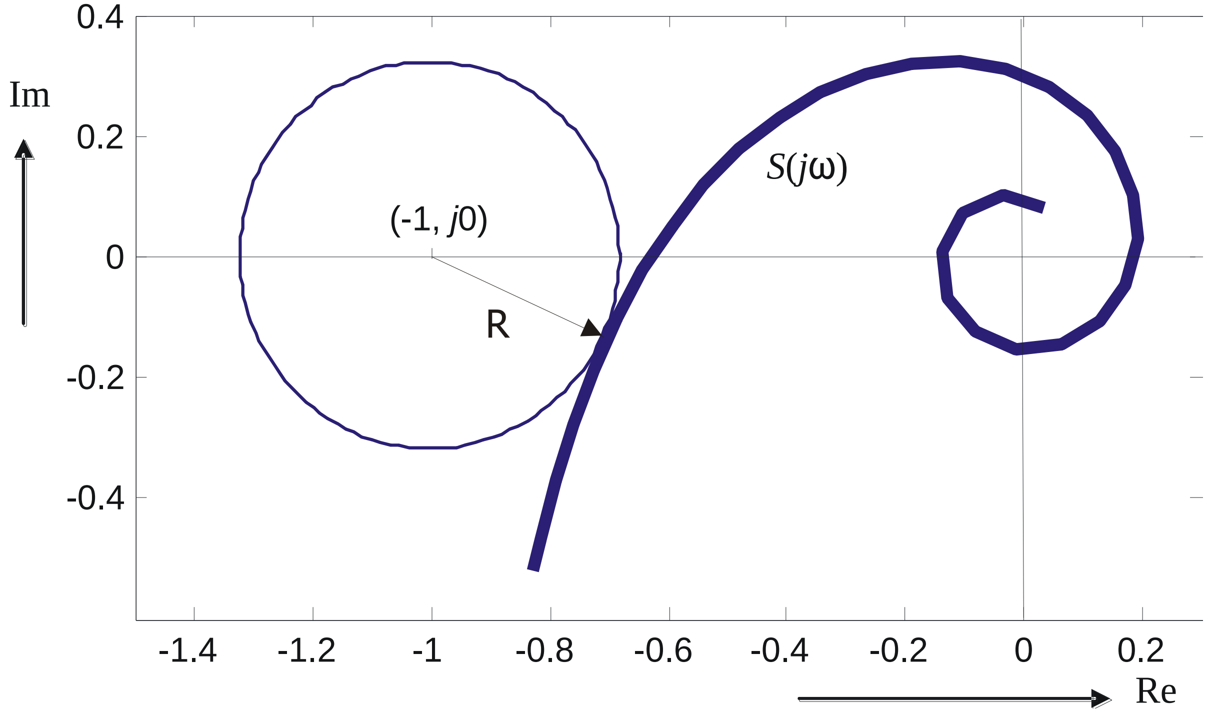
PI_1-IM controller

P controller + observer for input disturbance with inverse model ($a=a_0=0$)



Maximal Sensitivity M_s

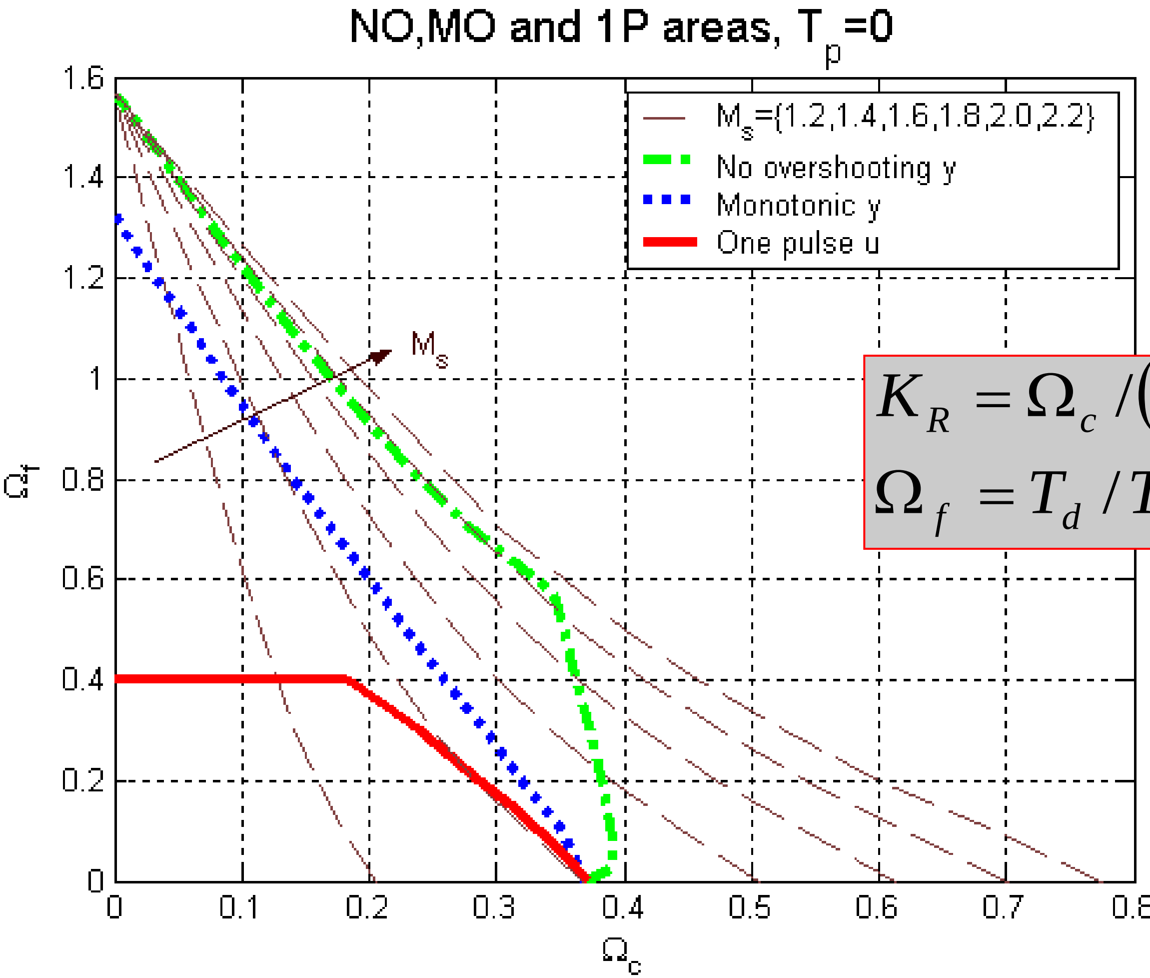
Maximal sensitivity M_s = equal to radius R of a circle with centre in critical point (-1, 0j) toughing the Nyquist curve of the closed loop system S(jω)



$$S(s) = 1/[1 + L(s)]$$

$$L(s) = R(s)F(s)$$

PI_1 Performance Portrait & M_s values

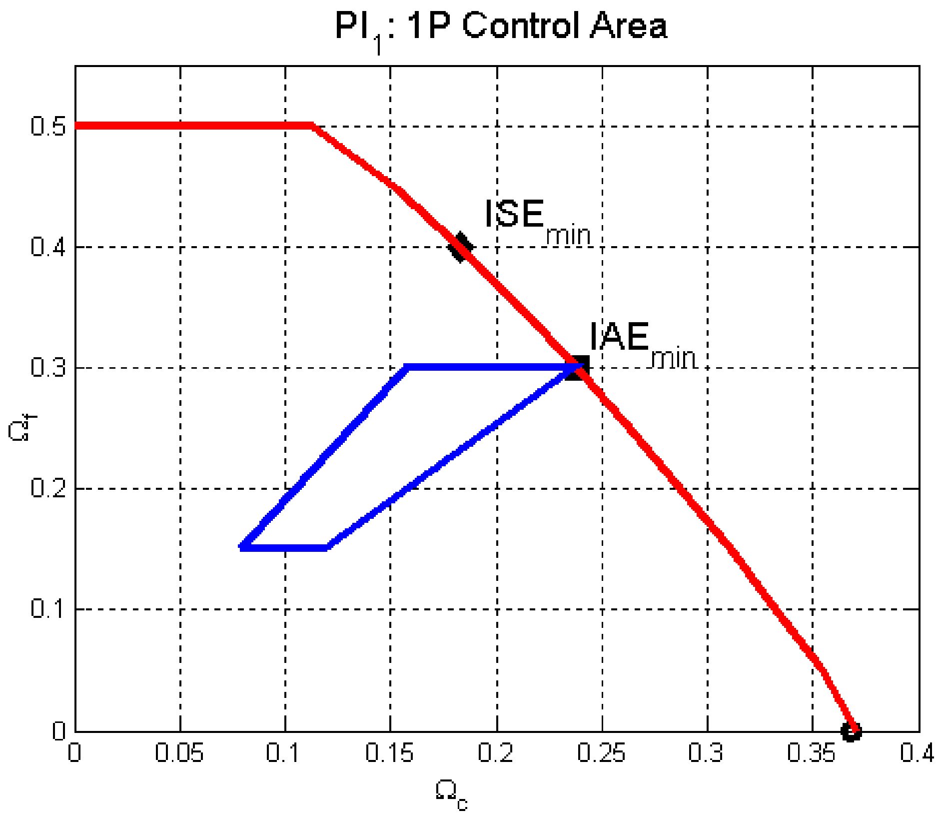


$$K_R = \Omega_c / (K_{s0} T_d)$$

$$\Omega_f = T_d / T_f$$

Uncertainty Set (US)

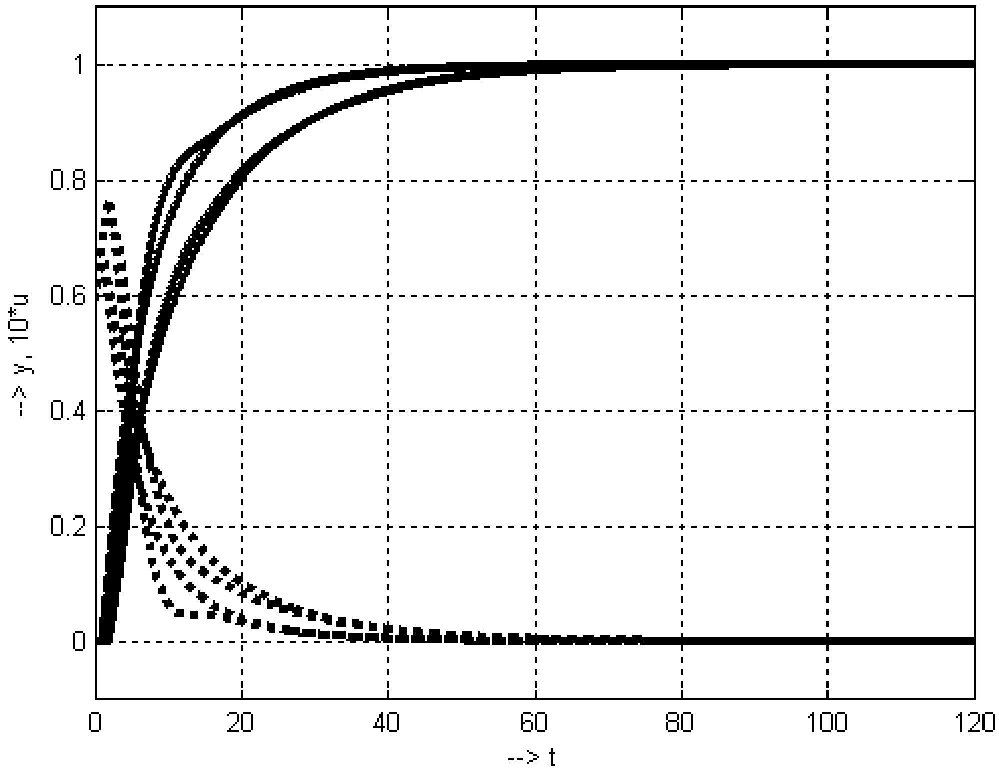
PI_1 controller – region 1P is convex, optimal point lying at its border**!**



IAE_{min}=4.12

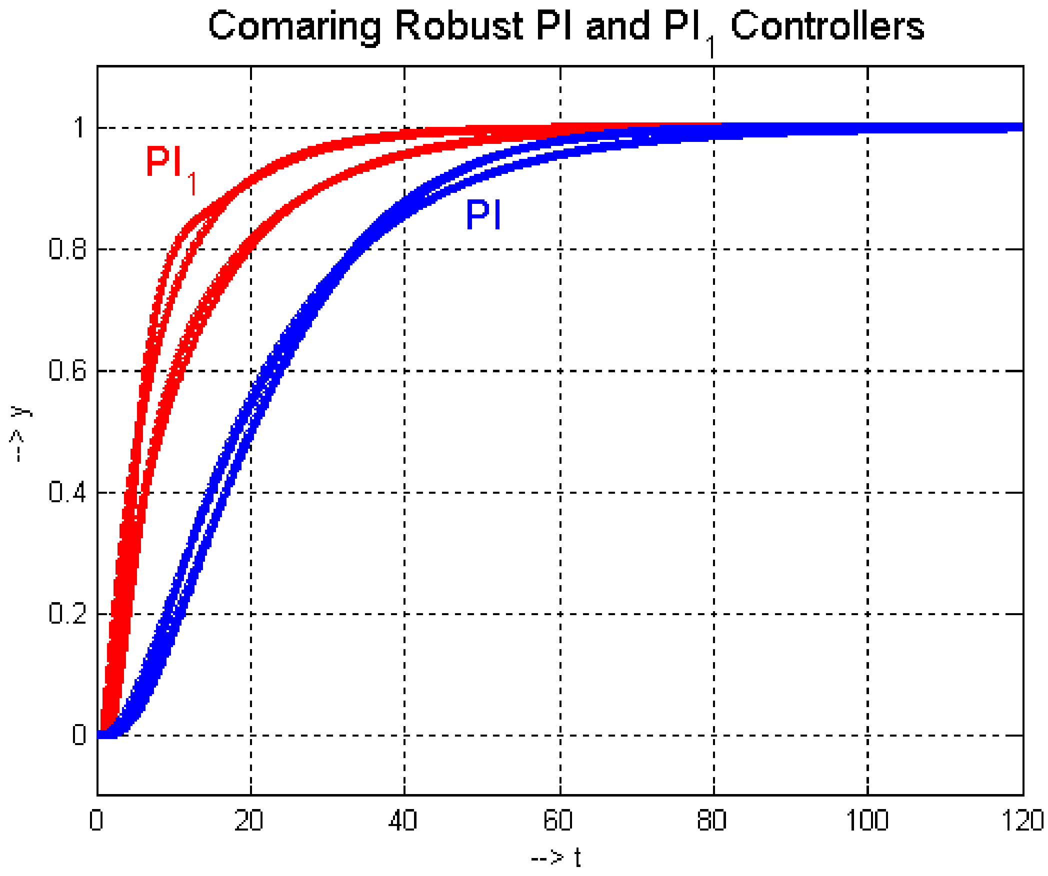
Step responses PI_1 controller

Checking results for limit values of Ks and Td



Step responses PI_1-IM and PI control

Comparing with the parallel PI controller/2D



PI_1-DTIM controller

- P controller + Disturbance Observer with compensation of dead time Td
- DTIM = Dead-Time + Inverse Model in Disturbance Observer

