Will the PID control survive within Industry 4.0?

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Paper Aims & Objectives

- To discuss main problems of automated PID control design
- To show some recent significant achievements in this field
- To analyze possible development in the area
- To point out new trends in the PID control framework including:
    - requirement on the controller tuning starting with appropriate plant modeling & identification,
    - magic of integral models,
    - integrated controller & filter optimization,
    - performance and robustness evaluation,
    - conclusions for the future,

and to relate these aspects to the alternative approaches

Rules appropriate for education and practice (Skogestad, 2003) should be:

1. well motivated,
2. preferably model-based,
3. analytically derived,
4. simple and easy to memorize and
5. work well on a wide range of processes.

Besides of this (Skogestad, 2006), controller tuning should enable achieving trade-off between:

(i) fast speed of response, good disturbance rejection,
(ii) stability and robustness, less input usage and
(iii) less sensitivity to measurement noise.

The performance requirements should be flexibly modifiable in a broad range

Analytical tuning - double real dominant pole (Oldenoburg and Sartorius, 1944)
Experimental approach - Ziegler and Nichols (1942)
finding the optimal solution by experimentally sweeping all relevant tunings:

- solved originally for optimal disturbance response,
- for quarter amplitude damping,
- by a model-based approach - approximation of the setpoint step response by IPDT plant-asymptote by the inflection point,
- simple and easy to memorize results,
- works well on a wide range of processes.

Main ideas of these approaches generalized by the **PID_n^m control** (2018) and **Performance Portrait Method - PPM** (2009-2018) are now joined together, supported by **magic of integral control**

- PID control represents **the most frequently used control technology in practice** (Astrom-Hagglund, 2006)
- The derivative action
  - is the most difficult to tune (Visioli, 2006)
  - is not appropriate for noisy processes (Astrom-Hagglund, 2006)
  - does not yield a significant improvements for time-delayed systems (Astrom-Hagglund, 2006)

  - thus, it is mostly switched-off (Visioli, 2006).
- As documented e.g. by the 3rd IFAC conference on PID control in Gent 2018, recent works in this area deal mostly
  - with robustness problems,
  - with long time-delays,
  - with noise filtration,
  - with nonlinear systems control,
  - and dominantly with the **fractional order (FO)** controllers.

- **New degrees of freedom** - “to get additional two knobs for controller tuning” (Tepljakov et all, 2018) = no satisfaction with performance and robustness of traditional PID control.
- Simplified (automated) plant modeling, identification, optimal & robust controller design.
- Heuristic optimization techniques, multi-objective cuckoo search, gravitational search algorithm combined with the Cauchy and Gaussian mutation, particle swarm optimization, gravitational search algorithm, bacterial-foraging chemotaxis gravitational search algorithm, etc.
- However, the simplifications hold just for the first design phases, because the FO controllers have finally be approximated and implemented by **high-order filters**.
- Fashion wave kicked off by our compatriots I. Podlubny in IEEE Trans. AC 44, 1, 1999 - nearly 2500 citations...).

Performance Portrait Method

- PP = information about loop performance corresponding to setpoint and disturbance step responses evaluated and stored over a grid of (possibly normalized) loop parameters
- Extension to the (analytical) Parameter Space method (Ackermann et al., 2002)
- The only known numerical optimization method ensuring **re-usability**
- Appropriate for both the nominal and robust controller design (interval plant parameters)
- Based on new (shape related) performance measures
- No convergence problems
- More at `https://www.researchgate.net/project/Performance-Portrait-Method`

PID_n^m control:

- A generalization of the proportional-integral-derivative control by possibly higher integer-order derivative action up to the degree m and by $n \geq m$th order low-pass binomial filters
- An alternative to the fractional-order PID control aimed at increasing the loop performance and robustness
- Overcoming traditional dogma that the derivative action is unsuitable for noisy systems with time delays and that it is difficult to tune
- Evaluation based on new (shape related) performance measures and on performance evaluation in the **Speed of transients** versus **excessive input/output changes** plane
- No convergence problems
- More at `https://www.researchgate.net/project/PIDmn-Control`

