1.3 Fundamentals of Process Dynamics and Control in the perspective of digitalization

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Digitalization Tools for the Chemical and Process Industries

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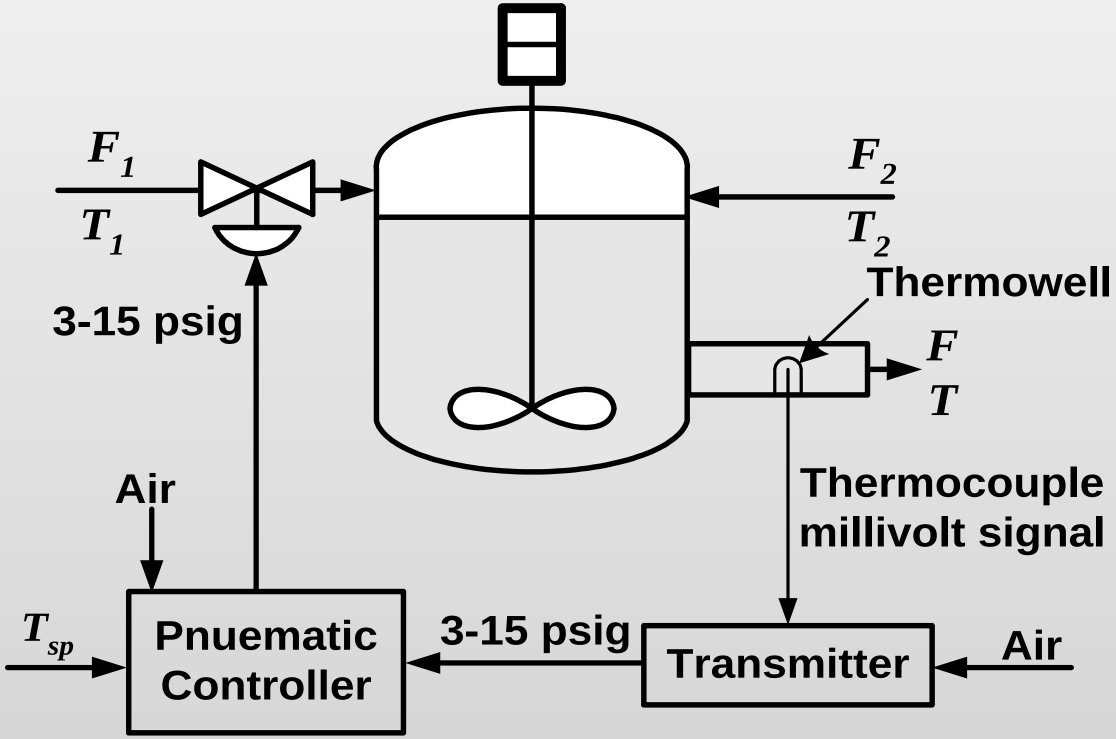
Outline

- A brief history of control system architecture
- Current basic algorithms implemented in DCS
- Current advanced control strategies
- Conclusions

A brief history of control system architecture

- Pneumatic controllers
- Electronic analog controllers
- Supervisory control computers
- Distributed Control Systems (DCS)
- Fieldbus technology

Pneumatic controllers



- Introduced in the 1920’s
- Installed in the field next to the valve
- Use bellows, baffles, and nozzles with an air supply to implement PID action.
- Provided automatic control and replaced manual control for many loops
- Transmitter type pneumatic controllers began to replace field mounted controllers in the late 1930’s.
- Controller located in control room with pneumatic transmission from sensors to control room and back to the valve.
- Allowed operators to address a number of controllers from a centralized control room.

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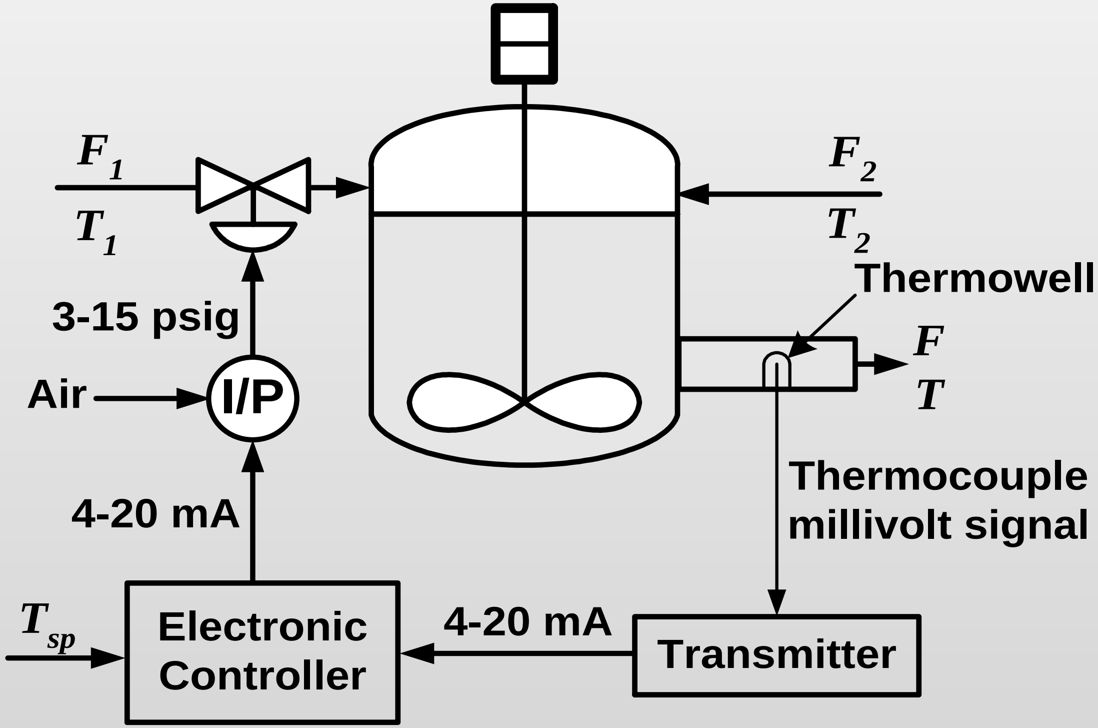
Electronic analog controllers



- Became available in the late 1950’s.
- Replaced the pneumatic tubing with wires.
- Used resistors, capacitors, and transistors-based amplifiers to implement PID action.
- Replaced pneumatic controllers by 1970.
- Allowed for advanced PID control: ratio, feedforward, etc.