Input Disturbance Compensation

- PI_1-IM Transfer functions

$$a_0 = a\,;\;\; K_{s0} = K_s\,,\, T_{d0} = T_d$$

$$F_w(s) = \frac{\left(K_s K_R + a\right)e^{-T_d s}}{\left(s + K_s K_R e^{-T_d s} + a\right)}\,;$$

$$F_{vo}(s) = \frac{\left(s+a\right)\left(1 - e^{-T_d s} + sT_f\right)}{\left(s + K_s K_R e^{-T_d s} + a\right)\left(1 + T_f s\right)}\,;\;\; F_{vi}(s) = \frac{K_s}{s+a} F_{vo}$$

$$F_w(0) = 1\,;\; F_{vo}(0) = 0\,;\;\; F_{vi}(0) = 0$$

- Setpoint response has poles of simple P-control
- Nominal stability condition for T_f>0 are the same as for the P controller
- Full robust design – 7D parameter space

Analytical Construction of PP

- Critical and optimal gains (aperiodicity border)

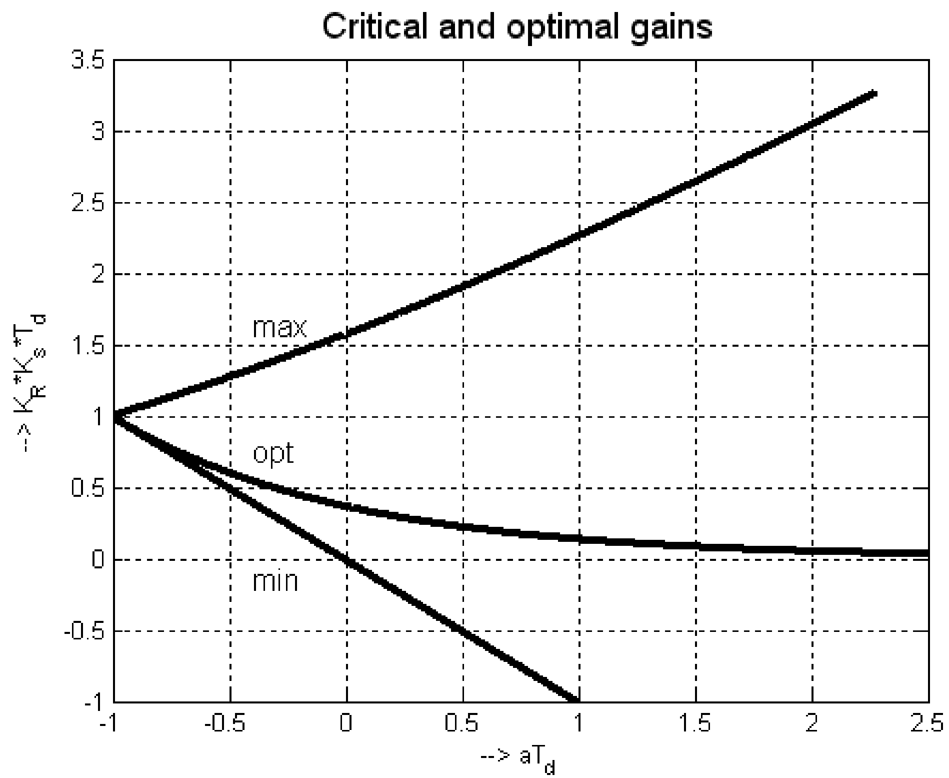
$$K_{min} < K < K_{max}\ ;\ K = K_R K_s T_d$$

$$K_{max} = \frac{\tau_d}{\sin\tau_d}\ ; A = -\frac{\tau_d \cos\tau_d}{\sin\tau_d}\ ;$$

$$\tau_d \in (0,\pi/2)\cup(\pi/2,\pi)$$

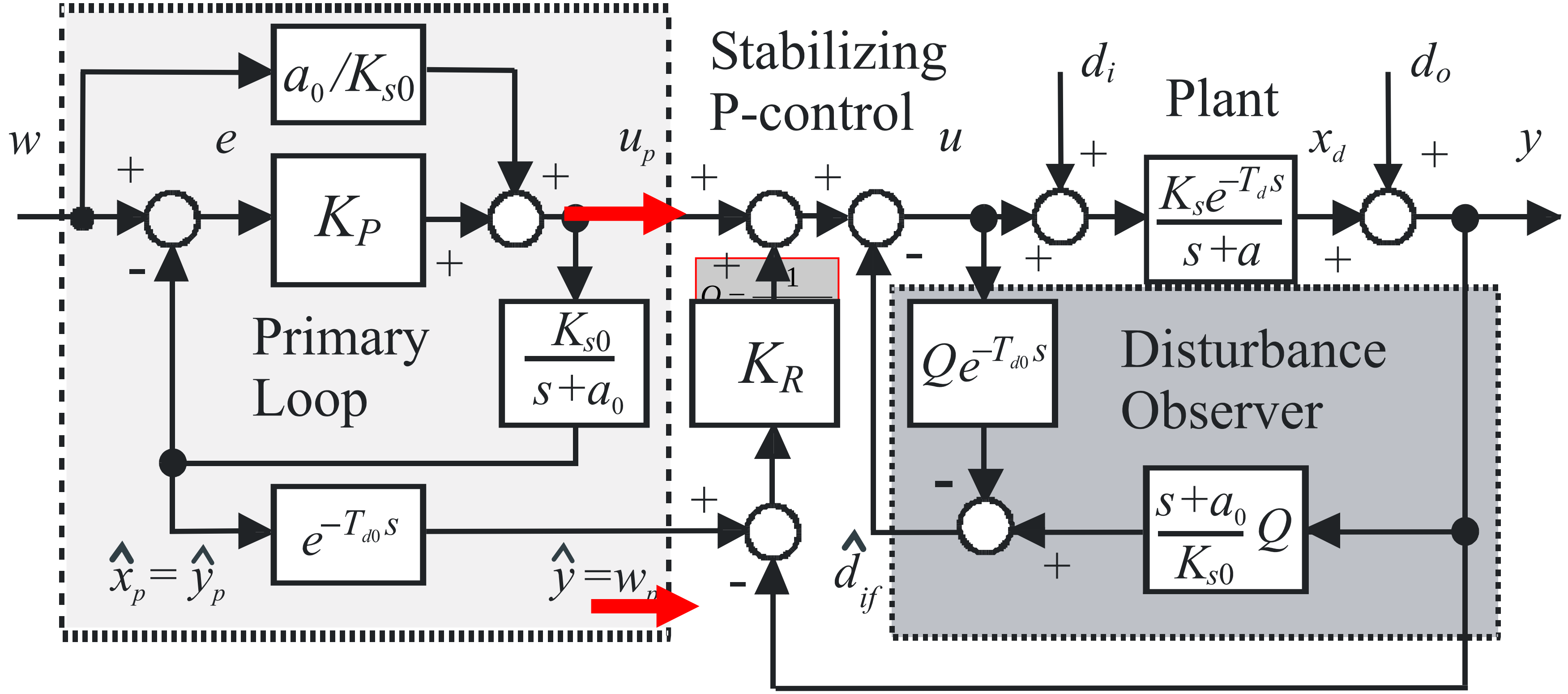
$$K_{min} = -A = -aT_d$$

$$K_{opt} = e^{-(1+aT_d)}$$



PI$_1$-DFF-DTIM controller

P control + dynamical feedforward + disturbance observer with inverse model and compensation of dead time T_d



Input Disturbance Compensation

- PI_1-IM Transfer functions

$$a_0 = a\ ;\ \ K_{s0} = K_s\ ,\ T_{d0} = T_d$$

$$F_w(s) = \frac{(K_s K_P + a)e^{-T_d s}}{(s + K_s K_P + a)} = \frac{e^{-T_d s}}{T_w s + 1}\ ;\ T_w = \frac{1}{K_s K_P + a}$$

$$F_{vo}(s) = \frac{(s+a)\left(1 - e^{-T_d s} + sT_f\right)}{\left(s + K_s K_R e^{-T_d s} + a\right)(1 + T_f s)}\ ;\ F_{vi}(s) = \frac{K_s}{s+a} F_{vo}$$

$$F_w(0) = 1\ ;\ F_{vo}(0) = 0\ ;\ F_{vi}(0) = 0$$

- Nominal setpoint response without T_d in denominator
- Nominal stability condition for T_f>0 are the same as for the P controller
- Full robust design – 8D parameter space

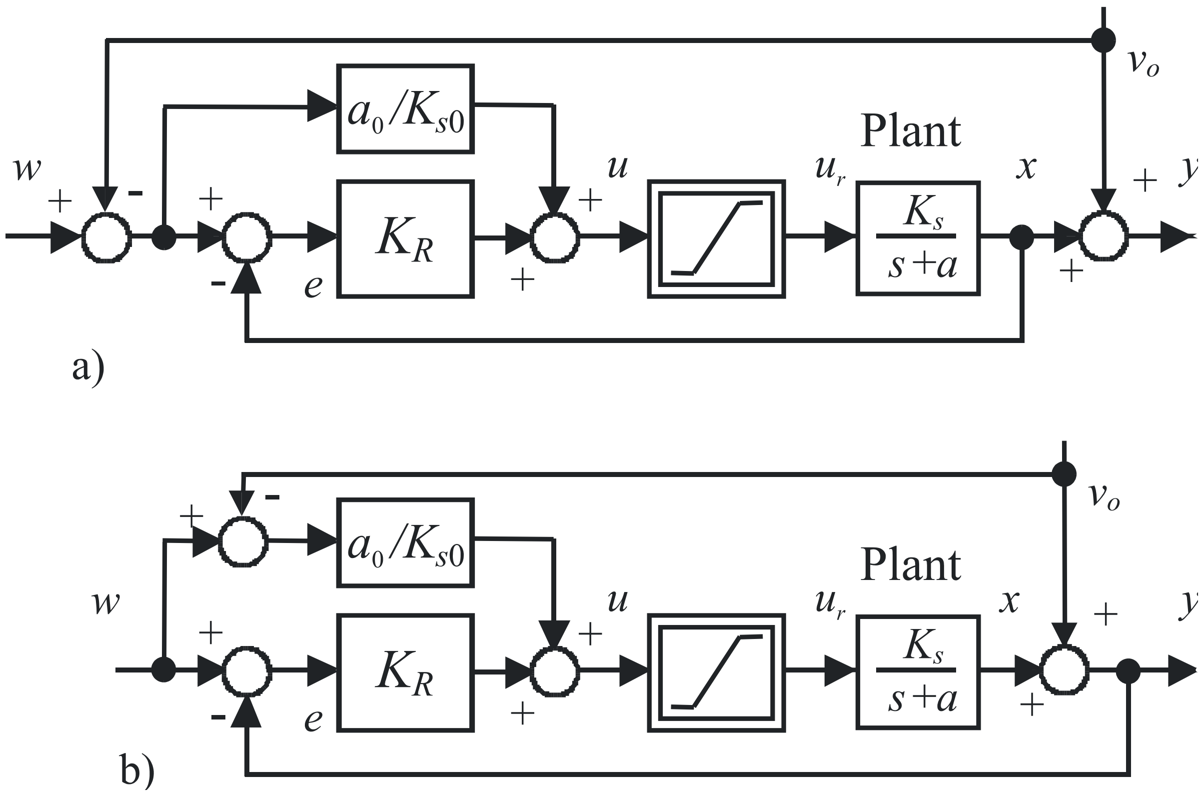
Conclusions 1

- Modular controller pack enabling extension from the simplest controllers not considering nonmodelled dynamics up to generalization of Smith Predictor
- Controller Tuning based on the Stability/Quality analysis of simple P controller
- Separate tuning of the setpoint and disturbance response
- Enabling unified treatment of both stable, integral and unstable FOPDT systems
- Setpoint response reasonably improved against parallel PI control

Output Disturbance Compensation

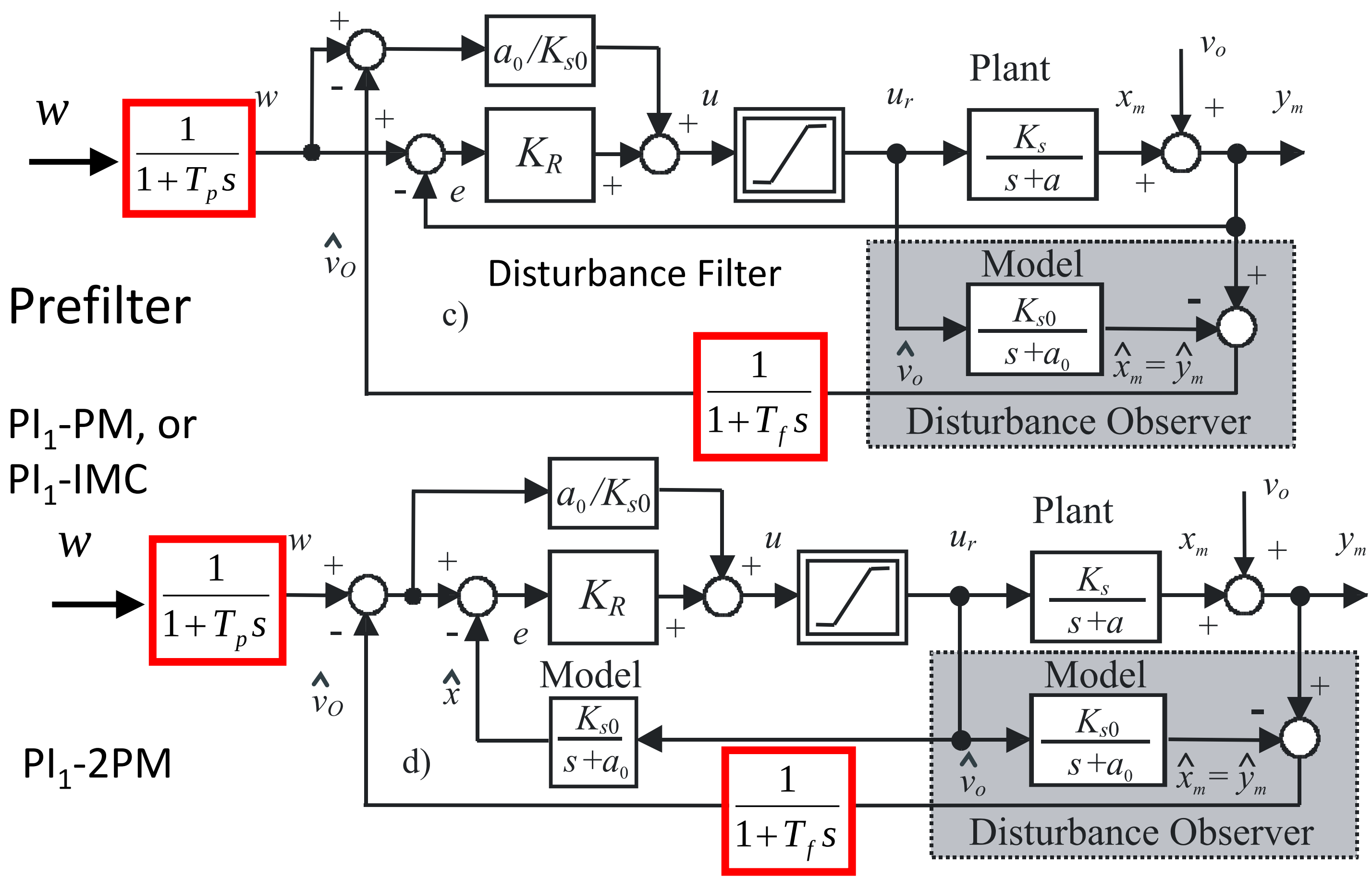
- Measurable output disturbance compensation

$$K_R = (\Omega - a_0)/K_{s0}$$



Output Disturbance Compensation

- Disturbance reconstruction & compensation



Output Disturbance Compensation

- PI_1-PM Transfer functions

$$a_0 = a \; ; \; K_{s0} = K_s$$

$$F_w(s) = \frac{1}{1+T_w s} \; ; \; T_w = \frac{1}{K_s K_R + a} = \frac{1}{\Omega};$$

$$F_{vo}(s) = \frac{sT_w}{1+T_w s} \; ; \; F_{vi}(s) = \frac{K_s}{s+a} F_{vo}$$

$$F_{vo}(0) = 0 \; ; \; F_{vi}(0) = 0 \;\; (\text{for } a \neq 0)$$

- nominal stability condition $K_R K_s + a > 0$
- but, already in the nominal case with step input disturbance, there is:
- a permanent steady state error for a=0 and
- unstable input disturbance response for a<0