Possible extensions of **PI** control by **Derivative Actions**

- **2DOF PID^m** controller + prefilter

$$C^m(s) = K_c\left(1 + \frac{1}{T_i s}\right) + T_{D1}s + T_{D2}s^2 + \dots + T_{Dm}s^m$$

$$F_p(s) = \frac{1+b_0 T_i s+b_1 T_i T_{D1} s^2+b_2 T_i T_{D2} s^3+\dots+b_m T_i T_{Dm} s^{m+1}}{1+T_i s+T_i T_{D1} s^2+T_i T_{D2} s^3+\dots+T_i T_{Dm} s^{m+1}} \tag{1}$$

- PI - No filtration at high frequencies!
- Choice of m - the 3rd degree of freedom in controller design.
- How to tune PID^m with respect to the plant dynamics?
- How to tune PID^m with respect to the noise impact?
- How to implement it = to choose an appropriate filter?

- The 4th DOF in controller design

$$Q_n(s) = \frac{1}{(T_f s + 1)^n}\,;\; n = 1,\, 2,\, \ldots \tag{2}$$

- $PID_n^m(s) = C^m(s)Q_n(s)$ - $Q_n(s)$ represents an **inevitable** part of the controller design
- PI=>PID_n^0, PID=>PID_n^1, PIDD^2 =>PID_n^2

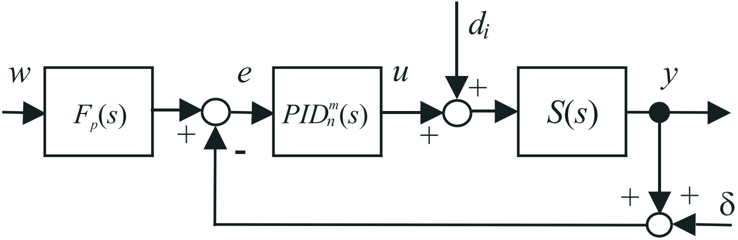


Figure: Considered control structure, δ- measurement noise

T_e - equivalent filter delay

$$K_o = K_c K_{sp}(T_{dp} + T_e);\ \tau_{io} = \frac{T_i}{T_{dp}+T_e};\ \tau_{jo} = \frac{T_{Dj}}{(T_{dp}+T_e)^j} \qquad (3)$$

Table: Optimal PID^m parameters derived by the multiple real dominant pole method, $m \in [0, 5]$

	$m=0$	$m=1$	$m=2$	$m=3$	$m=4$	$m=5$
K_o	0.4612	0.78361	1.08268	1.37114	1.65330	1.93117
τ_{io}	5.8284	3.73205	3.00000	2.61803	2.37980	2.21527
τ_{1o}	0	0.26289	0.37500	0.43673	0.47525	0.50120
τ_{2o}	0	0	0.04167	0.07492	0.09972	0.11843
τ_{3o}	0	0	0	0.00474	0.01020	0.01526
τ_{4o}	0	0	0	0	0.00042	0.00105
τ_{5o}	0	0	0	0	0	0.00003

Table: Equivalent time delays ratios T_f/T_e, $m \in [0,5], n \in [m,7]$

m	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
0	0.5690	0.3608	0.2647	0.2092	0.1729	0.1474	0.1284
1	0.7887	0.3943	0.2800	0.2180	0.1787	0.1514	0.1314
2	-	0.5000	0.3000	0.2279	0.1847	0.1555	0.1344
3	-	-	0.3618	0.2412	0.1917	0.1599	0.1374
4	-	-	-	0.2816	0.2012	0.1651	0.1408
5	-	-	-	-	0.2297	0.1722	0.1449

Filter design = specifying n and $T_e > 0$ - an additional dead time corresponding to filtration added to the plant model dead time T_{dp}