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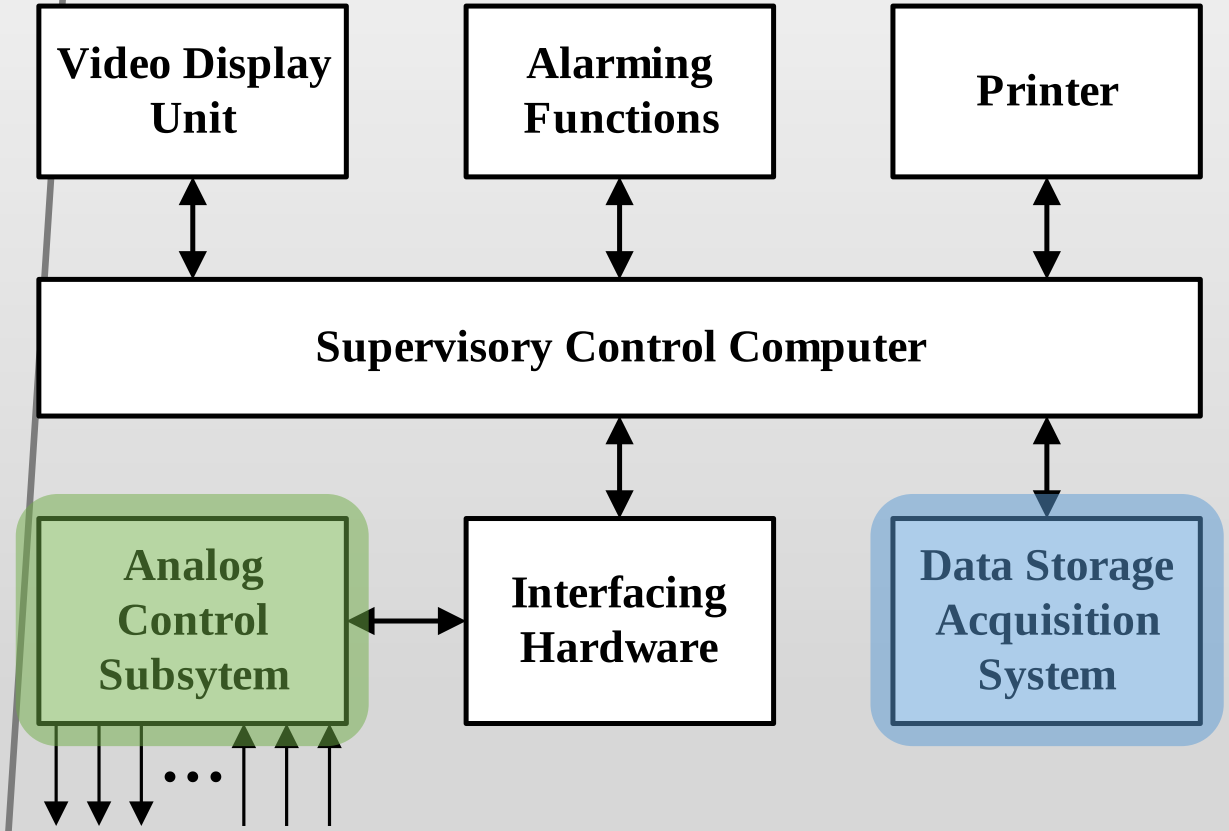
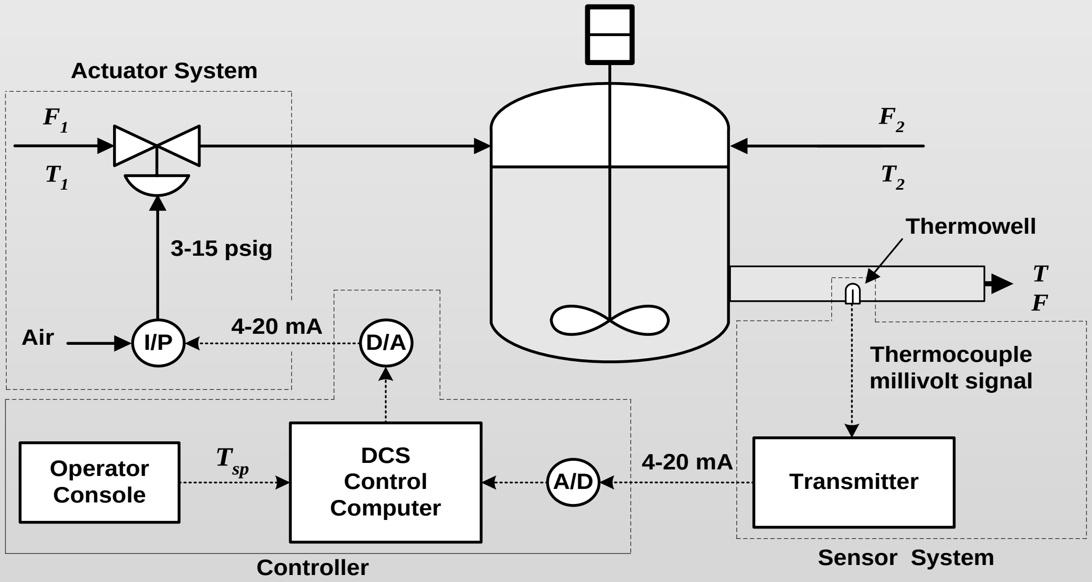
Supervisory control computers