Output Disturbance Compensation

- PI_1-PM Transfer functions (uncertain case)

$$F_w(s)=\frac{Y(s)}{W(s)}=\frac{K_s(s+a_0)\Omega}{K_s(s+a_0)\Omega+K_{s0}s(s+a)};$$

$$F_{vo}(s)=\frac{Y(s)}{V_o(s)}=\frac{sK_{s0}(s+a)}{K_s(s+a_0)\Omega+K_{s0}s(s+a)};$$

$$F_{vi}(s)=\frac{Y(s)}{V_i(s)}=\frac{sK_sK_{s0}}{K_s(s+a_0)\Omega+K_{s0}s(s+a)};$$

$$F_w(0)=1;\ F_{vo}(0)=0;\ F_{vi}(0)=0$$

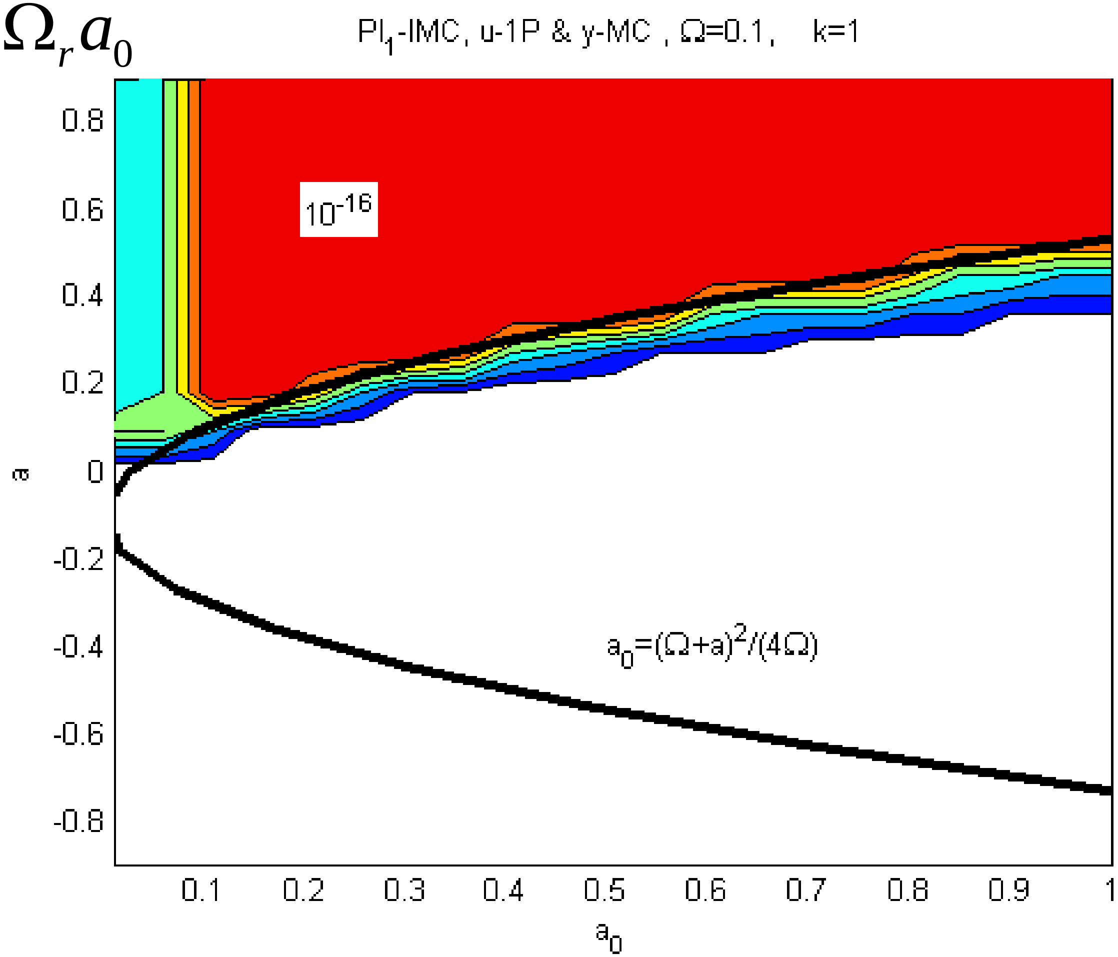
- Does not hold for F_{vi} a a=0, a_0=0
- Increased robustnes for prefilter with $T_p=1/a_0$

Analytical Tuning ver. PP for $K_{s0}=K_s$

$$A(s)=s^2+(\Omega_r+a)s+\Omega_r a_0$$

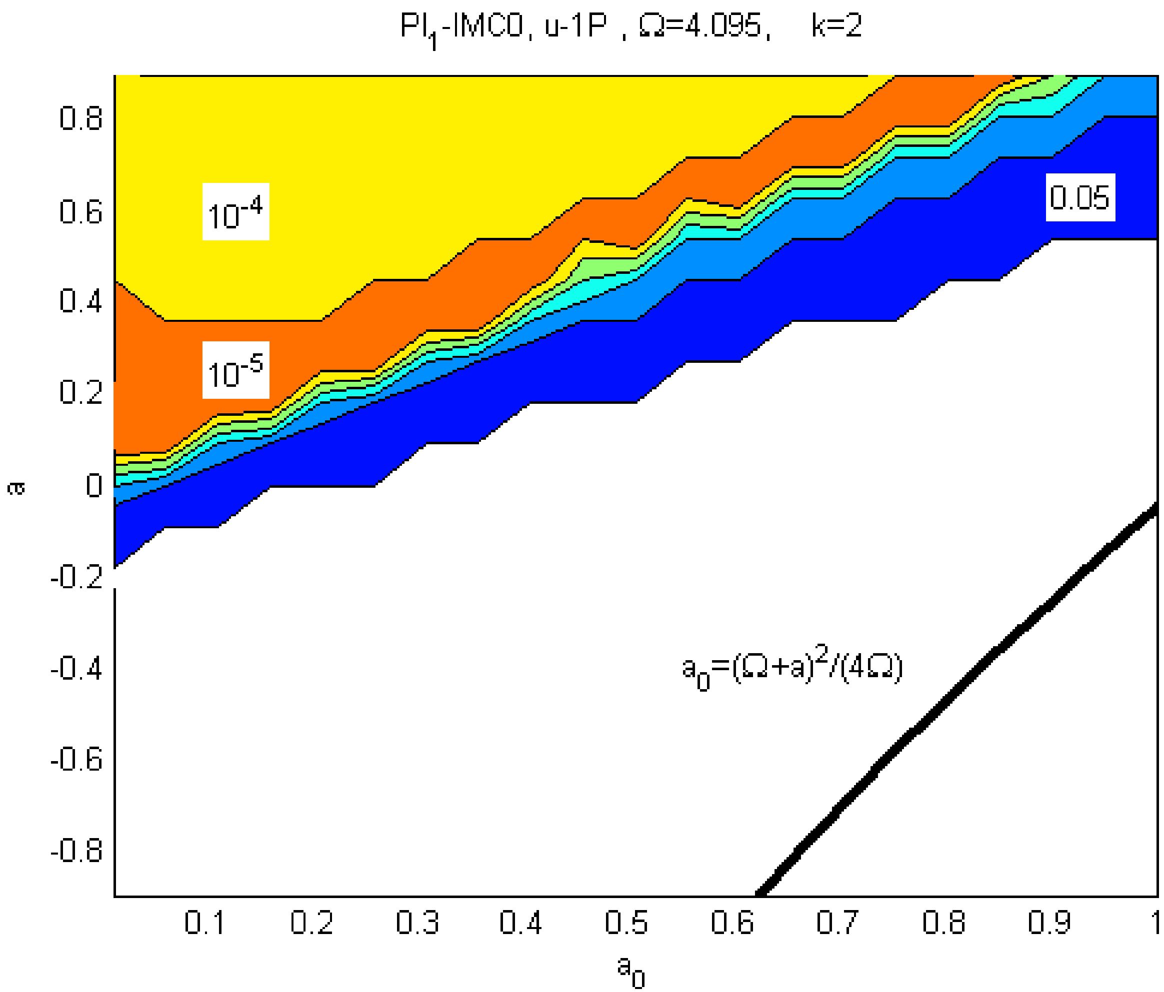
Aperiodicity Border

$$\frac{(\Omega_r+a)^2}{4\Omega_r}=a_0$$



Analytical Tuning ver. PP for $K_{s0}=K_s$

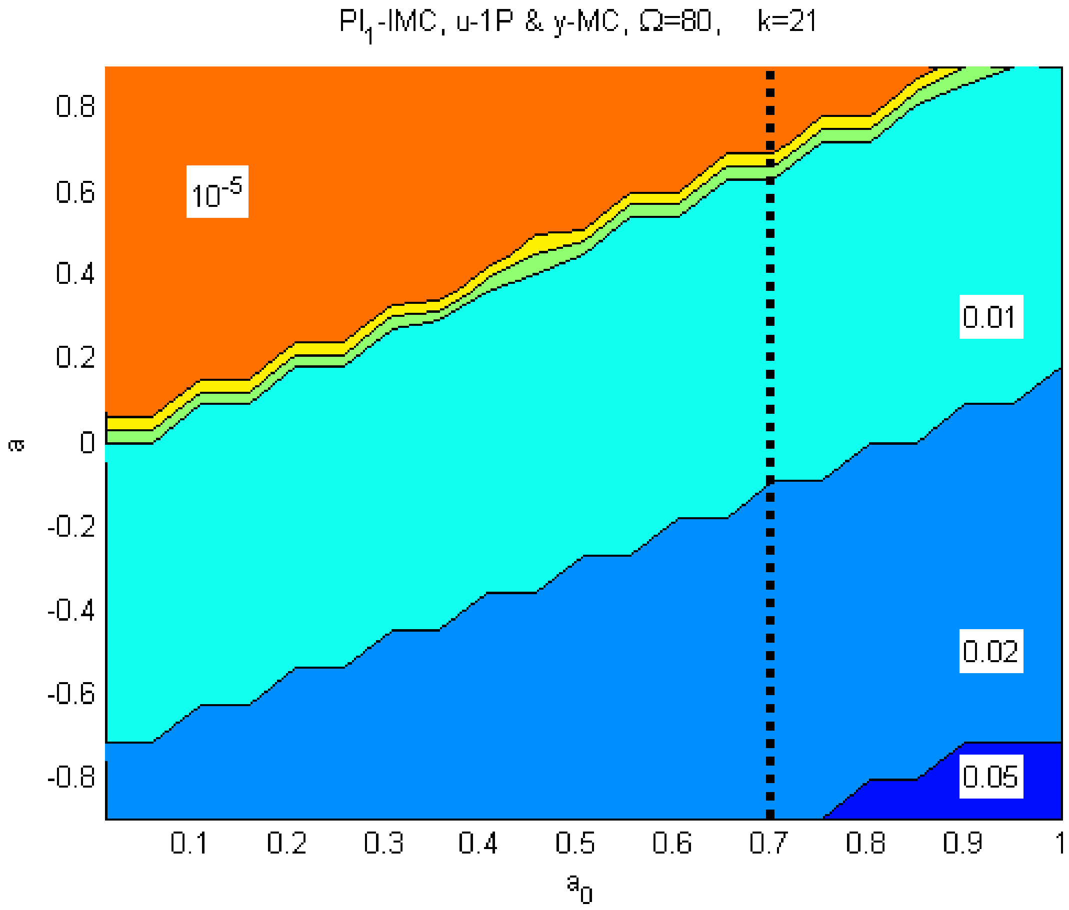
For increasing values the Aperiodicity Border gives no significant information



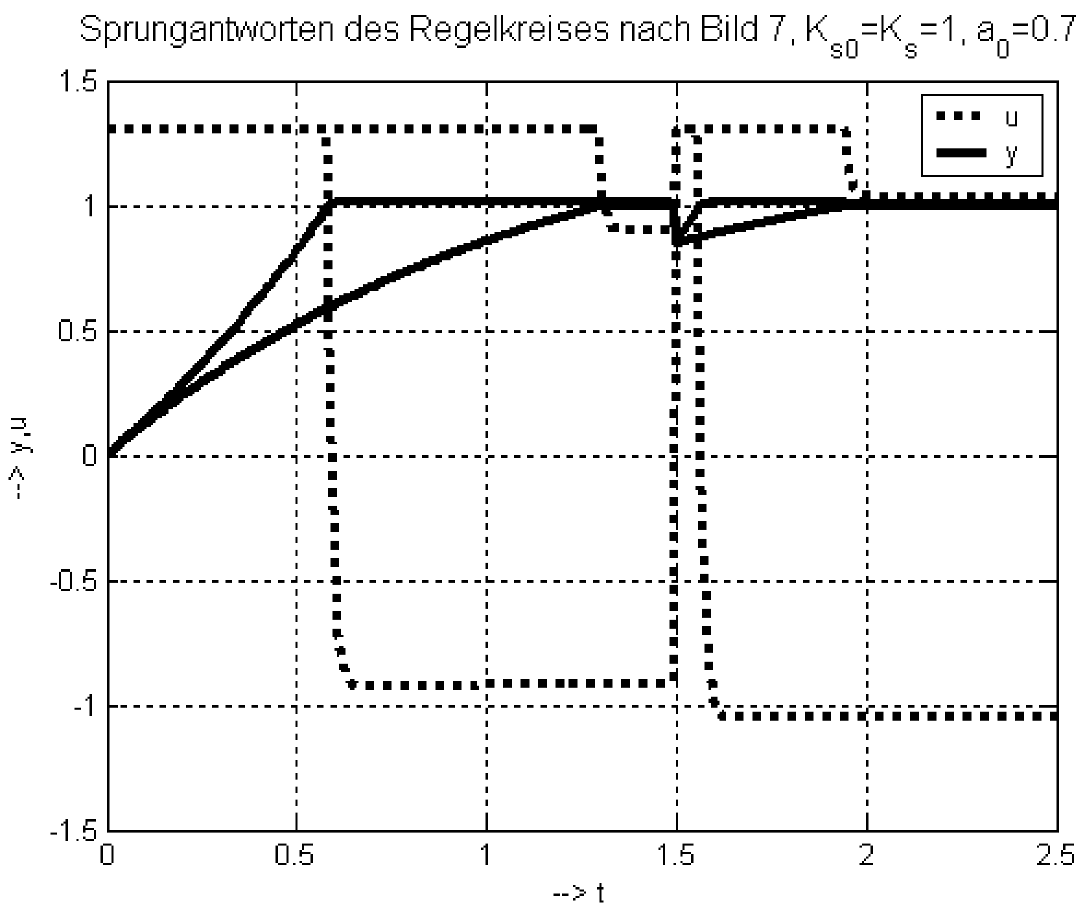
Robust Tuning based on PP for $K_{s0}=K_s$