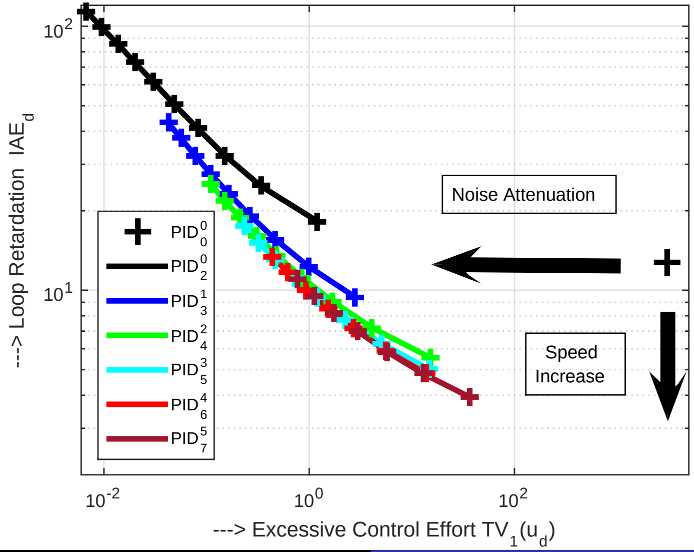
$$T_t = T_{dp} + T_e \tag{4}$$

Tuning procedure:

1. Choose $T_e > 0$ corresponding to a required filtration degree;
2. For $m > 0$ specify by the MRDP method the PID^m controller parameters as a function of $T_t, Q_n(s) = 1$;
3. Choose a filter order n
4. By considering $T_d = 0$ and $Q_n(s) = 1/(1 + T_f s)^n$ derive a delay equivalence $T_f = f(n, T_e)$ based on an equal dominant pole position and specify the filter time constant T_f; check if $T_f >> T_s$ - the available sampling period
5. By experimentally evaluating for different T_e, m, n, choose the optimal controller parameters guaranteeing the optimal loop performance.

PID_n^m, $n = m + 2$ - IPDT noise characteristics

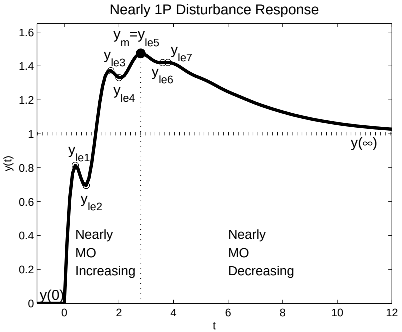
external noise "Uniform Random Number" with $|\delta| \leq 0.1$, $T_s = 0.001$, $T_{dp} = 1$



- TV_1 - **Deviations from 1P shapes** at the plant input (all step responses) and output (disturbance response)

$$TV_1(y_d) = \sum_i |y_{i+1} - y_i| - |2y_m - y_\infty - y_0| \; ; \; y_m = max(y)$$

- $TV_1(y_d) = 0$ just for strictly 1P response, else $TV_1(y_d) > 0$.



- Traditional robustness measures M_s and M_t
- User may specify the model parameters K_{sp} and T_{dp} and the controller parameters m, n, T_e
- **Robust stability** - stability areas for a given T_d, K_s as functions of K_{sp} and T_{dp}
- **Robust performance** - changes of the working point in the plane $\xi = TV_1(u_d), \eta = IAE_d^k$ as functions of an uncertain parameter $x_i, i = 1, 2, ..., N$
- **Performance sensitivity**:

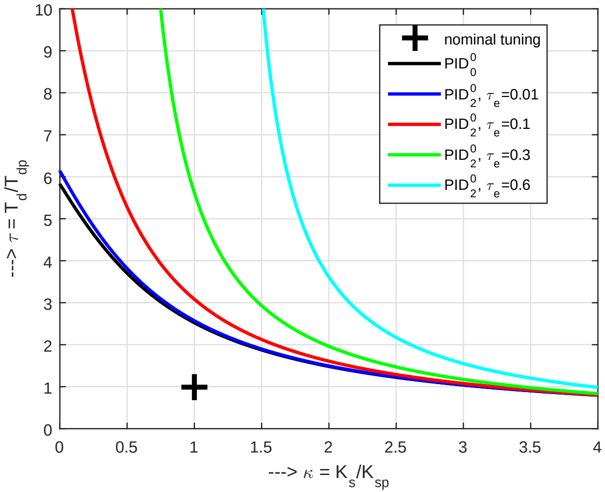
$$\begin{array}{l} S_d(u_d) = \sum_{i=1}^{N-1} \sqrt{(\xi_i - \xi_{i+1})^2 + (\eta_i - \eta_{i+1})^2} \\ \xi_i = TV_1(u_{di}), \eta_i = IAE_{di}^k) \end{array} \quad (5)$$