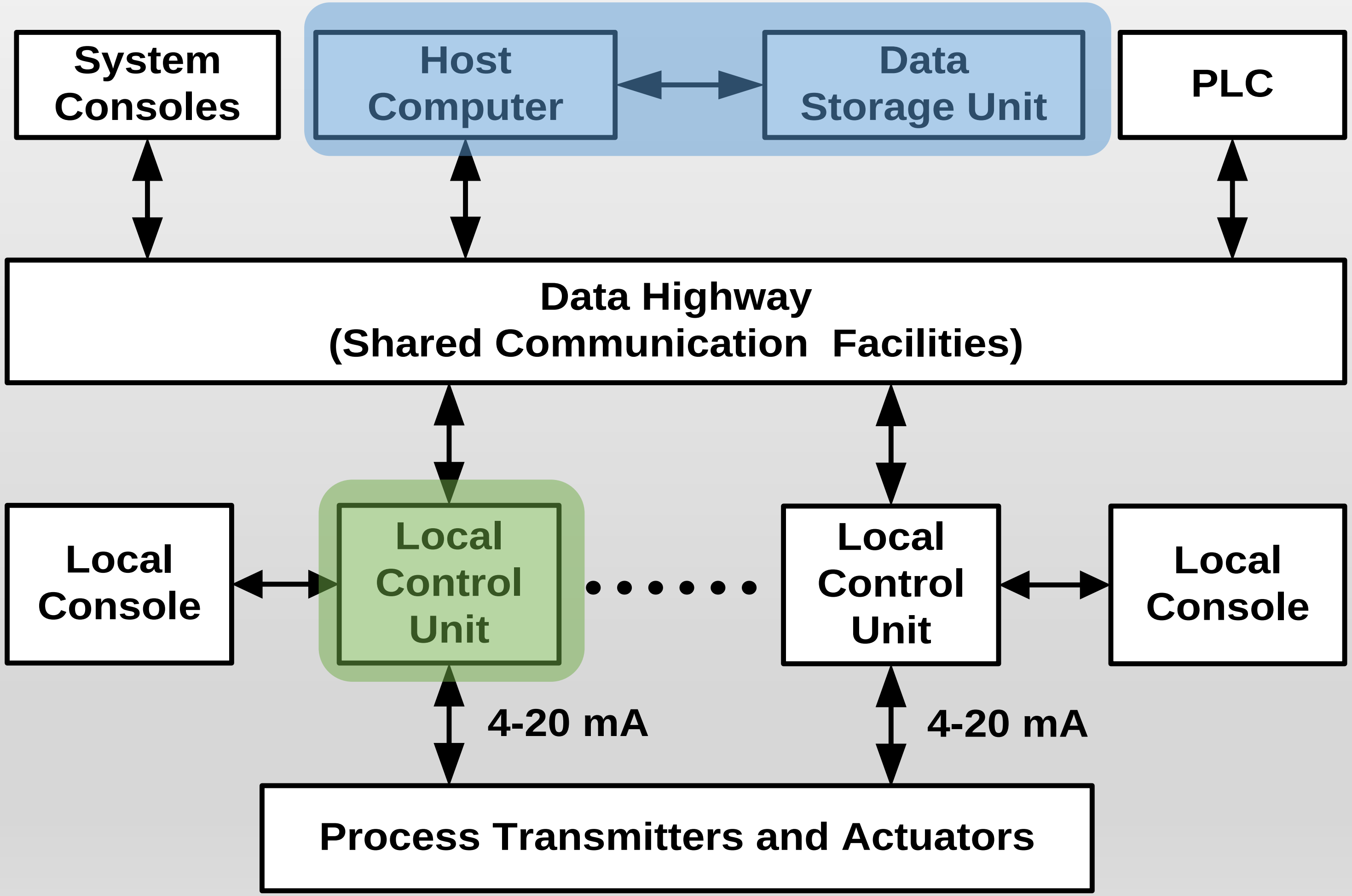
- Based upon a mainframe digital computer.
- Offered the ability to use data storage and retrieval, alarm functions, and process optimization.
- First installed on a refinery in 1959.
- Had reliability limitations (no redundancy).

Distributed Control Systems (DCS)

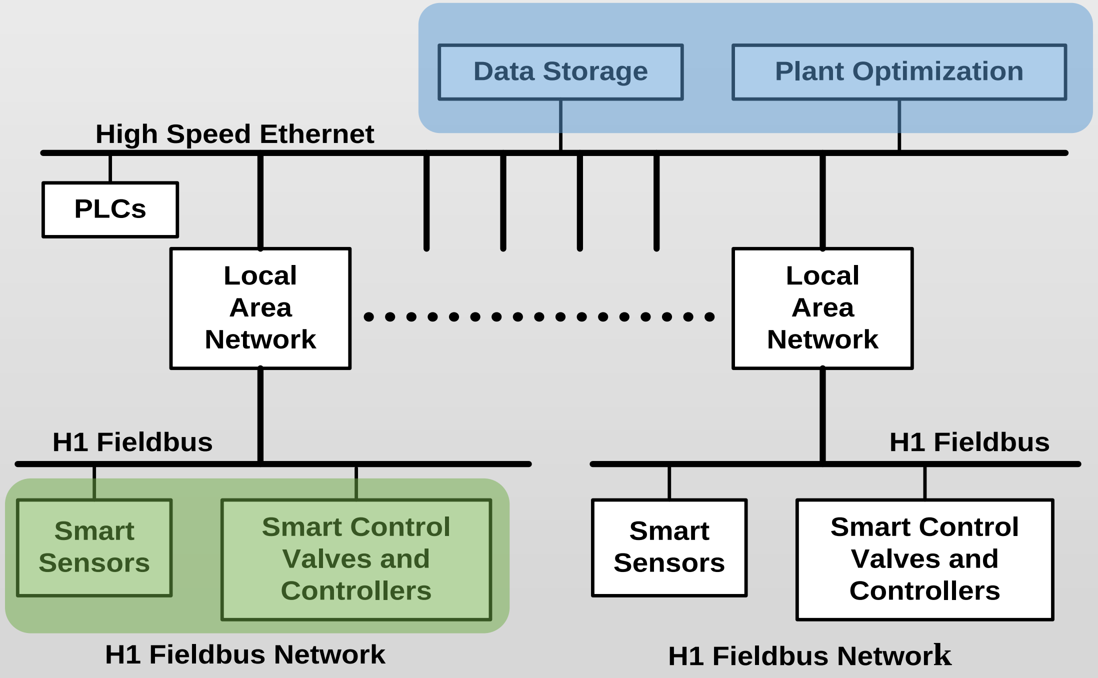


- Introduced in the late 1970's.
- Based upon redundant microprocessors for performing control functions for a part of the plant. SUPERIOR RELIABILITY
- Less expensive per loop for large plants.
- Less expensive to expand.
- Facilitates the use of advanced control.