Localizing Uncertainty Line Segment for uncertain *a*

$$a \in \langle -0.9, 0.9 \rangle$$



Corresponding transient responses



PP for uncertain *a* and K_s

$$\kappa = \frac{K_{s0}}{K_s} \in \langle 0.05, 2 \rangle$$

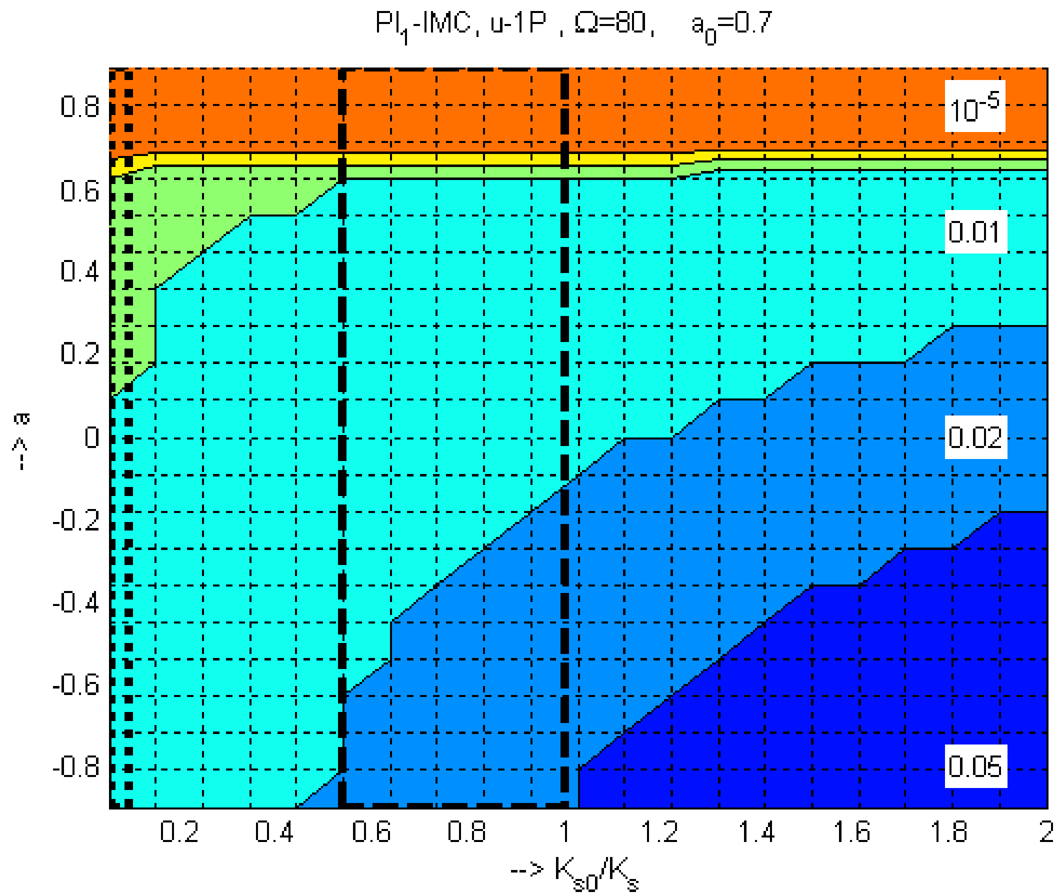
$$a \in \langle -0.9, 0.9 \rangle$$

$$a_0 = 0.7; \Omega_r = 80$$

Localizing UB for variable *a* and K_s

ε= 2%

$$\kappa = K_{s0} / K_s < 1$$



Output Disturbance Compensation

- It is enough to use the measured output for disturbance reconstruction
- The same transfer functions may be derived for the PI_1-2PM controller – both solutions are equivalent
- Basic Problem: *Integral and Unstable Plants*
- It is not possible to stabilize two parallel unstable plants by a single input (divergence of the output disturbance reconstruction error)
- Divergence of the output disturbance equivalent to a constant input (load) disturbance – computer overfloat problem
- Well known within the Internal Model Control (IMC)

Output Disturbance Compensation

- Basic Problem: *Integral and Unstable Plants*
- **First solution**:
- Choosing a_0>0 even if a≤0
- Effect of the imperfect approximation may be reduced by robust tuning procedure
- Basic question: how far does the imperfect approximation influence the achievable performance?
- Response possible by the Performance Portrait method

Output Disturbance Compensation

- Basic Problem: *Integral and Unstable Plants*
- **Second solution**:
- Modifying the output disturbance reconstruction for unstable plants

$$y = x + v_o \;;\; v_o = const \Rightarrow \frac{dy}{dt} = \frac{dx}{dt}$$

- From the plant model

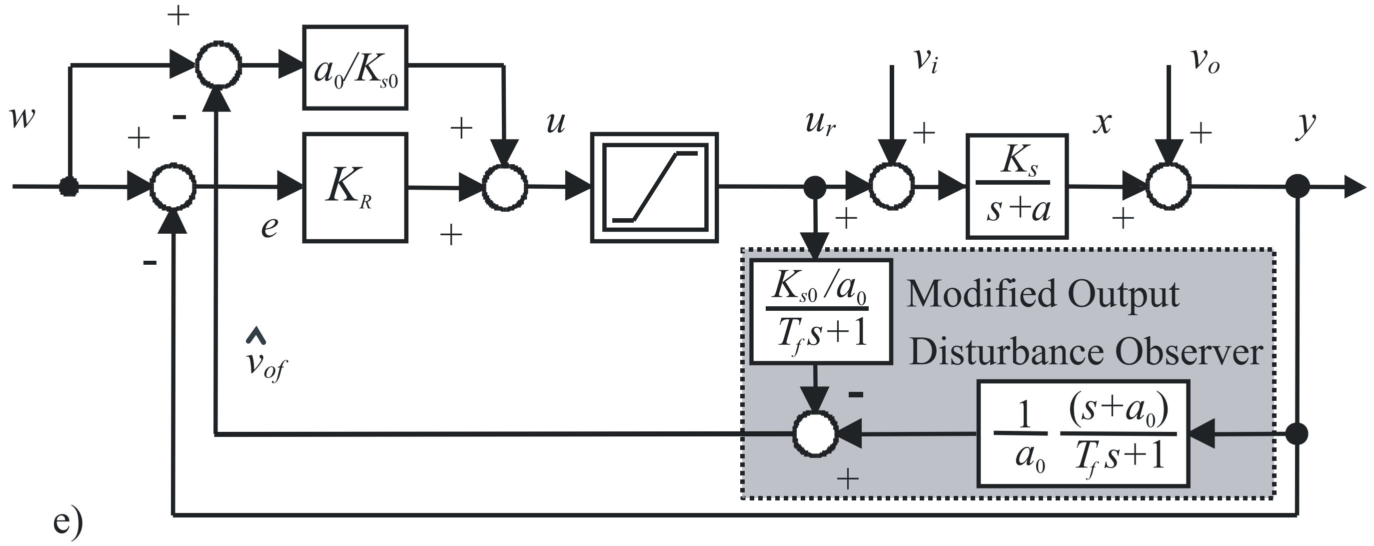
$$\hat{x} = \frac{1}{a}\left[K_s u - \frac{dx}{dt}\right] = \frac{1}{a}\left[K_s u - \frac{dy}{dt}\right]$$

- Modified reconstruction algorithm

$$\boxed{\hat{v}_o = y - \hat{x} \;\; = y - \frac{1}{a}\left[K_s u - \frac{dy}{dt}\right]}$$

Output Disturbance Compensation

- Basic Problem: *Integral and Unstable Plants*
- **Second solution**: Control Scheme
- Modified output disturbance reconstruction for unstable plants – *disturbance observer filter*
- Close to the input disturbance reconstruction



Output Disturbance Compensation

- In general, output disturbance equivalent to a constant load disturbance is not constant
- Usability Check: Loop transfer functions

$$F_w(s) = \frac{1}{1+T_w s} \; ; \; T_w = \frac{1}{K_s K_R + a} \; ; \; a_0 = a \; ; \; K_{s0} = K_s$$

$$F_{vo}(s) = \frac{sT_f T_w (s+a)}{(1+T_w s)(1+T_f s)} \; ; \; F_{vi}(s) = \frac{sT_f T_w K_s}{(1+T_w s)(1+T_f s)}$$

$$F_{vo}(0) = 0 \; ; \; F_{vi}(0) = 0 \; \text{ (for } a \neq 0\text{)}$$

- Integral case should again be approximated by $a_0 \neq 0$ – but now it is possible to choose also $a_0 < 0$

Output Disturbance Compensation

- PI_1-2PM Transfer functions (general case)

$$F_w(s)=\frac{Y(s)}{W(s)}=\frac{K_s(T_f s+1)\Omega}{K_{s0}T_f s(s+a)+K_s\left(1+T_f(\Omega-a_0)\right)s+K_s\Omega};$$

$$F_{vo}(s)=\frac{Y(s)}{V_o(s)}=\frac{s(s+a)K_{s0}T_f}{K_{s0}T_f s(s+a)+K_s\left(1+T_f(\Omega-a_0)\right)s+K_s\Omega};$$

$$F_{vi}(s)=\frac{Y(s)}{V_i(s)}=\frac{sK_sK_{s0}T_f}{K_{s0}T_f s(s+a)+K_s\left(1+T_f(\Omega-a_0)\right)s+K_s\Omega};$$

$$F_w(0)=1;\ F_{vo}(0)=0;\ F_{vi}(0)=0$$

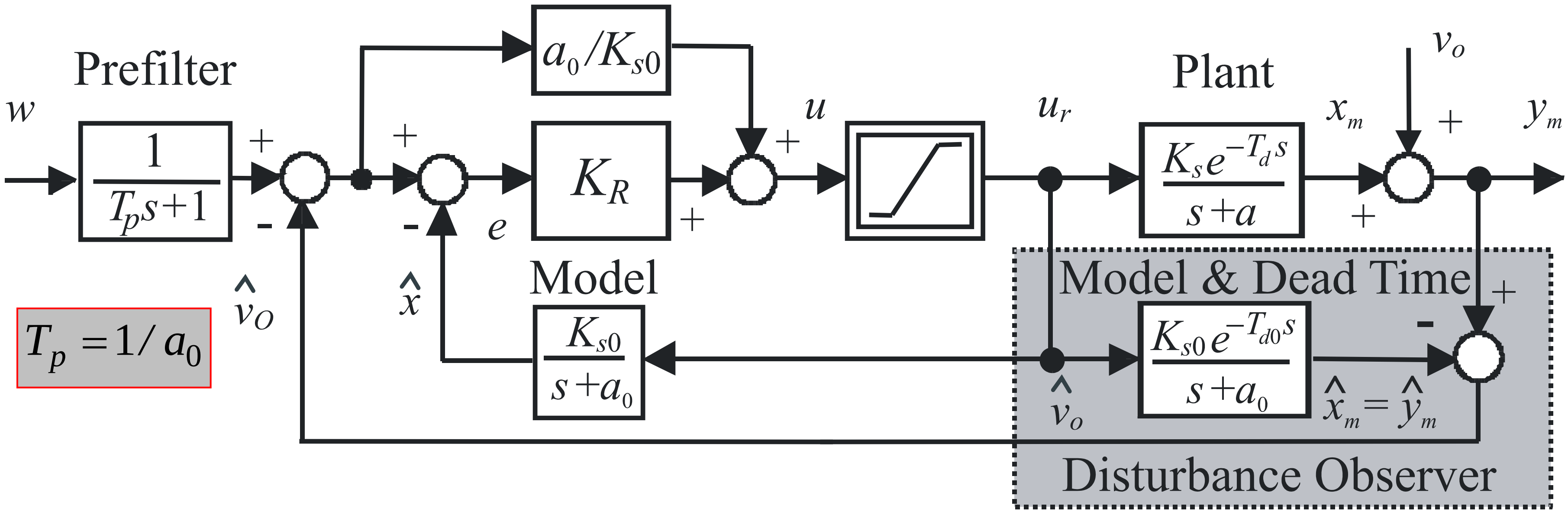
- This holds also for F_{vi} and a=0, a_0=0, but the reconstruction formulas are not defined
- Increased robustnes for prefilter with $T_p=T_f$

Output Disturbance Compensation

- $T_{d0} \neq 0$
- Output disturbance reconstruction & compensation (parallel model – IMC like structure – Smith predictor)

$$K_R = (\Omega_r - a_0) / K_{s0}$$

$$T_p = 1/a_0$$

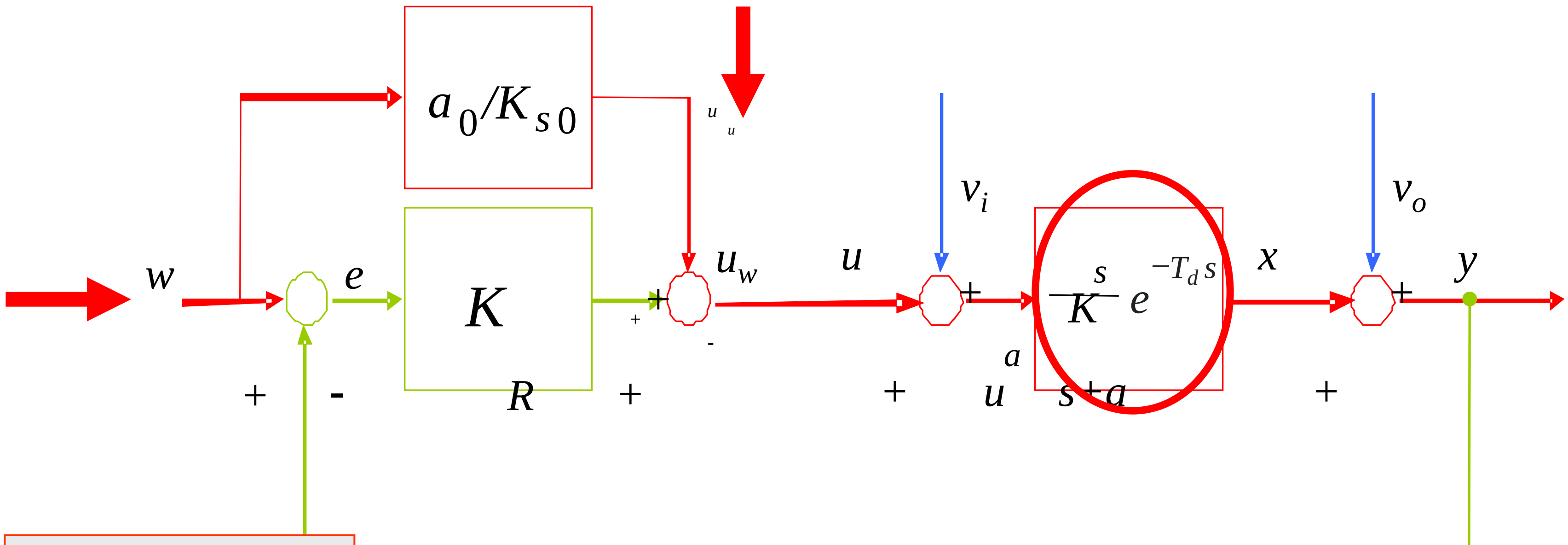


Conclusions 2

- Two classes of model based PI controller from the dynamical class 1 were introduced and compared
- The IMC like structures with parallel plant model seem to be simpler (no disturbance filter is strictly required), but they are limited just to controlling stable plants and the disturbance filter is also here welcomed due to improved robustness
- Solutions with Inverse Model seem to be more universal (no problems with control of unstable plants).