- Ideally, $S_d(u_d) = 0$

Robust Stability PID_2^0

$\tau_f = T_f/T_d$ - normed filter time constant enlarges stability area

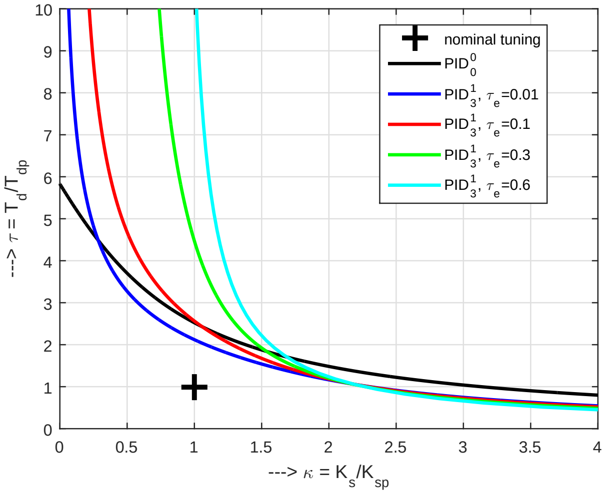
- T_d, K_s and T_{dp}, K_{sp} - plant and model dead time and gain



Robust Stability PID_3^1

$\tau_f = T_f / T_d$ - normed filter time constant

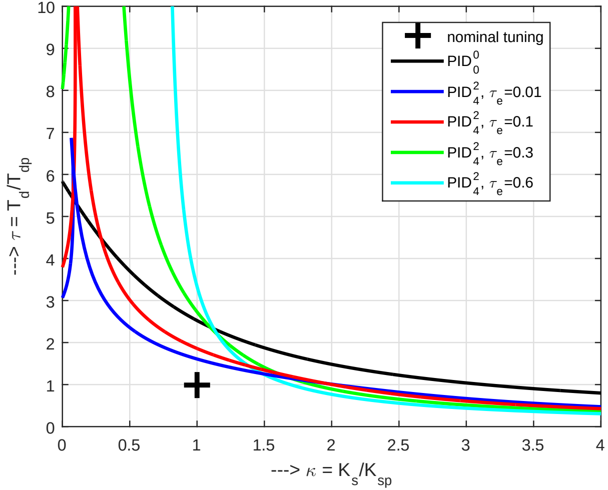
- T_d, K_s and T_{dp}, K_{sp} - plant and model dead time and gain



Robust Stability PID$^2_4$

$\tau_f = T_f/T_d$ - normed filter time constant

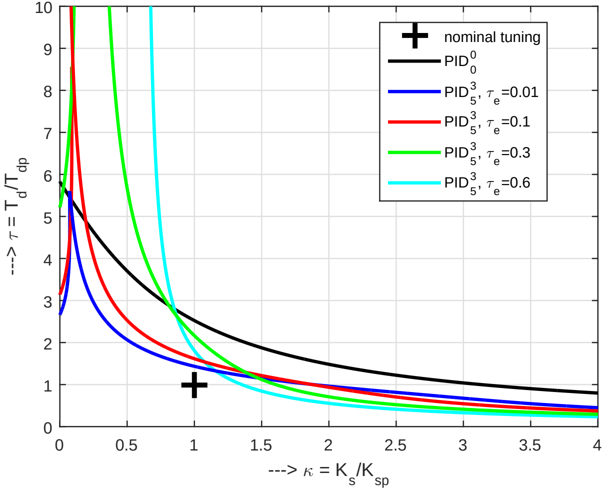
- T_d, K_s and T_{dp}, K_{sp} - plant and model dead time and gain