DCS Architecture

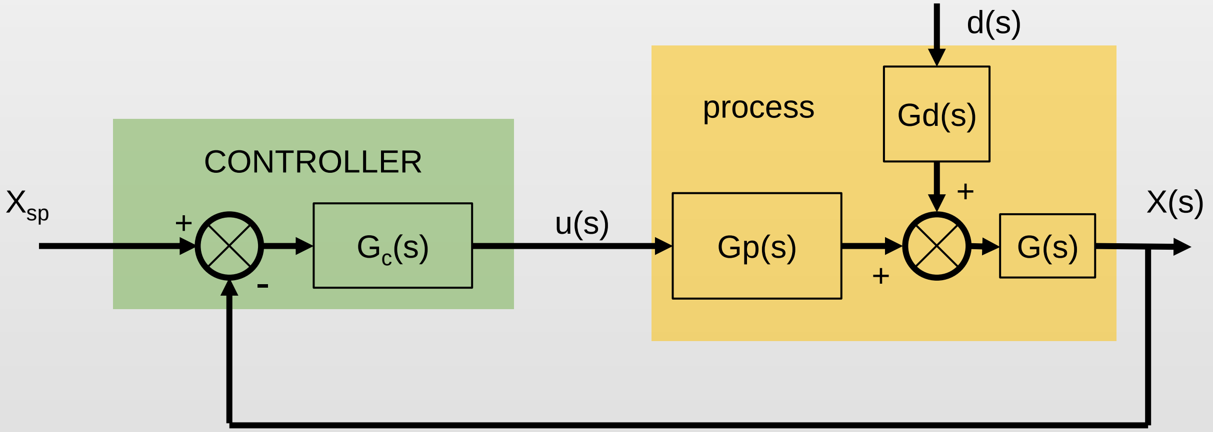


Fieldbus technology



- Based upon smart valves, smart sensors and controllers installed in the field.
- Uses data highway to replace wires from sensor to DCS and to the control valves.
- Less expensive installations and better reliability.
- Can mix different sources (vendors) of sensors, transmitters, and control valves.
- Now commercially available and should begin to replace DCSs.

Current basic control configuration (FB)



Basic controllers of chemical and process plants are (or were?) practically all made with PID FB controllers (single-loop or multi-loop) with any variations/improvements (e.g. feedforward).

Current basic algorithms implemented in DCS (PID)

$$G_c(s) = K_c \cdot \left(1 + \frac{1}{\tau_I \cdot s} + \tau_D \cdot s\right)$$

Discrete **position** form

$$m_k = m_0 + K_c \cdot \left[(x_{sp,k} - x_k) + \sum_1^k (x_{sp,j} - x_j) + \frac{\tau_D}{\Delta t} \cdot \left((x_{sp,k} - x_{sp,k-1}) - (x_k - x_{k-1})\right)\right]$$

Discrete **velocity** form

$$m_k = m_{k-1} + K_c \cdot \left[(x_{sp,k} - x_k) - (x_{sp,k-1} - x_{k-1}) + \frac{\Delta t}{\tau_I}(x_{sp,k} - x_k) + \tau_D \cdot \frac{(x_{sp,k} - x_{sp,k-1}) - (x_k - x_{k-1})}{\Delta t}\right]$$

Limitations of Conventional PID Controllers

- The performance of PID controllers can be substantially limited by:
  - Disturbances and **process nonlinearity**
  - Measurement error/deadtime
  - Process constraints
- These problems can be handled using different techniques (sometimes with the help of digitalization)

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Cascade, Ratio and Feedforward Control

- Each of these techniques offers advantages with respect to **disturbance rejection:**
  - Cascade reduces the effect of specific types of disturbances.
  - Ratio reduces the effect of feed flow rates changes
  - Feedforward control is a general methodology for compensating for measured disturbances.

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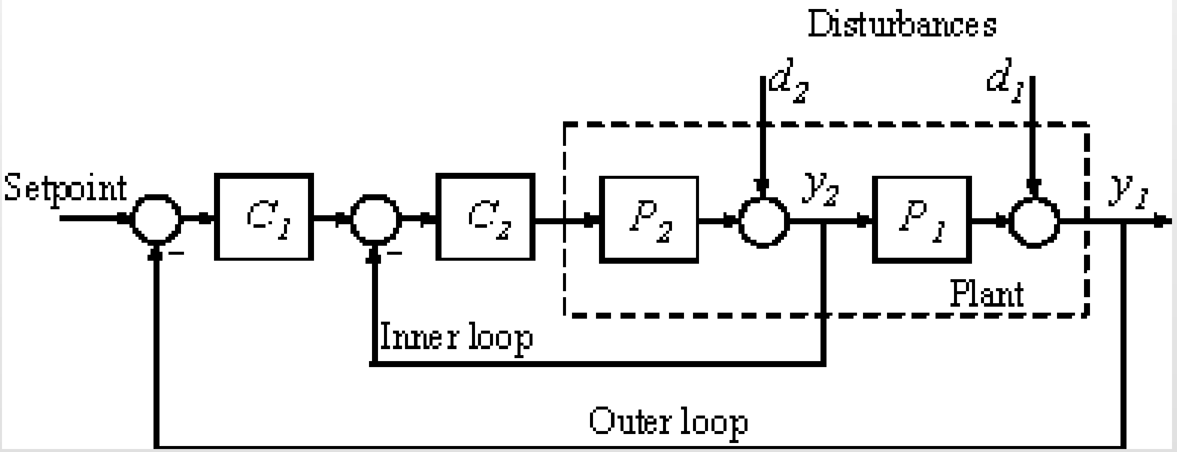
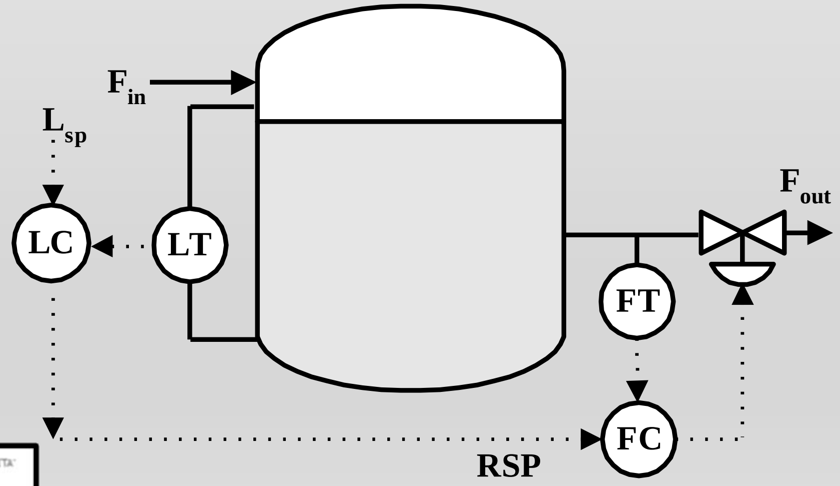
Cascade Control