Dynamic class 1

- Linear pole assignment P-controller

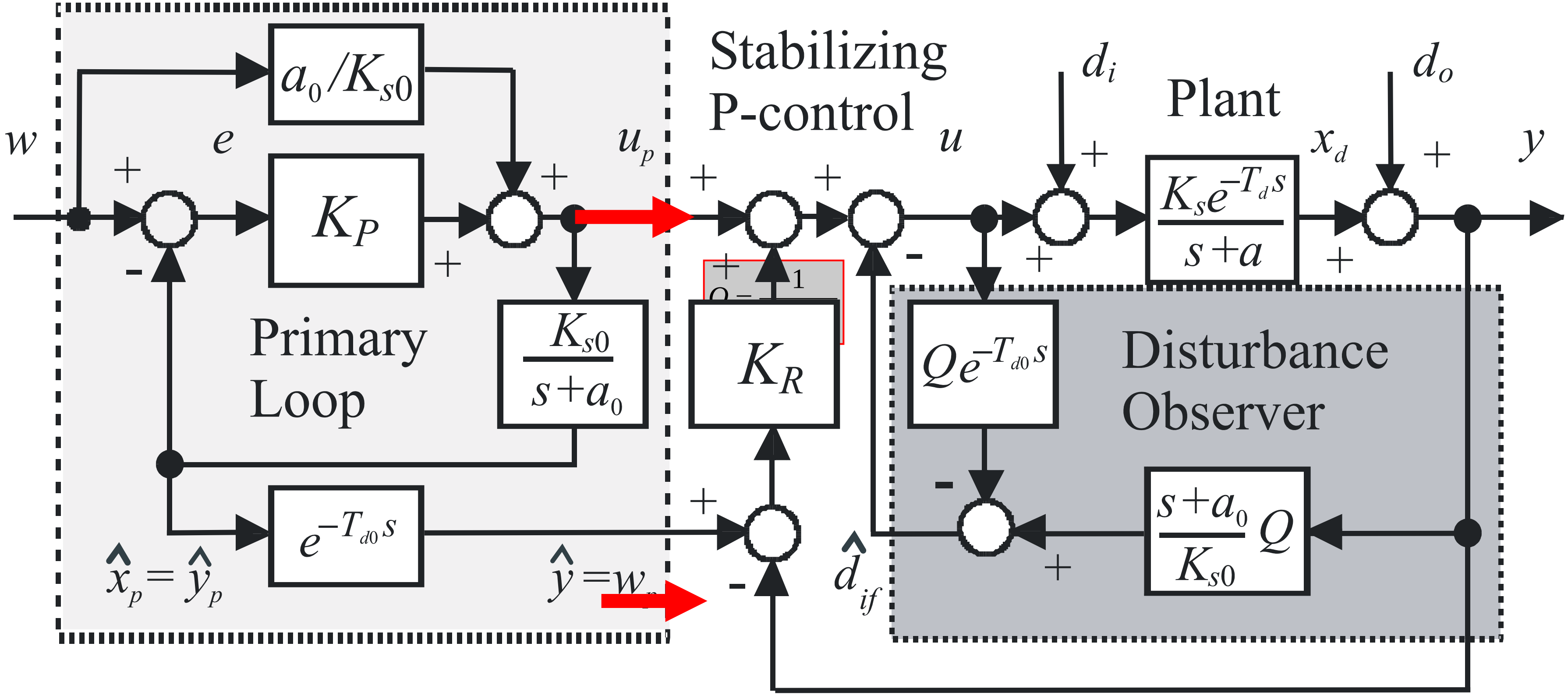


$$e = w - y$$

$$u = K_R e + u_w \ ; \ K_R = \frac{e^{-\left(1+a_0 T_{d0}\right)}}{K_{s0} T_{d0}} \ ; \ u_w = \frac{a_0}{K_{s0}} w$$

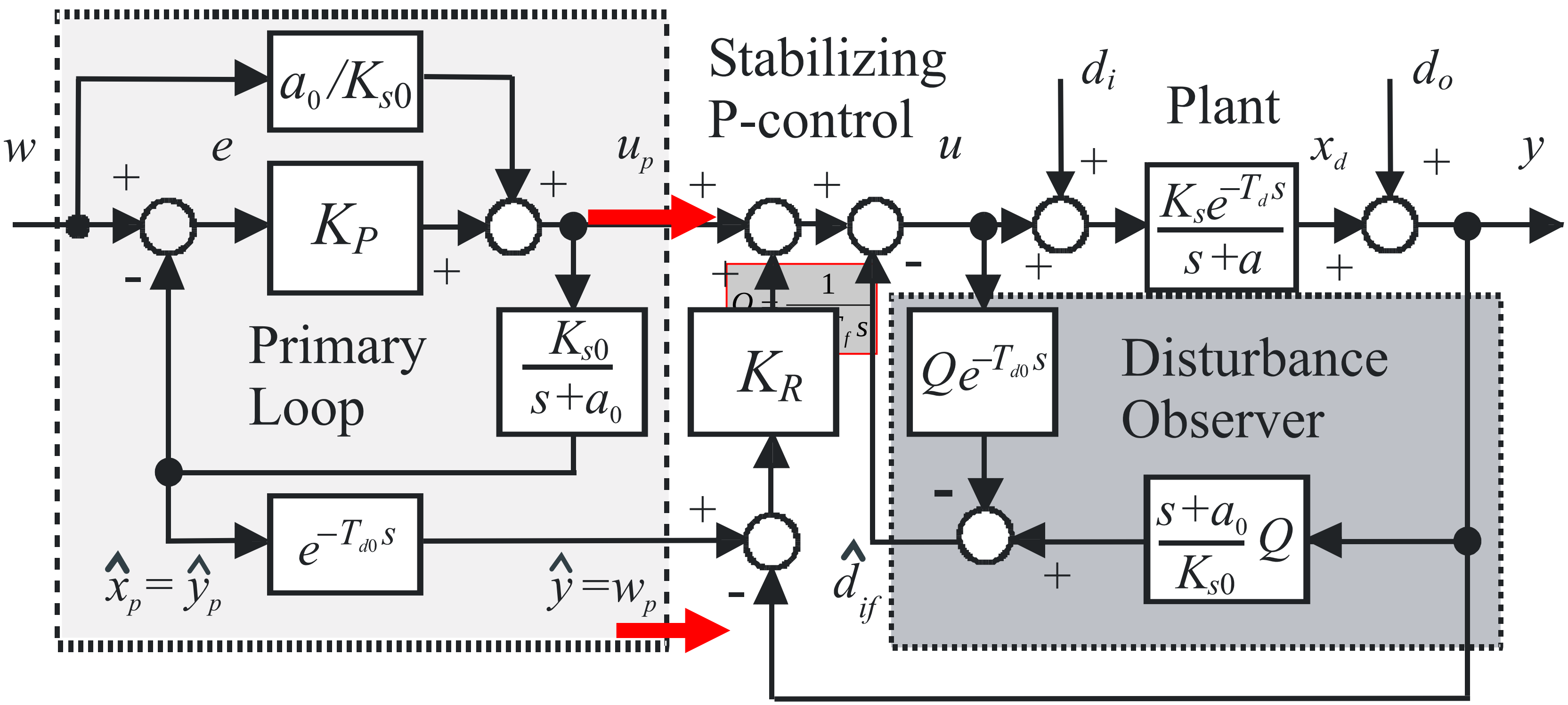
PI_1-DFF-DTIM controller

P controller + dynamical feedforward + observer for input disturbance with IM and compensation of dead time T_d



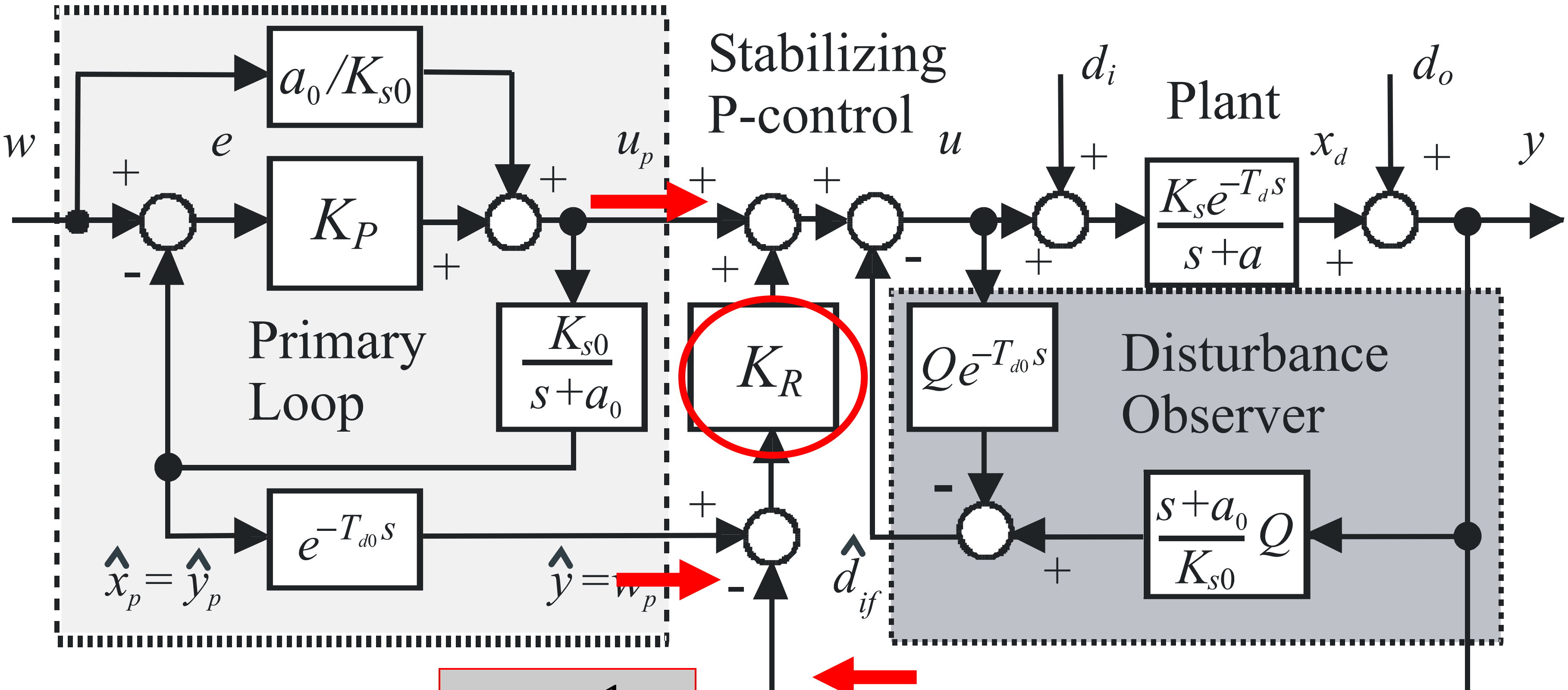
PI_1-DFF-DTIM controller

P controller + dynamical feedforward + observer for input disturbance with IM and compensation of dead time T_d



PI1-DFF-DTIM controller

P controller + dynamical feedforward + observer for input disturbance with IM and compensation of dead time T_d

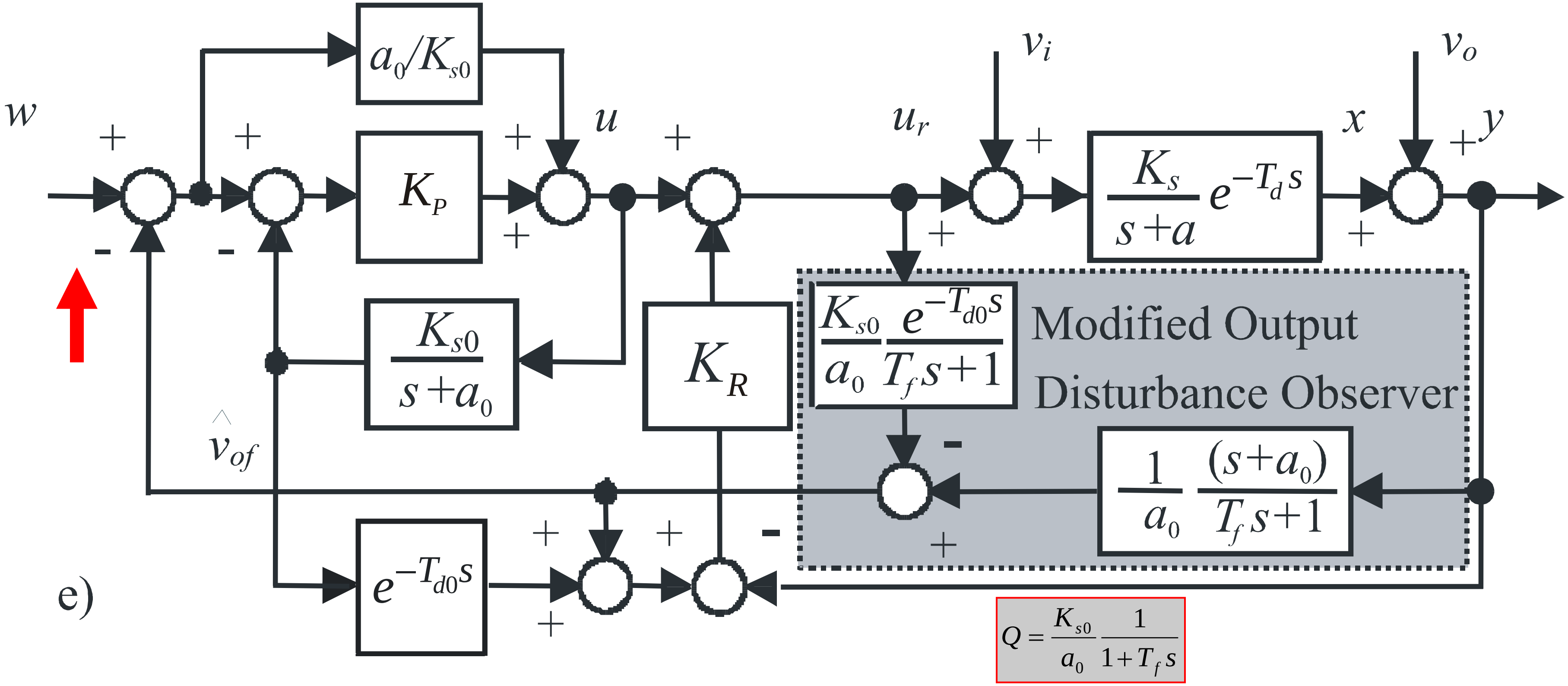


$$Q = \frac{1}{1+T_f s}$$

PI$_1$-DFF-DTMPM controller

P controller + dynamical feedforward + observer for output disturbance with MPM and compensation of dead time T_d

