PID controller design, tuning and performance analysis

DINAMICA E CONTROLLO DEI PROCESSI CHIMICI
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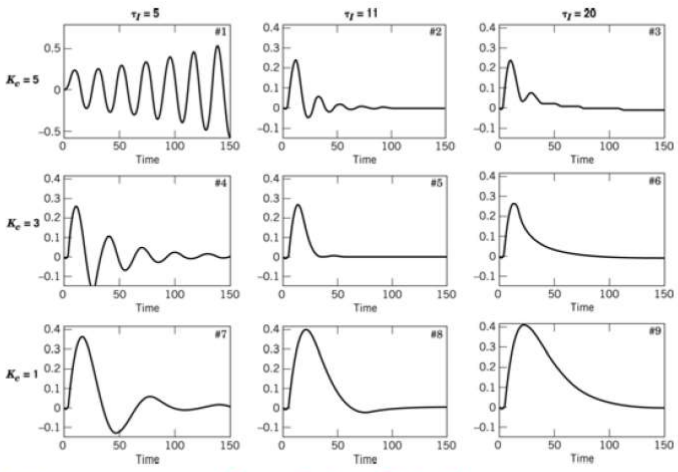
TUNING

- It is the procedure through which the PID controller settings (K_c, τ_I, τ_D) are adjusted to achieve an acceptable closed-loop response



(Seborg *et al.*, 2011)

(Process: $K_p = 1$; $\tau_p = 20$; $\theta_p = 1$)

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WHAT DO WE ASK TO A FEEDBACK CONTROL SYSTEM?

- The closed-loop system must be **stable**
- The impact of disturbances should be minimized (**disturbance rejection**)
- The transition to a new set-point (**set-point tracking**) should be fast and smooth
- **Steady-state offset** should be eliminated
  - But it is not always necessary
- Excessive intervention on the **manipulated variables** should be avoided
- **Robustness** of the control system should be guaranteed
  - Despite of changes in the process conditions or inaccuracy in the process model used to tune the controller

Adapted from Barolo M

PERFORMANCE VS ROBUSTNESS

- It is generally impossible to achieve both performance and robustness simultaneously

A **tradeoff** between **performance** and **robustness** must be achieved

- Good performance
  - The control system faces disturbances and set-point changes fast and smoothly, generating minimum oscillations
- Good robustness
  - The performance remains satisfactory over a wide range of operating conditions
    - All real systems have some degree of nonlinearity, but PID controller are essentially linear
- The robustness can be increased through conservative tuning
  - Using small gain K_c and large time constant τ_I
- However, the performance decreases if the tuning is conservative

Adapted from Barolo M

DISTURBANCE REJECTION VS SET-POINT TRACKING

- No tuning is equally effective for both regulatory control and servo control
  - Excellent disturbance rejection → large oscillations for set-point changes
  - Excellent set-point tracking → very sluggish response to disturbance changes

A tradeoff between **disturbance rejection** and **set-point tracking** must be achieved

- Some tuning rules change according to the fact that the requirement is good disturbance rejection or good set-point tracking

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HOW TO ACHIEVE THE FINAL TUNING

- **Hundreds** of loops exist in a large-scale plant
  - Only for critical loops is tuning done «on-field» using ad-hoc, time consuming tests (on-line tuning, field tuning)
  - For all other loops, a «preliminary» tuning is usually enough, possibly (but not necessarily) with subsequent fine tuning on field

Tuning parameters derived off-line, usually by experience with similar loops

Preliminary tuning → On-field adjustment of the tuning parameters by trial-and-error (fine tuning)

Field tuning → Ad-hoc tests → On-field adjustment of the tuning parameters by trial-and-error (fine tuning)

Ad-hoc tests: *Tuning parameters*

- **The loop performance is not affected very much by <u>small</u> variations in the tuning parameters**
  - ± 10% tuning parameter variations hardly affect the response
  - This is an advantage from the tuning viewpoint