Simply two (or sometimes even more) FB loops one into another.
Useful when specific disturbances may affect slave (or secondary) loop before affecting the master (or primary control loop).

Example: disturbance in downstream pressure in the classical level-outlet flow rate configuration.

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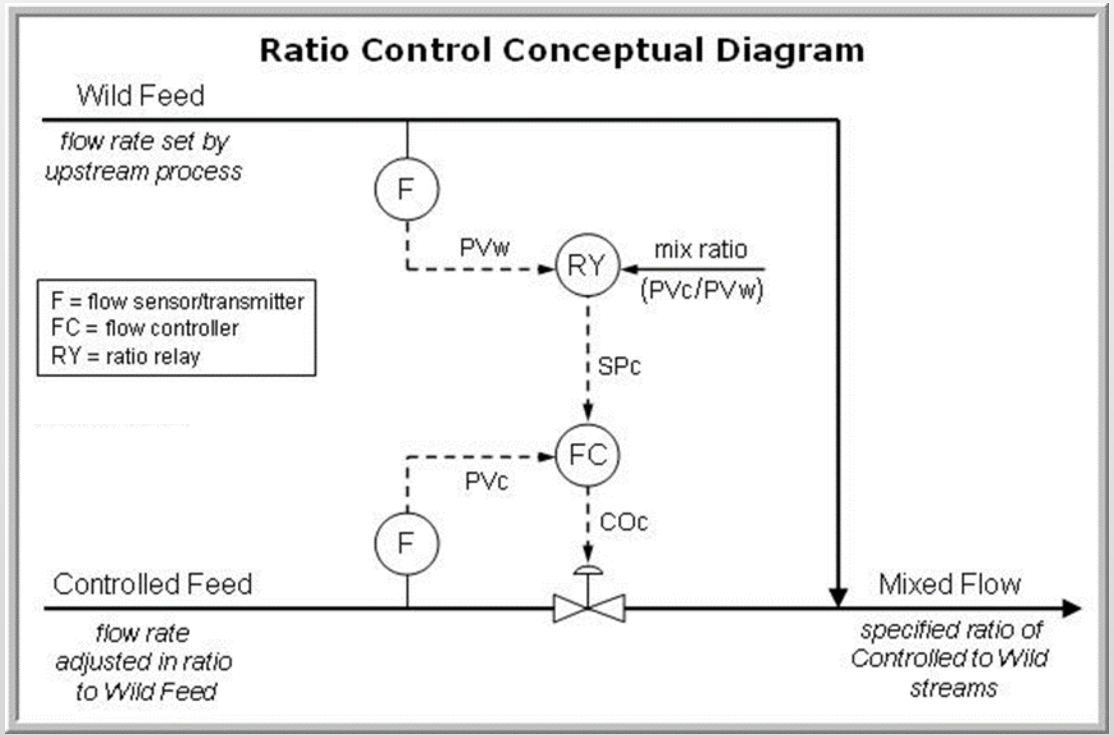
Ratio Control



Useful when the output depends (mainly) on the ratio between two inputs (usually 2 feed flow rates).
Typical application: reactants or mixing

Still a FB control but with a simple ratio **calculated from process model** (simplest example of FF control)