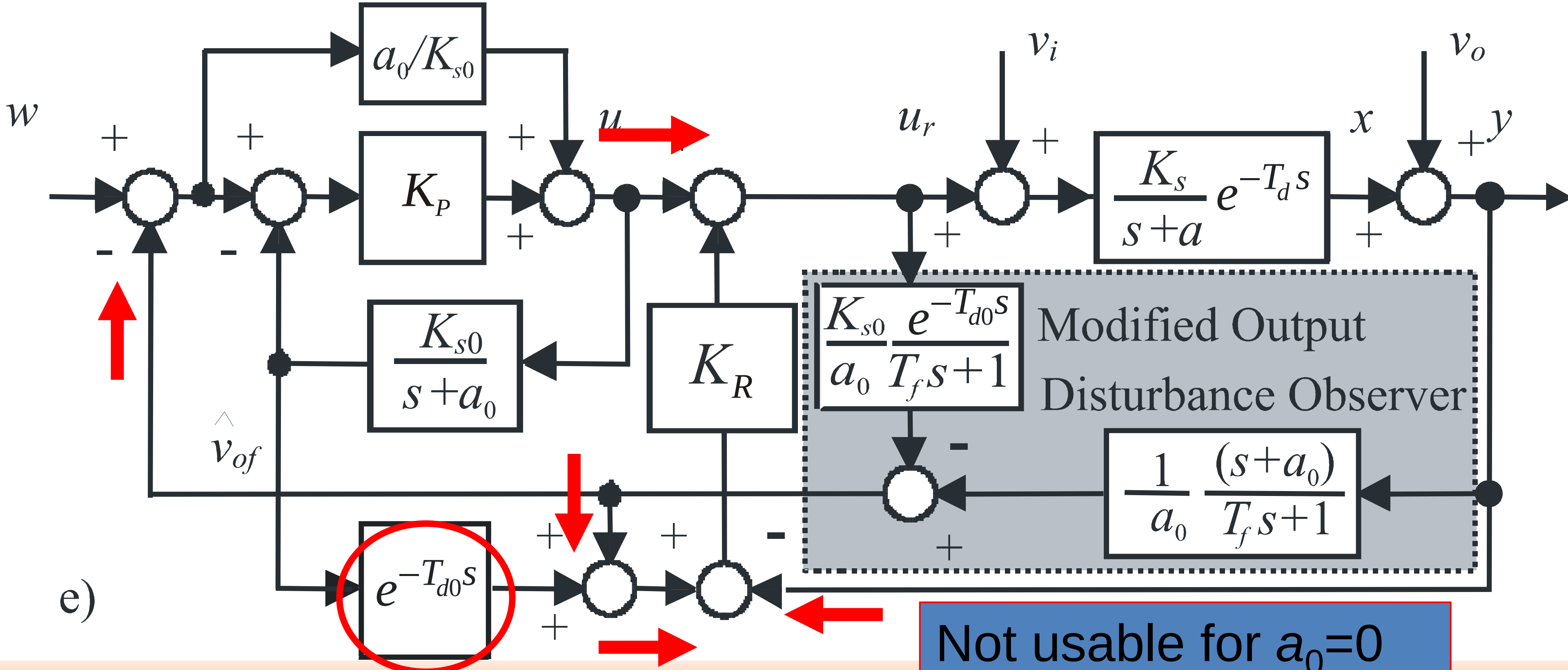
- MPM = Modified Parallel Model



PI1-DFF-DTMPM controller

P controller + dynamical feedforward + observer for output disturbance with MPM and compensation of dead time T_d

- MPM = Modified Parallel Model



Not usable for a_0=0

Analytical Construction of PP

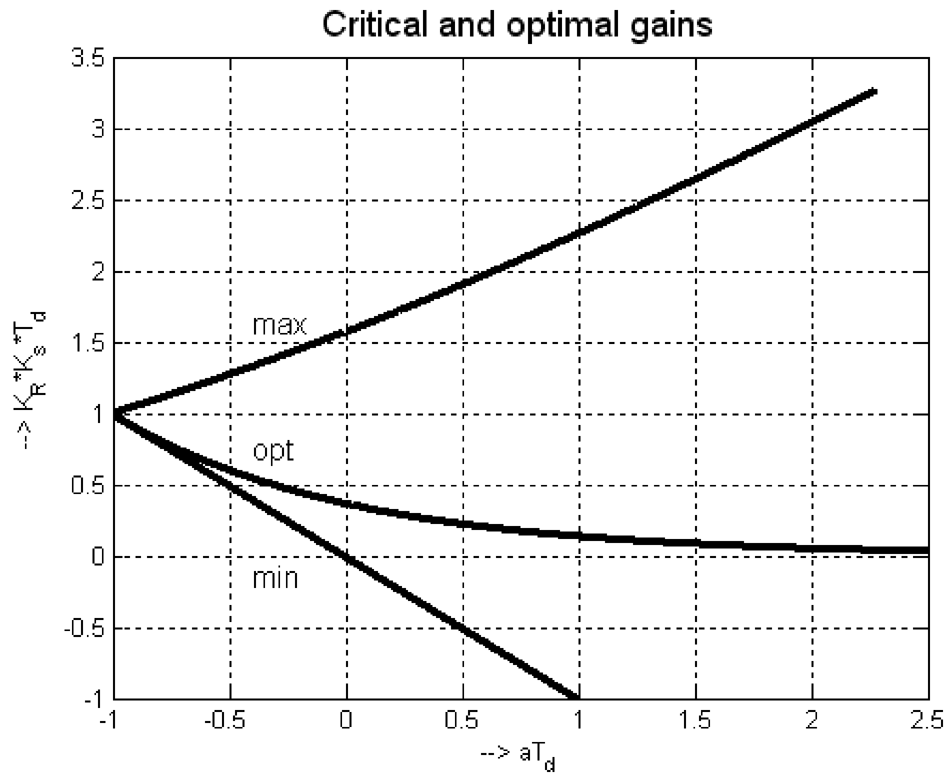
- Critical and optimal gains (aperiodicity border)

$$K_{min} < K < K_{max} \;;\; K = K_R K_s T_d$$

$$K_{max} = \frac{\tau_d}{\sin\tau_d} \;; A = -\frac{\tau_d \cos\tau_d}{\sin\tau_d} \;;$$
$$\tau_d \in (0, \pi/2) \cup (\pi/2, \pi)$$

$$K_{min} = -A = -aT_d$$

$$K_{opt} = e^{-(1+aT_d)}$$



Basic Questions

- Is it not possible to design nominal dead-time compensator with parallel model for reconstruction and compensation of an output disturbance of pure integrator?
- Is it not possible to control unstable plants with $aT_d<-1$
- Is it not possible to improve the disturbance response?

Modifications of SP for IPDT Systems

- C. C. Hang and F. S. Wong, “Modified Smith Predictors for the control of processes with dead time,” in Proc. ISA Annual Conf., 1979, 33-44.
- K. Watanabe and M. Ito, “A process-model control for linear systems with delay,” IEEE Trans. Automat. Conrr., vol. AC-26, no. 6, Dec. 1981, 1261-1266.
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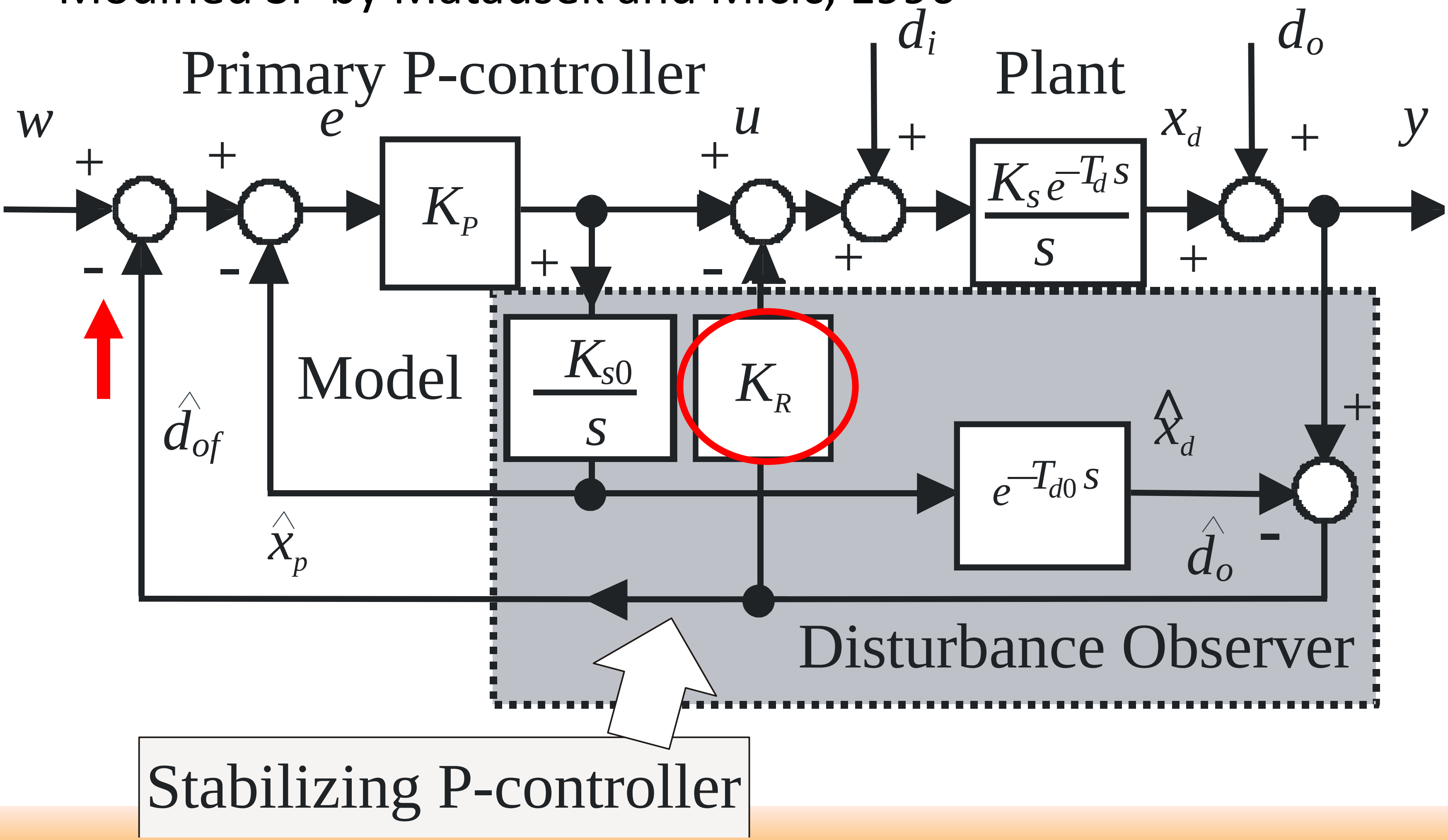
Stabilized SP (SSP)

Modified SP by Mataušek and Micič, 1996



Stabilized SP (SSP)

Modified SP by Mataušek and Micič, 1996

- Transfer functions

$$\boxed{a_0 = a\ ;\ K_{s0} = K_s\ ,\ T_{d0} = T_d}$$

$$F_w(s) = \frac{K_s K_P e^{-T_d s}}{(s + K_s K_P)} = \frac{e^{-T_d s}}{T_w s + 1}\ ;\ T_w = \frac{1}{K_s K_P}$$

$$F_{vo}(s) = \frac{s\left(s + K_s K_P - K_s K_P e^{-T_d s}\right)}{\left(s + K_s K_R e^{-T_d s}\right)\left(s + K_P K_s\right)}\ ;\ F_{vi}(s) = \frac{K_s}{s} F_{vo}$$

$$F_w(0) = 1\ ;\ F_{vo}(0) = 0\ ;\ F_{vi}(0) = 0 \text{ for } K_P K_s > 0$$

$$K_{Ropt} = 1/(K_s T_d e) \approx 1/(2 K_s T_d)$$

Comparing PI$_1$-DTIM and SSP

- IM has dist. response independent from Tw

Ks=1

a=0

Td=1

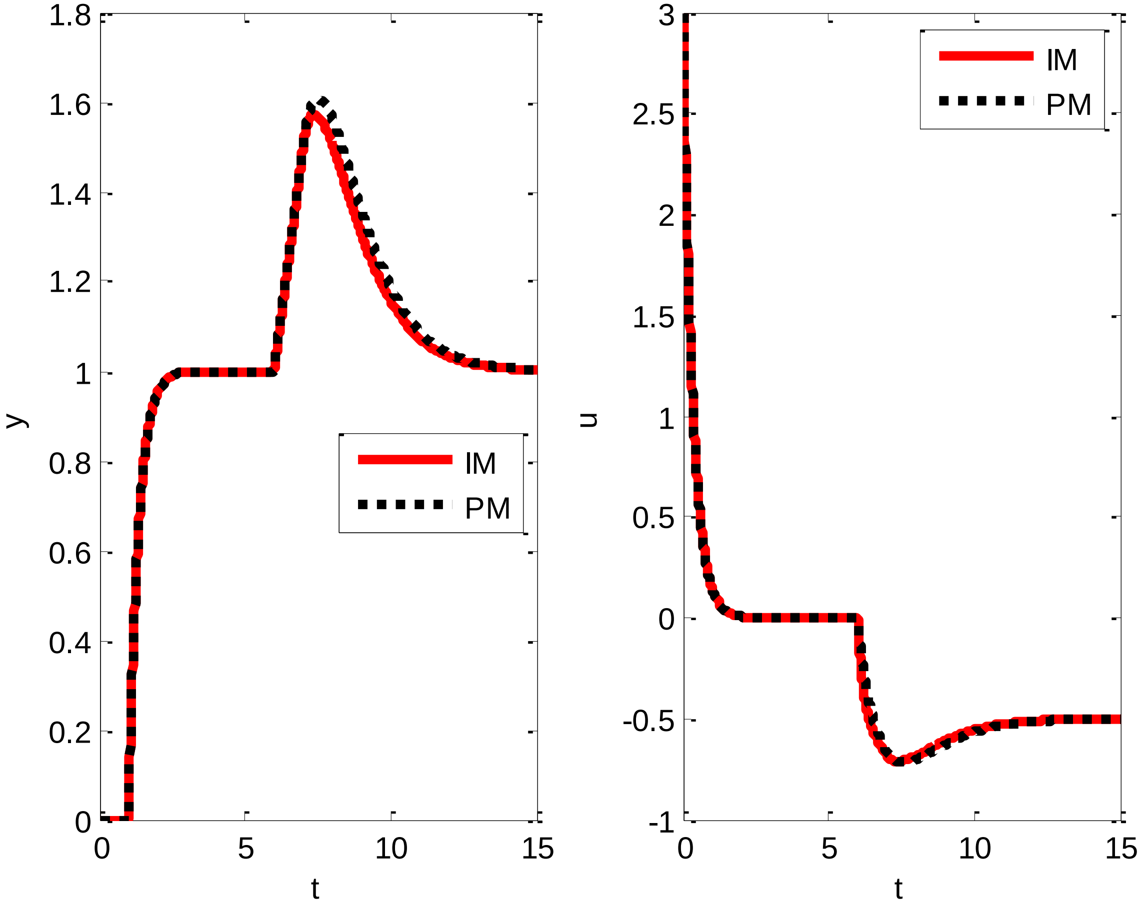
Kp=3

Tw=0.33

Tf=0.2

vi=0.5

KR=KRopt



Comparing PI_1-DTIM and SSP

- Stabilizing P-controller of SSP compensates input disturbances (black)
- Stabilizing P-controller of PI_1-DTIM is active just during transients