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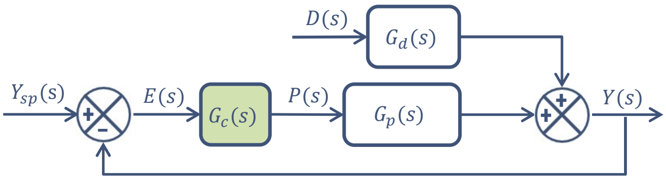
FEEDBACK CONTROLLER SYNTHESIS VS TUNING

- G_c might be a PID controller, but in principle also a dynamic system with a structure (i.e., a TF) **different from that of a PID controller**.
  - E.g., feedback control structures that use a **process model** within the control law may be convenient (model-based controllers)



- Synthesis (design) of the controller
  - The problem is determining the **structure of $G_c(s)$** (i.e., its TF) and the values of any parameters included in $G_c(s)$
  - The structure is designed starting from the **desired closed-loop performance**
  - Usually, a **dynamic model of the process** (in TF form) is required
- Tuning of the PID controller
  - The structure of $G_c(s)$ is known (its TF is that of a PID controller)
  - The problem is assigning appropriate values to **the tuning parameters** (K_c, τ_I, τ_D)

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SYNTHESIS OF A MODEL-BASED CONTROLLER OR TUNING OF A PID?

- In principle, synthesizing (i.e., designing) a model-based feedback controller is very convenient
  - Instead of modulating the manipulated variable using **only the error** as the «driving force», the controller **also uses a model** to calculate the control action
    - Therefore it «knows» what dynamic effect its control action will have on the process
    - It does not work by «trial-and-error»
- The main limitation of a model-based design controller approach is that an **accurate dynamic model** of the process is required
  - If the model is not accurate enough, the performance decreases and may become (possibly much) worse than that of a PID controller

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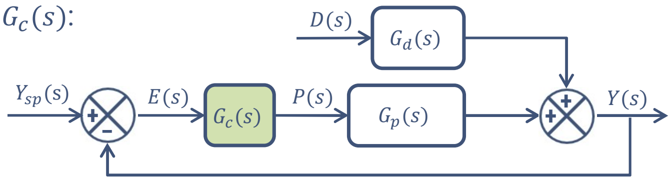
SYNTHESIS OF MODE-BASED CONTROLLERS

- We will consider two approaches to synthesize (design) $G_c(s)$:
  - Direct synthesis (DS) or «sintesi diretta»
  - Internal model control (IMC)
- Both assume that a dynamic model of the process, written in the form of a TF, is available
- This amounts to assuming that $G_p(s)$ is available
  - $G_p(s)$ represents the true (and unknown) process
  - In general, only an **approximation** of $G_p(s)$ can be available, that is called $\tilde{G}_p(s)$
    - E.g., $\tilde{G}_p(s)$ may have been determined a priori by step testing the true process
  - We may (or may not) neglect the existence of process-model mismatch or «disallineamento processo-modello»
    - i.e., we may simplistically assume that $\tilde{G}_p(s) = G_p(s)$ or that $\tilde{G}_p(s) \neq G_p(s)$
- The objective is designing the **structure** of $G_c(s)$, according to some rationale



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DIRECT SYNTHESIS OF FEEDBACK CONTROLLERS

- The **direct synthesis** of a controller is a method requiring:
  - The existence of a dynamic process model (of the TF type)
  - The assignment of a desired CLTF (usually, for set-point changes)
- An ideal controller is obtained that is able to **perfectly** track the assigned CLTF
  - It is ideal when:
    - The model perfectly represents the process dynamics (no process-model mismatch)
    - There are no constraints on either the manipulated variable or the controlled variable
- **Not necessarily will the resulting controller $G_c(s)$ have a PID structure**
  - **Not all** the CLTFs, which one can assign arbitrarily, can be obtained by controlling the system with a PID controller
  - However, we will see that, for some systems, the resulting ideal controller has a PID structure if the CLTF is chosen appropriately

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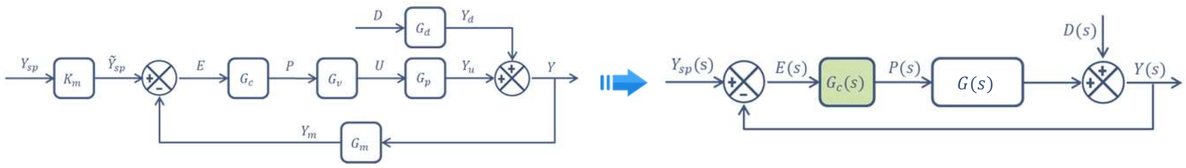
DIRECT SYNTHESIS (DS)