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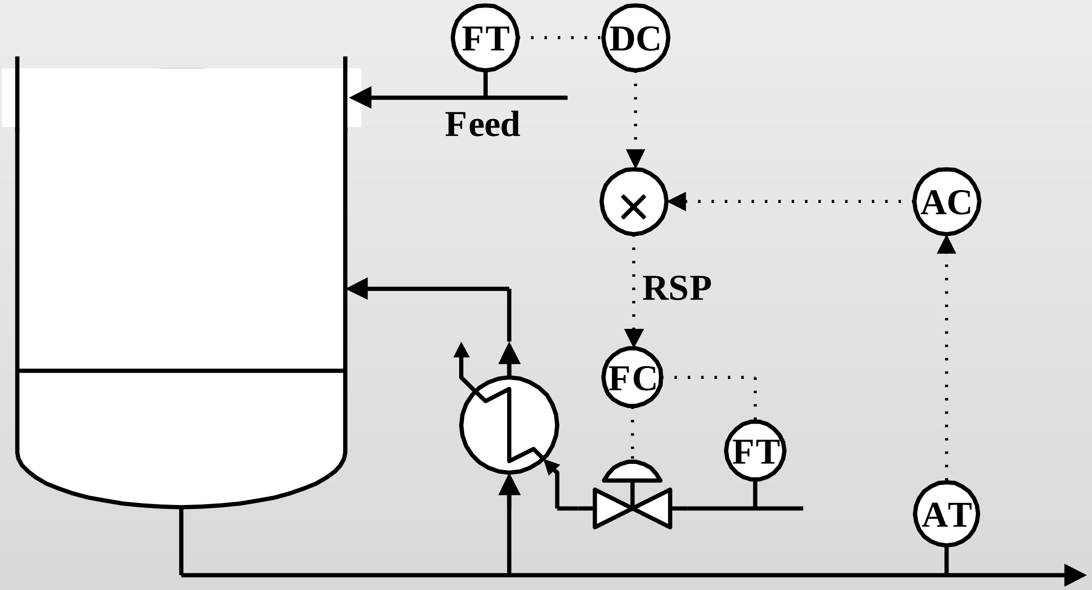
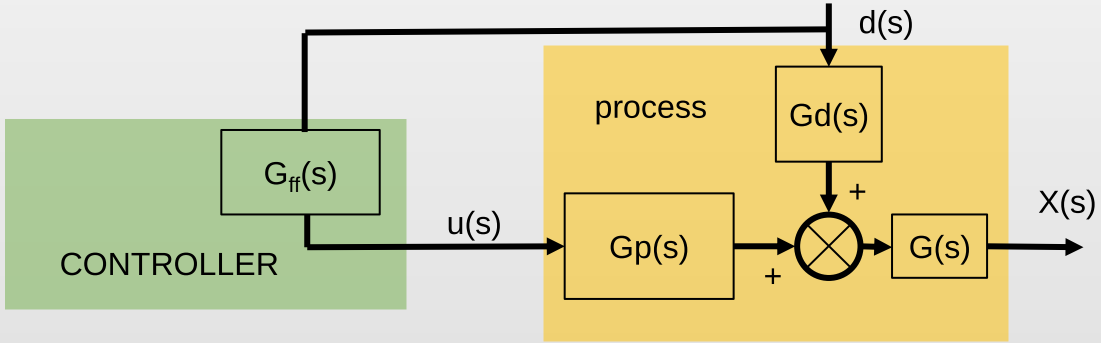
Ratio Control Requiring Dynamic Compensation



Dynamic compensation may be required when the controlled variable (output) responds dynamically different to one feed rate changes than it does to the other one (fast response for one slow for the other).

In general this lead to FF control

Feedforward control



$$X(s) = G_d(s)d(s) + G_p(s)u(s)$$
$$= G_d(s)d(s) + G_p(s)G_{ff}(s)d(s)$$
$$0 = G_d(s)d(s) + G_p(s)G_{ff}(s)d(s)$$
$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)}d(s)$$

FF tries to **predict** the output on the basis of one (or more…) disturbances that can be measured: a **process model** is required.

It can be a simple ss model ($G_c = K$) or a dynamic linear model: $G_c = \frac{Ke^{-\theta s}}{1+\tau s}$

but also a **non-linear model** (usually in the time domain)

Input variables to the controller can be **more than one…**

Feedforward Control

- Most effective for slow processes and for processes with significant deadtime.
- Compensates for d's before process is affected, but **it cannot eliminate the offset alone**
- Can improve reliability of the feedback controller by reducing the deviation (overshoot) from setpoint.
- Since it is a linear controller, its performance will deteriorate with nonlinearity.

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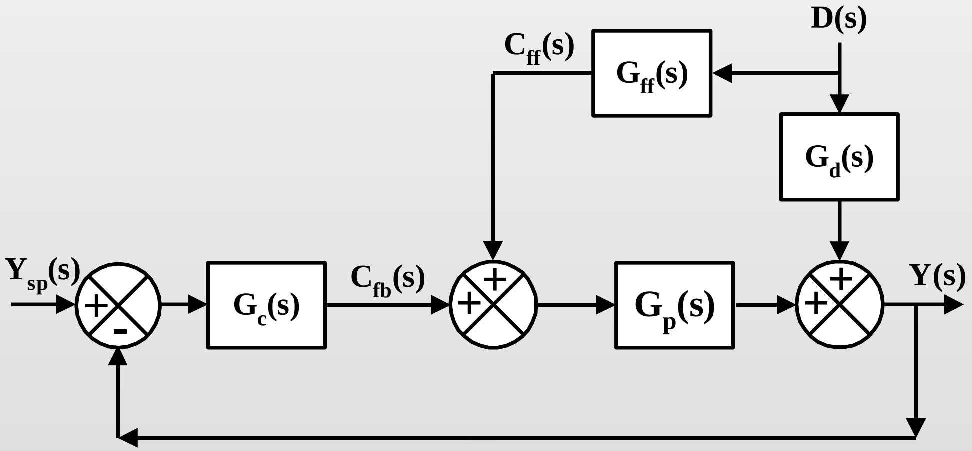
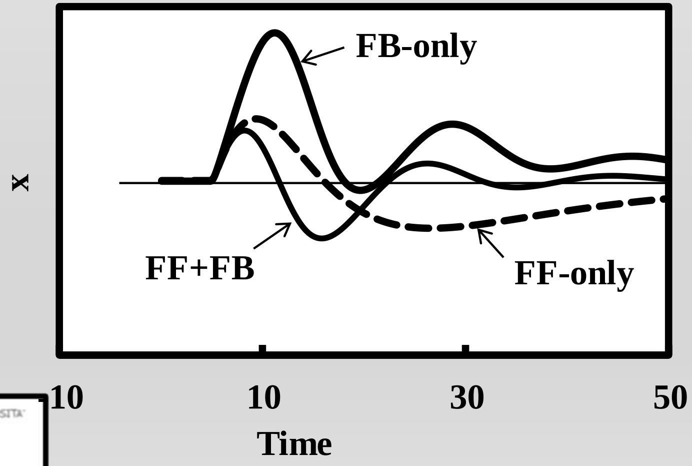
Combined FF and FB Control