Ks=1

a=-0

Td=1

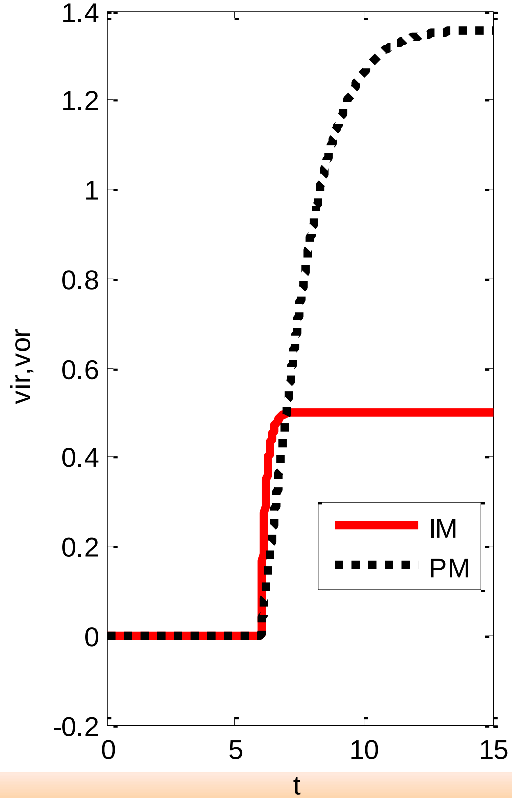
Kp=3

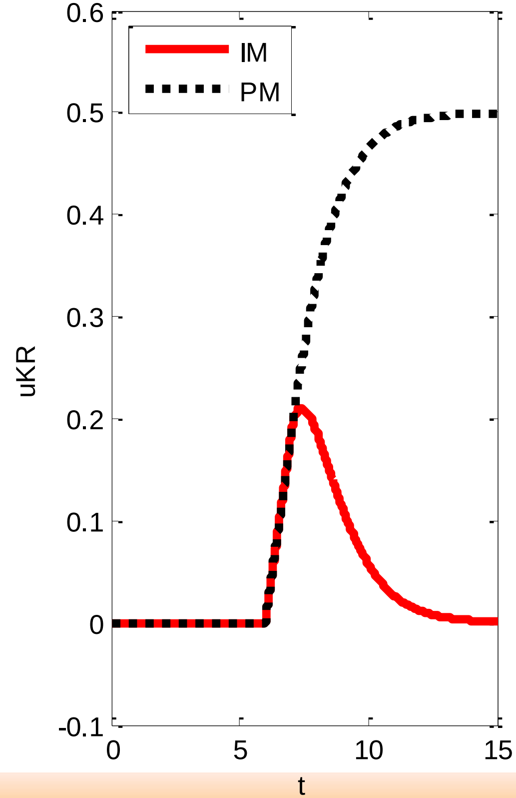
Tw=0.33

Tf=0.2

vi=0.5

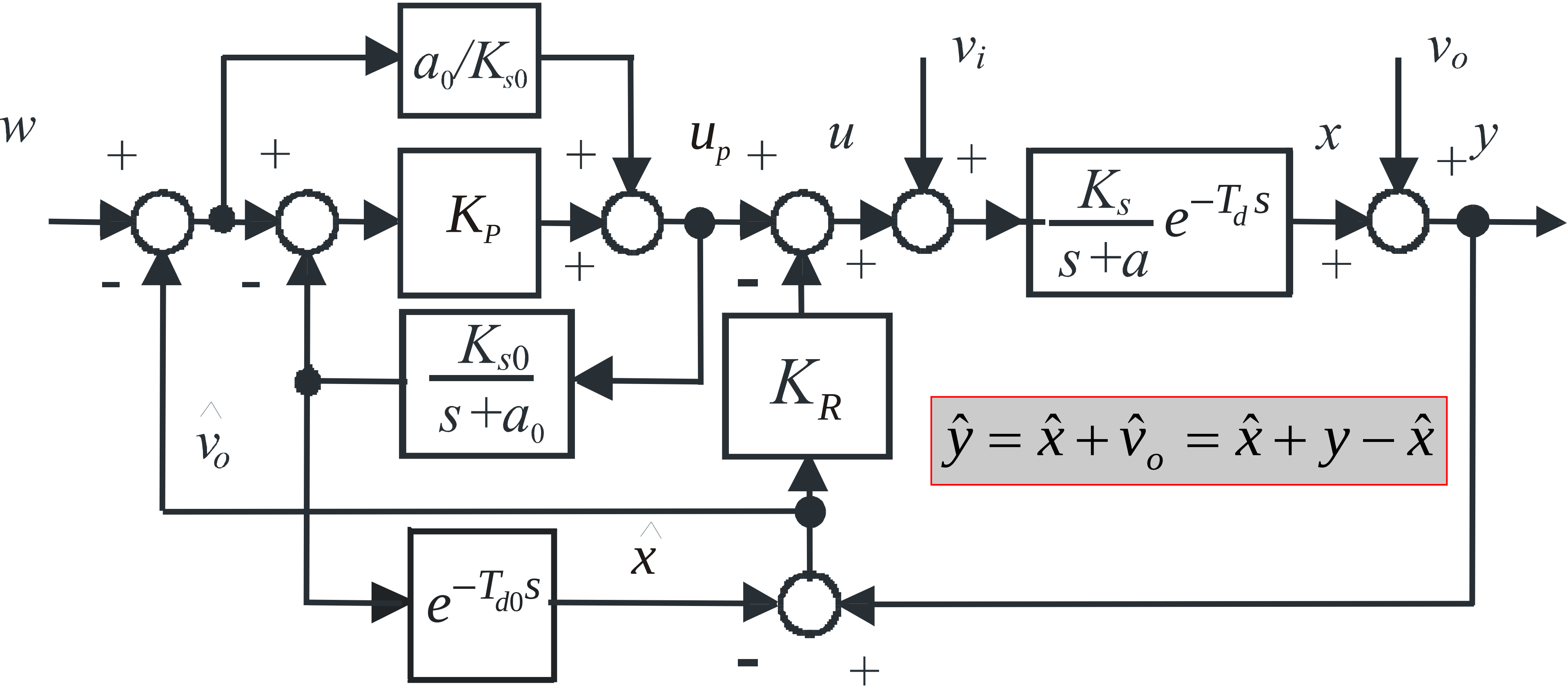
KR=KRopt





Generalized Stabilized SP (GSSP)

Generalization of
solution proposed by Mataušek and Micič, 1996



$$\hat{y} = \hat{x} + \hat{v}_o = \hat{x} + y - \hat{x}$$

Generalized Stabilized SP (GSSP)

Generalization of solution by Mataušek and Micič, 1996

- Transfer functions

$$\boxed{a_0 = a \; ; \; K_{s0} = K_s \, , \, T_{d0} = T_d}$$

$$F_w(s) = \frac{(K_s K_P + a)e^{-T_d s}}{(s + K_s K_P)} = \frac{e^{-T_d s}}{T_w s + 1} \; ; \; T_w = \frac{1}{K_s K_P + a}$$

$$F_{vo}(s) = \frac{(s+a)\left(s + a + K_s K_P - (K_s K_P + a)e^{-T_d s}\right)}{\left(s + K_s K_R e^{-T_d s} + a\right)(s + K_P K_s + a)} \; ; \; F_{vi}(s) = \frac{K_s}{s+a} F_{vo}$$

$$F_w(0) = 1 \; ; \; F_{vo}(0) = 0 \; ; \; F_{vi}(0) = 0 \text{ for } K_P K_s + a > 0$$

$$K_{Ropt} = \exp(-(1 + aT_d)) / (K_s T_d)$$

PI$_1$-DTIM,MPM and GSSP

- IM has dist. response independent from Tw

Ks=1

a=-0.5

Td=1

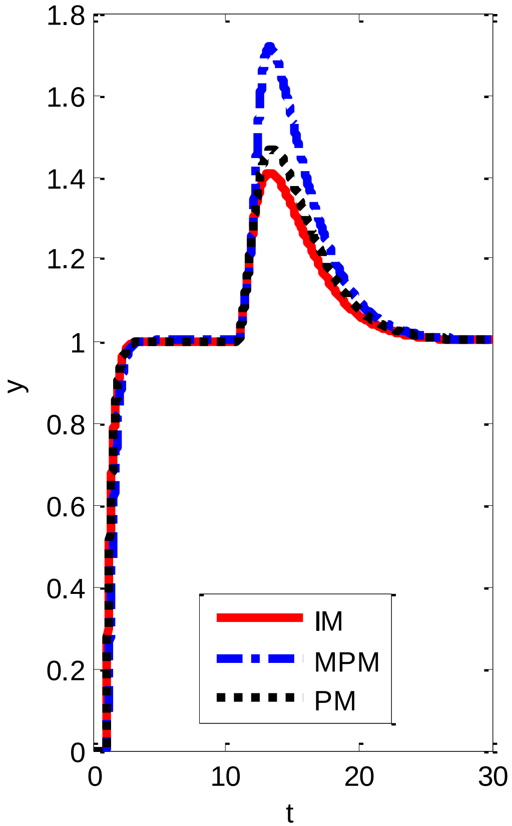
Kp=3

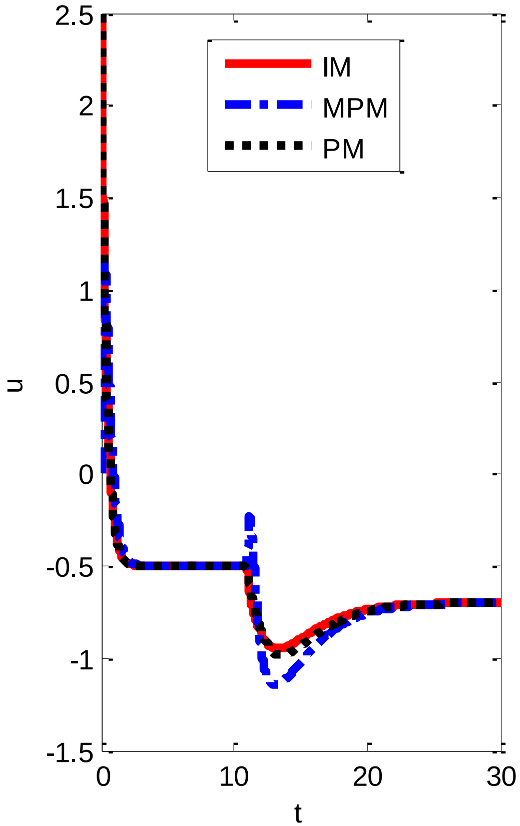
Tw=0.4

Tf=0.2

vi=0.2

KR=KRopt





PI_1-DTIM, MPM and GSSP

- Stabilizing P-controller compensates inp.dist.