- Which controller $G_c(s)$ allows obtaining the desired Y/Y_{sp}?
- The CLTF results: $\frac{Y(s)}{Y_{sp}(s)} = \frac{G_cG}{1+G_cG} \rightarrow Y(1+G_cG) = G_cGY_{sp} \rightarrow Y + G_cGY = G_cGY_{sp} \rightarrow G_cG(Y_{sp} - Y) = Y \rightarrow G_c = \frac{1}{G} \times \frac{Y}{Y_{sp} - Y}$
- The controller able to generate the desired CLTF is: $\boxed{G_c = \frac{1}{G} \times \frac{Y/Y_{sp}}{1 - Y/Y_{sp}}}$
  - The «shape» of the desired CLTF $[Y(s)/Y_{sp}(s)]_d$ needs to be specified
  - One has available only a model $\tilde{G}$ of the true process G

$$\boxed{G_c = \frac{1}{\tilde{G}} \times \left[\frac{(Y/Y_{sp})_d}{1 - (Y/Y_{sp})_d}\right]}$$

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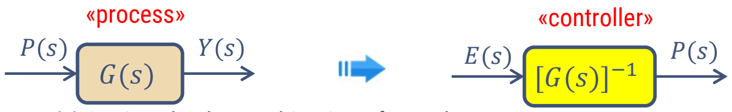
DIRECT SYNTHESIS: THE MODEL INVERSE

$$\boxed{G_c(s) = \frac{1}{\tilde{G}(s)} \times \left[\frac{(Y/Y_{sp})_d}{1 - (Y/Y_{sp})_d}\right]}$$

- The required controller contains the inverse $\frac{1}{\tilde{G}}$ of the process model
- Therefore, the controller structure depends on:
  - The process model
  - The desired CLTF
- In general, the resulting structure is **not that of a PID** controller!
- The fact that the controller contains the **inverse** of the process (model) seems reasonable



- $G_c(s)$ is given by the combination of two elements
  - The inverse of the response model, which represents the «knowledge» one has on the process to be controlled
  - A «filter», which forces the response to have a desired «shape»

Filter

Process inverse

$$G_c(s) = \boxed{\frac{1}{\tilde{G}(s)}} \times \boxed{\left[\frac{(Y/Y_{sp})_d}{1 - (Y/Y_{sp})_d}\right]}$$

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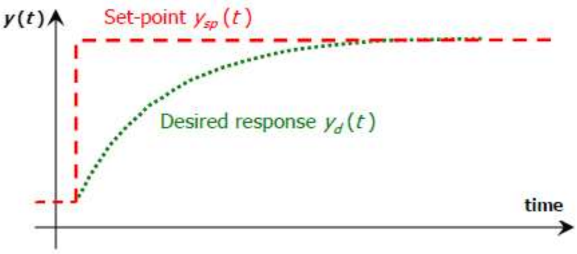
DIRECT SYNTHESIS: ASSIGNING THE CLTF

$$G_c(s) = \frac{1}{\tilde{G}(s)} \times \left[\frac{(Y/Y_{sp})_d}{1-(Y/Y_{sp})_d}\right]$$

- How to choose the CLTF $(Y/Y_{sp})_d$?
- Ideally, $(Y/Y_{sp})_d = 1$ $\rightarrow$ perfect control
  - Impossible: $G_c = \infty$ would be obtained
  - Seems reasonable: for feedback control to start working, $e \neq 0$ must occur $\rightarrow y_{sp}(t) \neq y(t) \rightarrow Y(s) \neq Y_{sp}(s)$
  - Alternatively, one may require that the transition to the new set-point is achieved with a given dynamics, e.g. that of a FO system (with time constant τ_c selected «arbitrarily»)



$$\left[\frac{Y(s)}{Y_{sp}(s)}\right]_d = \frac{1}{\tau_c s + 1}$$

τ_c: costante di tempo in anello chiuso

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