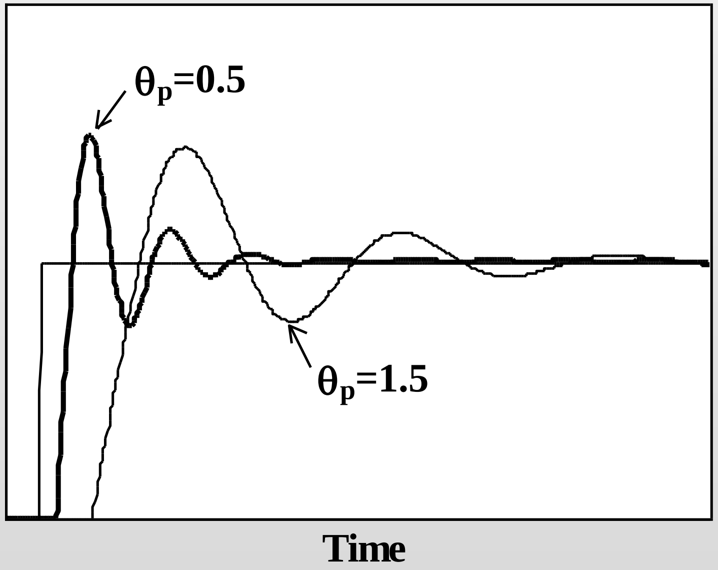


- FB-only returns to setpoint but has large deviation from setpoint.
- FF-only reduces the deviation from setpoint but cannot return exactly to setpoint (model…)
- FF+FB reduces deviation from setpoint and provides fast return to setpoint

Inferential Control

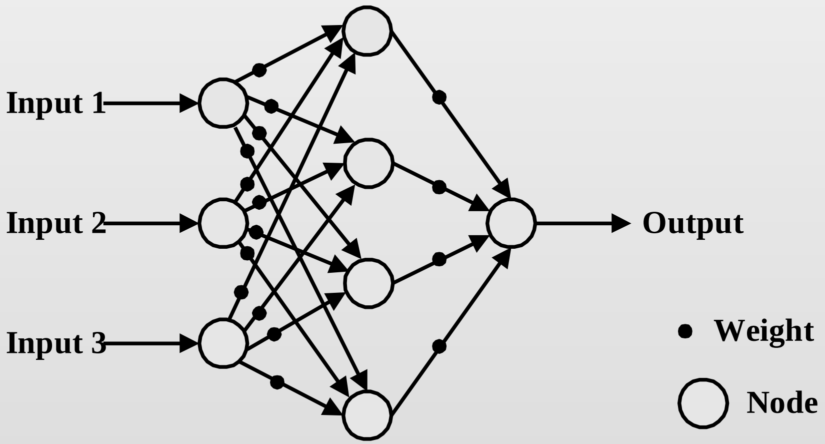
- Uses easily measured process variables (T, P, F,…) to infer more difficult to measure quantities such as compositions and molecular weight.
- Can substantially reduce analyzer delay (deadtime).
- Can be much less expensive in terms of capital and operating costs.
- Can provide measurements that are not available any other way.

Effect of Deadtime on Control Performance



- Deadtime can increase the time required for returning to SP (increase oscillations). It can even lead to instability.
- The main problem is how to infer controlled variable from other (measured) variables especially in complex cases (e.g. polymer molecular weight)
- Non-linear relationships, dependency on many variables, etc…

Soft Sensors Based on Neural Networks



- Neural network (NN) provides nonlinear correlation.
- Weights are adjusted until NN agrees with plant data

(example: NN-based soft sensors are used to infer NOx levels in the flue gas from power plants)

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Scheduling Controller Tuning

- Tuning is based on process parameters, usually estimated with linear approx. (K_p, τ_p, θ_p) (e.g. Ziegler-Nichols, Cohen-Coon, Tyreus- Luyben,…). This approx. is accurate only around the initial point.
- Tune the controller at different levels of the scheduling parameter(s) and combine the results so that the controller tuning parameters vary over the full operating range.

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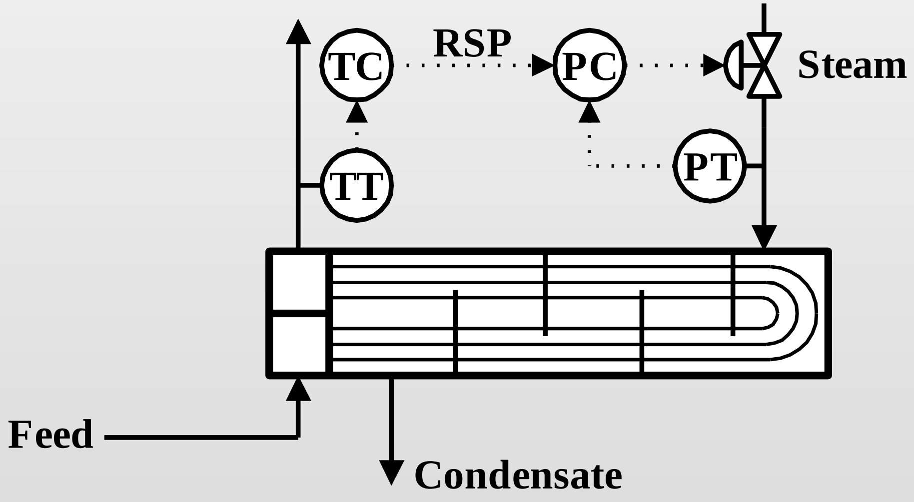
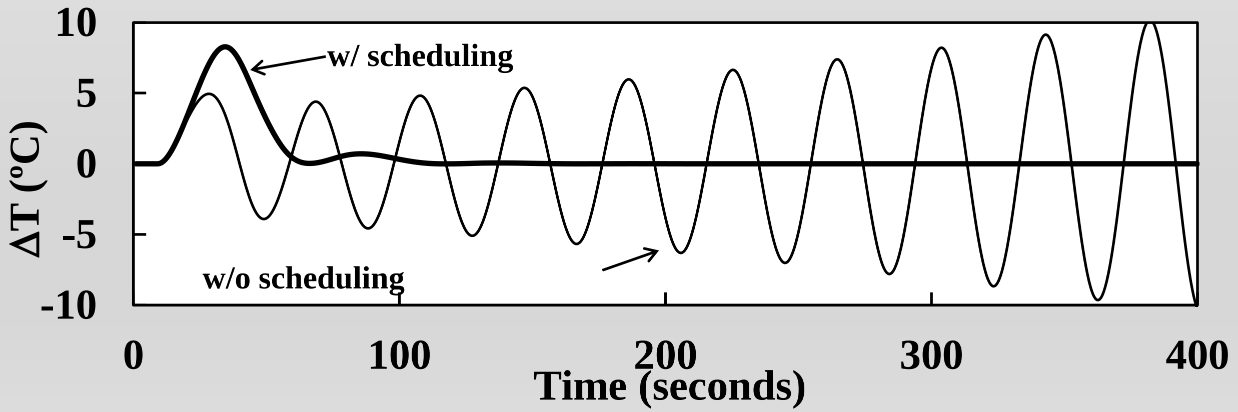
Effect of Scheduling Controller Tuning



- Example: T-P casc control for a steam heat exchanger.
- Outlet T is non-linear with tube side v (change in h_i)
- Results for a nonscheduled controller that was tuned for v=2.1 m/sec after the feed rate is changed to v=1.2 m/sec and the results for a scheduled controller for the same upset.