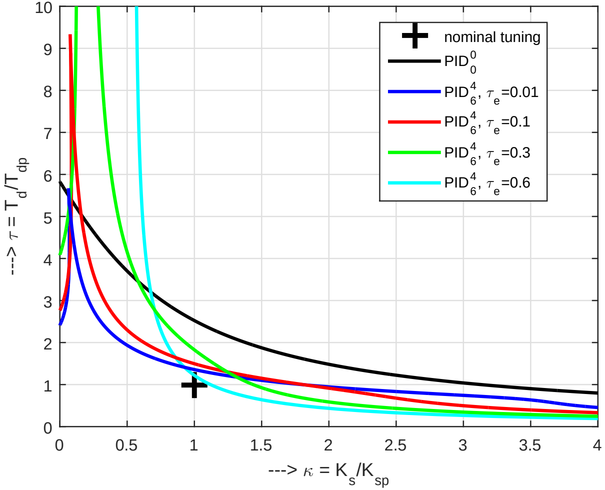
Robust Stability PID_5^3

$\tau_f = T_f / T_d$ - normed filter time constant

- T_d, K_s and T_{dp}, K_{sp} - plant and model dead time and gain



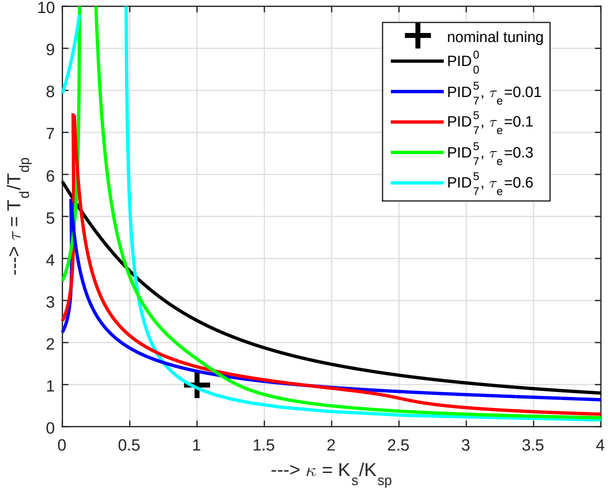
- T_d, K_s and T_{dp}, K_{sp} - plant and model dead time and gain



Robust Stability PID$_7^5$

$\tau_f = T_f/T_d$ - normed filter time constant

- T_d, K_s and T_{dp}, K_{sp} - plant and model dead time and gain



Robust Performance $S(s) = K_s e^{-T_d s}/(s+a)$

Optimal IAE_s for PID^0-PID^2 control of FOTD system

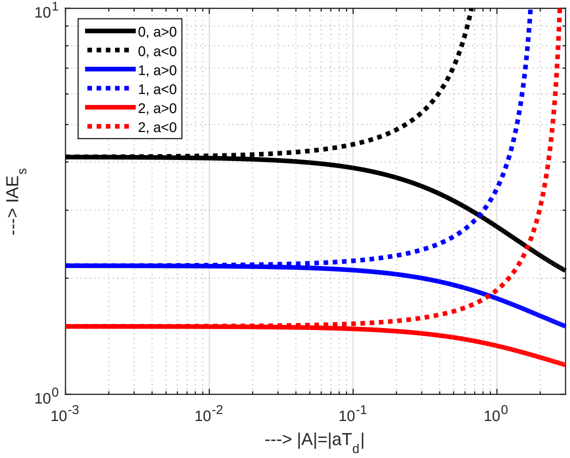
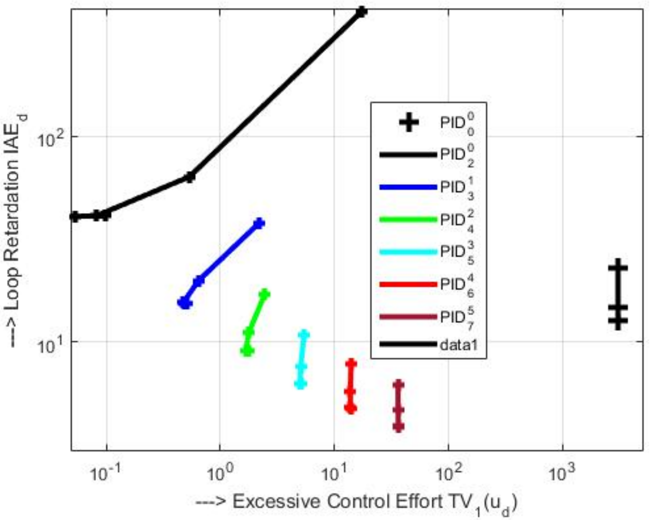