Ks=1

a=-0.5

Td=1

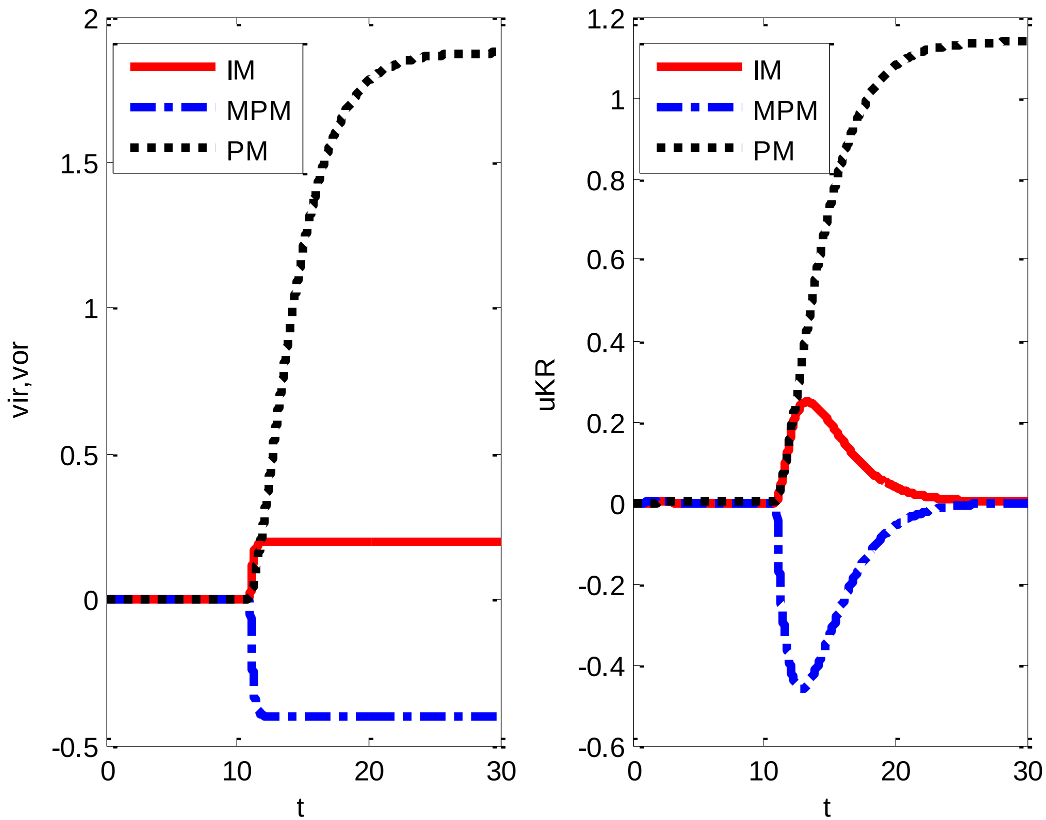
Kp=3

Tw=0.4

Tf=0.2

vi=0.2

KR=KRopt



PI_1-DTIM, MPM and GSSP

- IM has slightly better disturbance response

Ks=1

a=0.5

Td=1

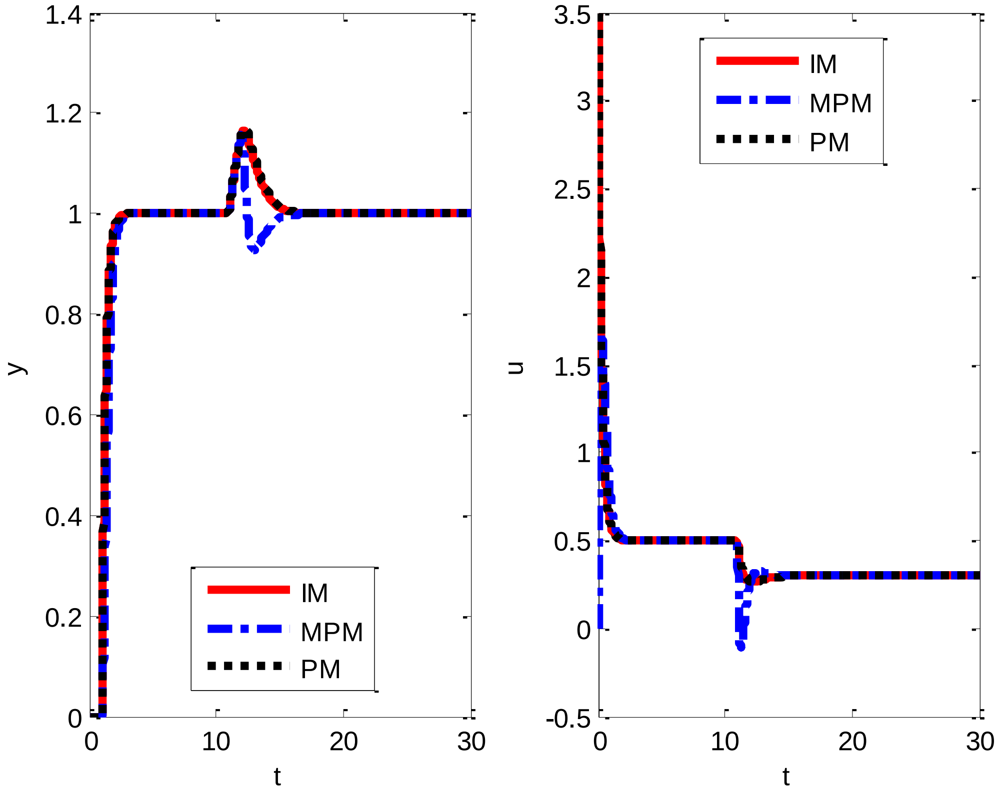
Kp=3

Tw=0.286

Tf=0.2

vi=0.2

KR=KRopt



PI$_1$-DTIM,MPM and GSSP

- Stabilizing P-controller compensates inp.dist.

Ks=1

a=0.5

Td=1

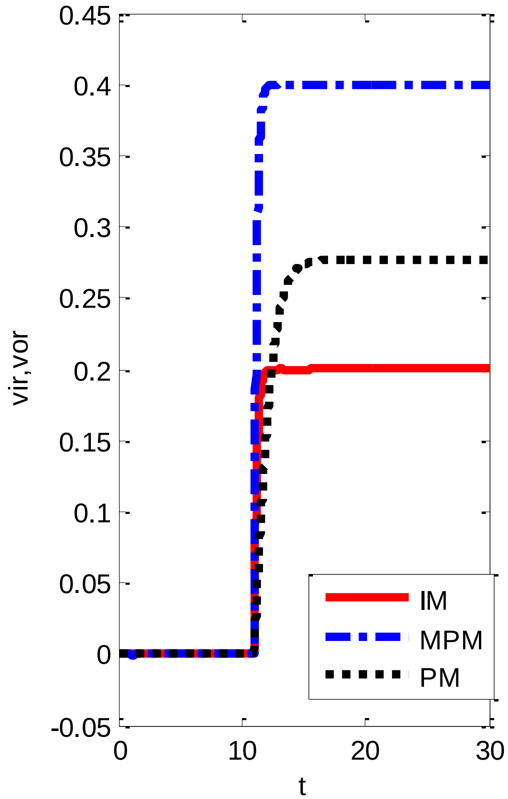
Kp=3

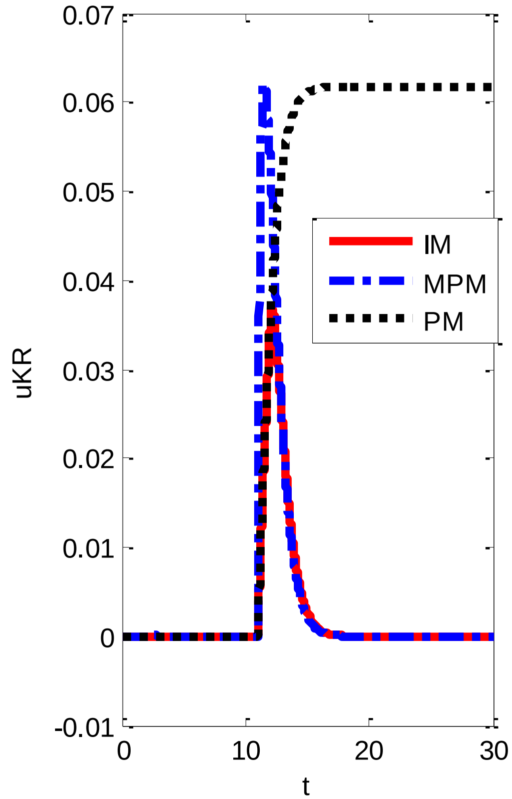
Tw=0.286

Tf=0.2

vi=0.2

KR=KRopt

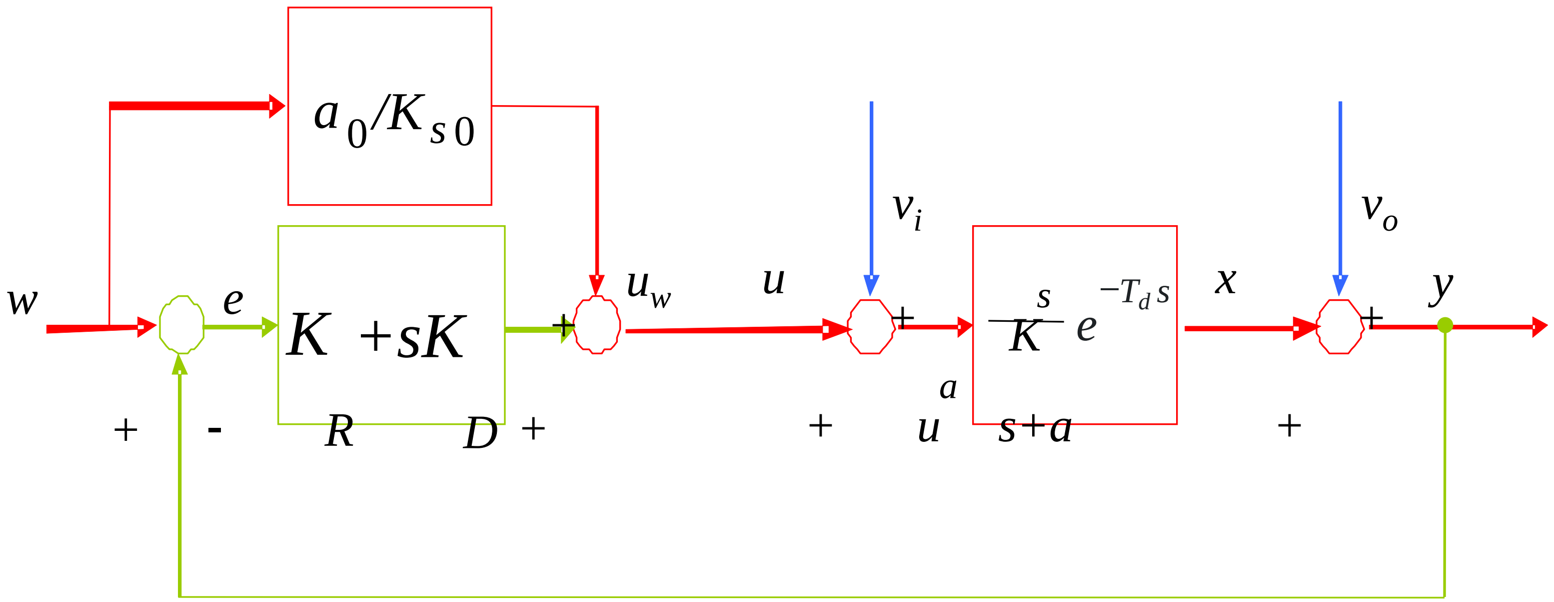




Conclusions 3

- Several alternatives for constructing P-controlllers with dynamical feedforward for integral and unstable FOPDT plants
- All of them keep the disturbance observer+stabilizing controller structure – important for constrained control – no windup
- All of them guarantee no influence of disturbances on the output in steady states, but internally they are different
- All of them keep poles of simple P-controller with FOPDT plant – easy tuning of stabilizing controller
- However, transients after disturbance steps are different – the same will hold for robustness

Linear pole assignment PD-controller



$$u = K_R e + K_D \frac{de}{dt} + u_w \; ; \; K_R = \frac{\left(4 + a_0 T_d\right) e^{-\left(2 + a_0 T_{d0}\right)}}{K_{s0} T_{d0}} \; ;$$

$$u_w = \frac{a_0}{K_{s0}} w \; ; \; K_D = \frac{e^{-\left(2 + a_0 T_{d0}\right)}}{K_{s0}} \; ; \; T_D = \frac{K_D}{K_R} = \frac{T_{d0}}{4 + a_0 T_d}$$

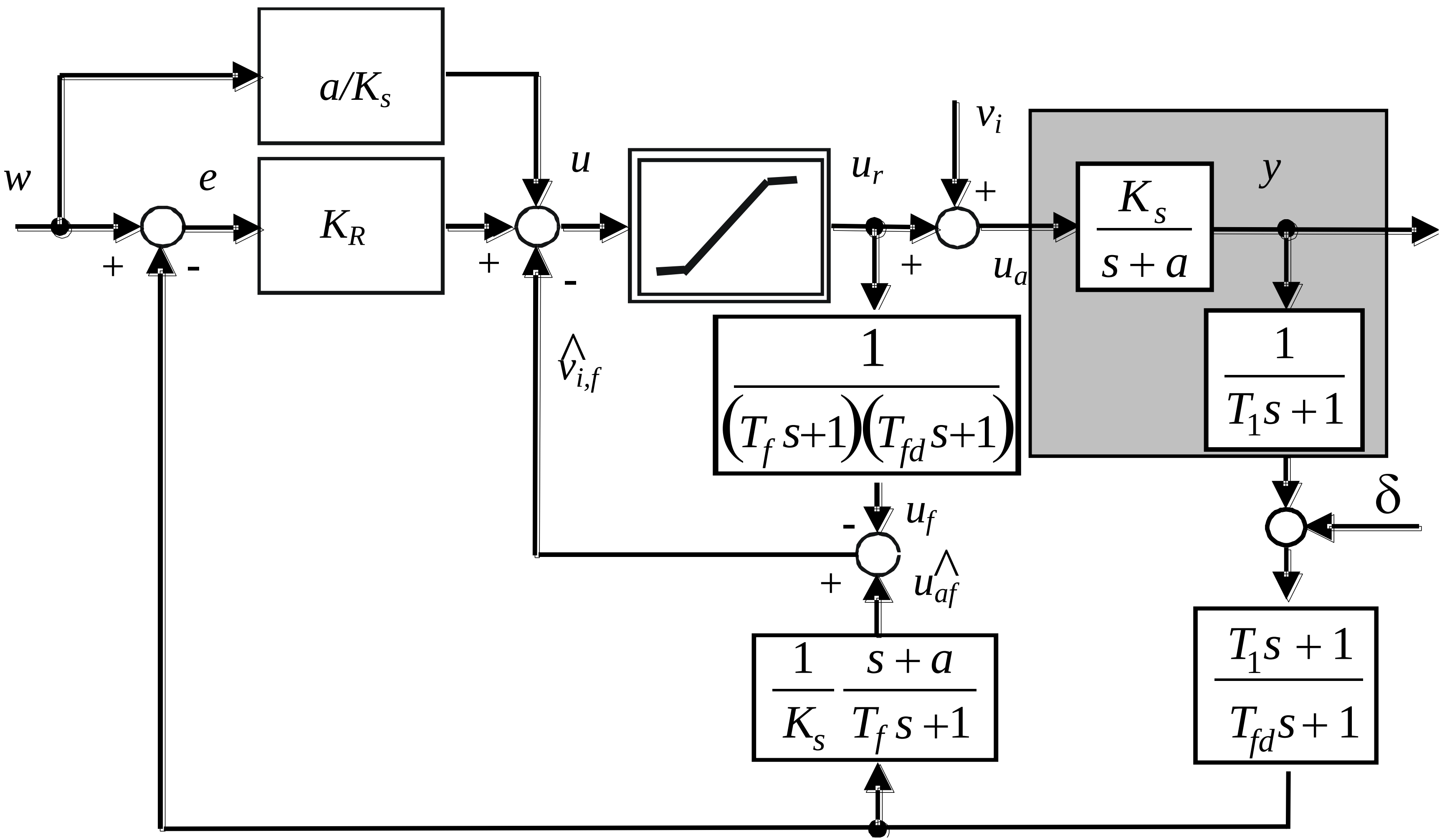
Conclusions 4

- Introduction of D-action can ideally double the admissible negative product aT_d from -1 up to -2
- This, however, holds just for ideal PD controller without filter in denominator, so the real extension will be less and depends on the signal quality (measurement noise)
- Due to this it is also not realistic to think about more advanced controllers with higher order derivatives of control error

PID_1-controller

- Loop approximation with the second order dominant plant
- Stable time constant is located in the feedback (e.g. the sensor dynamics)
- Gives reliable results also in the case with this time constant in the feedforward path (e.g. the actuator time constant) – however, just for the DC1
- Optimal solutions for such configuration are already from DC2

Windupless PID_1 Controller



Advantages of PI_1 and PID_1 controllers

- Do not need Anti-Windup
- Tuning of lower number of parameters,
- Convex regions of MO and 1P control
- Optimal nominal point may be included in US – less steep quality decrease
- Simple performance portrait generation
- Modular structure
- Simple compensation of dead time T_d
- Possibility to use more complex filters (increased filter properties, increased robustness)