Figure: In a broad range of aT_d values (increasing with m), FOTD system may be controlled by simplified controllers derived for IPDT models

Robust Performance $S(s) = K_s e^{-T_d s}/(s+a)$

Uncertainty - internal plant feedback gain $a \in [-0.2, 0.2]$, $T_e = 0.8T_{dp}$, $T_{dp} = 1$, $K_s = 1$



Robust Performance $S(s) = K_s e^{-T_d s}/(s+a)$

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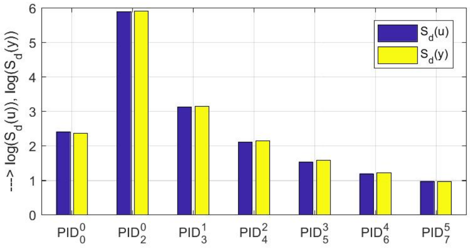
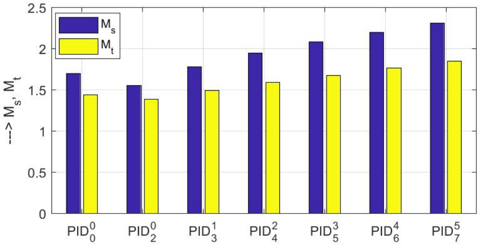




- Several modes of heat transfer (radiation and convection)
- Astrom, Panagopoulos, Hagglund showed that it is enough to consider the fastest mode (Design of PI Controllers based on Non-Convex Optimization, Automatica 34, 5, 1998)
- However, they have not observed that it is enough to approximate the fastest mode by IPDT model.
- No re-usability of such traditional optimization approaches.
- Simplified (automated) plant modeling, identification, optimal & robust controller design by FO models.
- However, the simplifications hold just for the first design phases, because the FO controllers have finally to be approximated by high-order filters.

Experimental verification

Detail of a step response - short measurement is enough

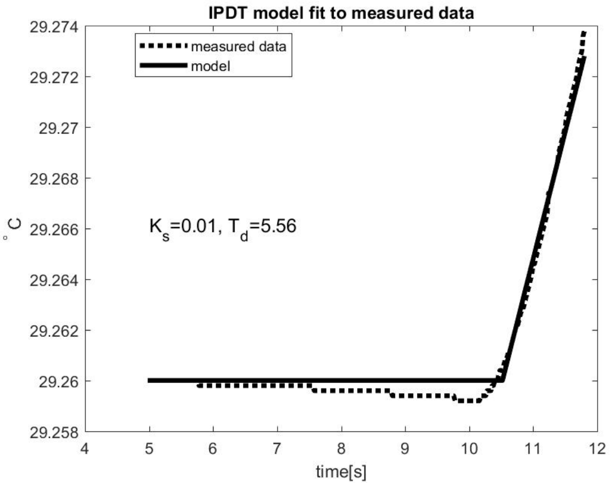
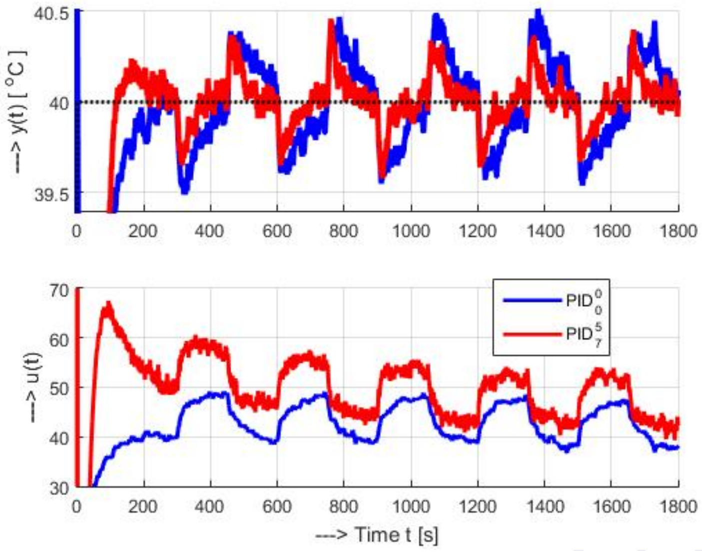


Figure: Approximation of an initial segment of a thermal plant step response by the IPDT model yielding $K_{sm} = 0.01$, $T_{dm} = 5.56$s

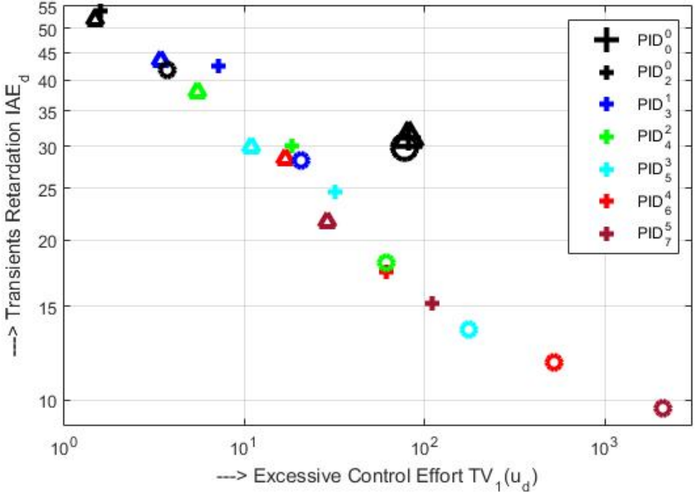
Experimental verification

Close loop step responses with a periodical disturbance - PID_0^0 and PID_7^5 with $T_e = T_d$



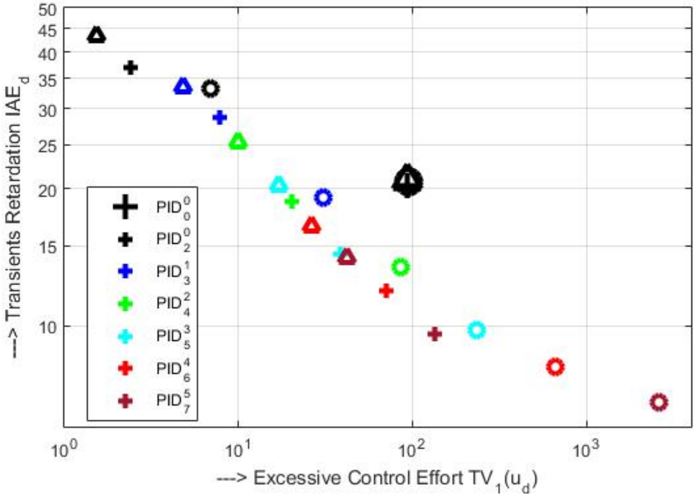
Illustrative Example

Measured noise characteristic, $T_e = \{0.5, 1, 1.5\}T_{dp}$ (o, +, Δ), $T_{dp} = 5.5$s



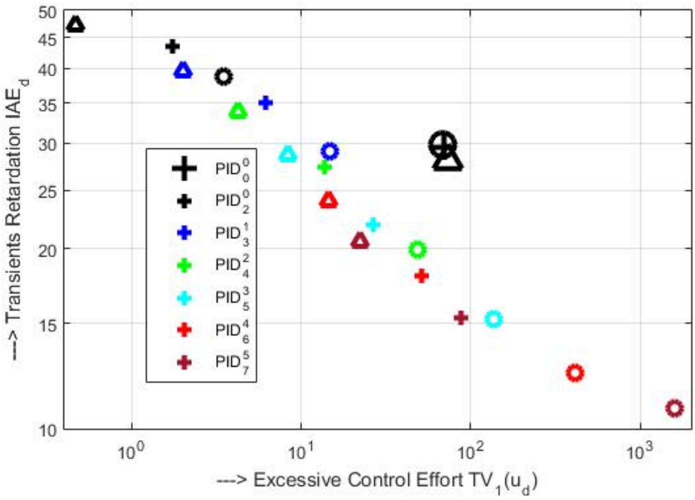
Illustrative Example

Measured noise characteristic, $T_e = \{0.5, 1, 1.5\}\, T_{dp}$ (o, $+$, Δ), $T_{dp} = 4.5$s



Illustrative Example

Measured noise characteristic, $T_e = \{0.5, 1, 1.5\} T_{dp}$ (o, $+$, Δ), $T_{dp} = 6.5$s



Illustrative Example
Evaluation of the speed of transients and of the excessive control effort

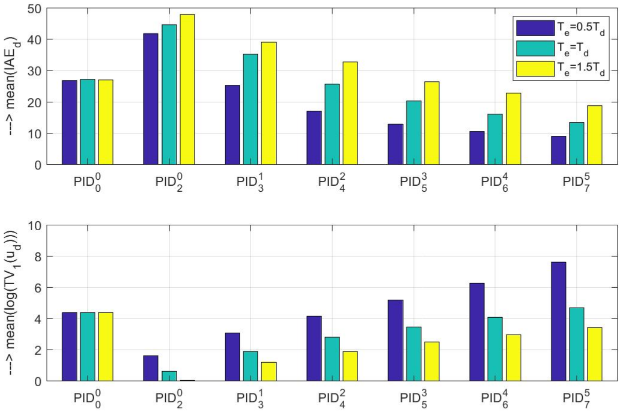


Figure: Mean performance measures - disturbance step responses evaluated for $T_{dp} = \{4.5, 5, 5.5, 6, 6.5\}$s with three different values of T_e

Illustrative Example

Cost function $J_k = IAE_d^k TV_1(u_d)$ combining speed of transients & excessive control effort

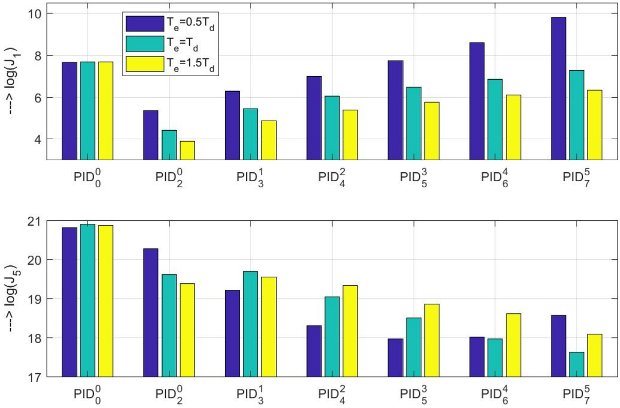


Figure: Mean values of the cost function $J_k = IAE_d^k TV_1(u_d)$ for $k = 1$ and $k = 5$ calculated for $T_{dp} = \{4.5, 5, 5.5, 6, 6.5\}$s with three different values of T_e

Conclusions I.

- PID$_n^m$ control = modifying the PI and PID control by higher order derivative actions.
- Together with low pass filters $Q_n(s)$ it introduces the **3rd and 4th degrees of freedom** devoted to speed of transients and measurement noise filtration.
- The use of higher order filters enables to speed up transients by simultaneously decreasing the corresponding control effort also in a noisy environment.
- Simple integrated tuning method for the introduced *n*th order binomial filters and controllers with *m*th order derivative.
- It may be further refined by the performance portrait method to stress the setpoint or disturbance responses.
- Performance portraits - kept in central repositories they may be repeatedly used via networks.

Conclusions II.

- Use of higher order derivatives increases performance robustness and thus allows to use simple integral models also for systems with much more complex dynamics.
- The traditional loop optimization becomes useless.
- Use of simple integral models also significantly simplifies the plant identification.
- Lower number of parameters = better conditioned calculations
- Lower number of determined parameters = use of much shorter step responses, without necessity to reach a steady state (applicable also to unstable systems, adaptive control).
- A paradigm shift documented already today by Model-Free Control (Fliess et al.) and Advanced Disturbance Rejection Control (Gao et al.) will yet accelerate...
- Similar features as in PID$_n^m$ control may be found in IMC and Disturbance Observer based control.

Thank you for your attention.
And do not forget to visit http://iolab.sk/ifac/