Scheduling Controller Tuning

- Can be effective when either a measured disturbance or the controlled variable correlates with **nonlinear process** changes.

- Can be even more effective when tuning is **automatically** scheduled, and tuning parameters are updated on the basis of **several** input variables **non-linearly correlated** with the output.

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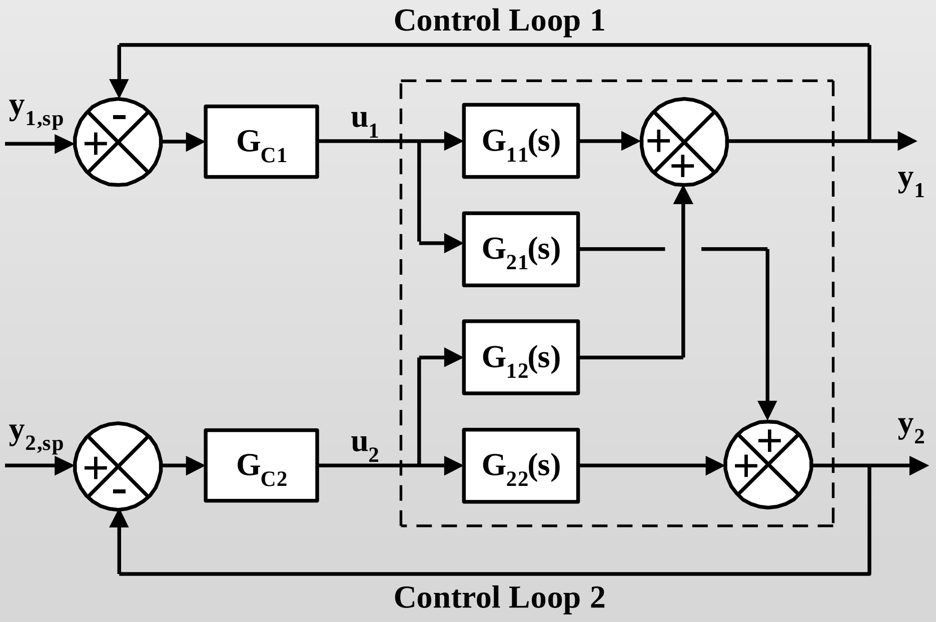
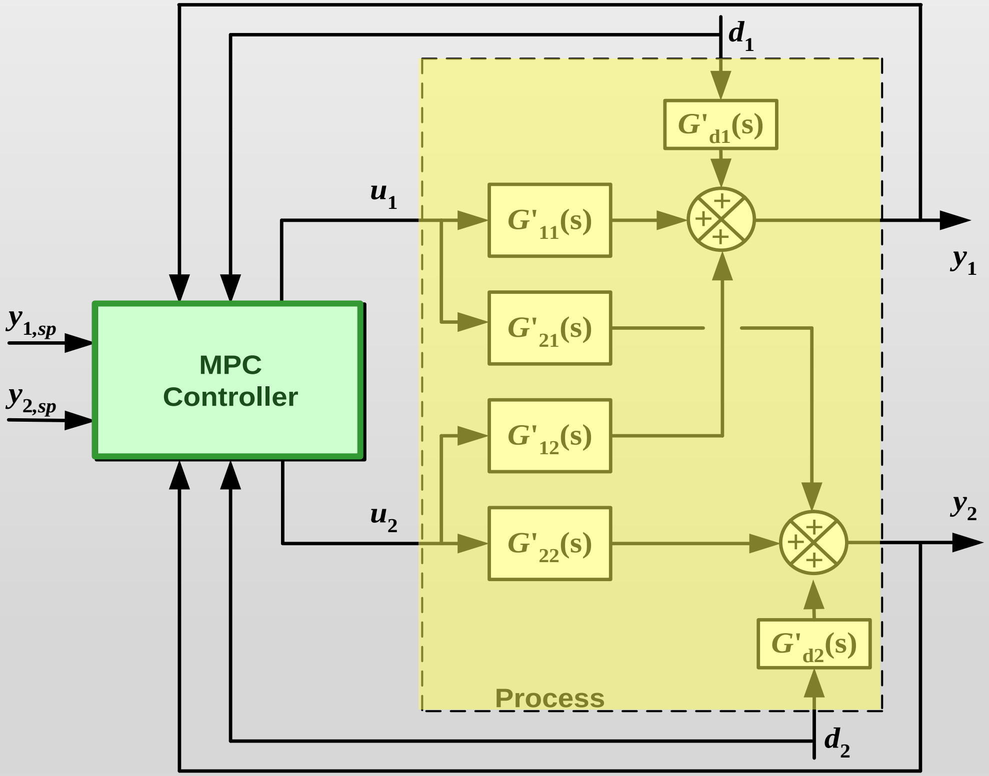
MIMO systems (2x2 example)



- The combined effect of coupling, sensitivity to disturbances, and dynamic response determine the performance of a configuration
- Decoupling (analysis of RGA or of TFs matrix) can be effective, sometimes…

Model Predictive Control



- Most popular form of multivariable control (more than 2x2 system…)
- Effectively handles complex sets of variable configurations including **disturbances** and **constraints**.
- Has an LP on top of it so that it controls against the most profitable set of constraints. (optimization)
- Several types of industrial MPC but DMC is the most widely used form.

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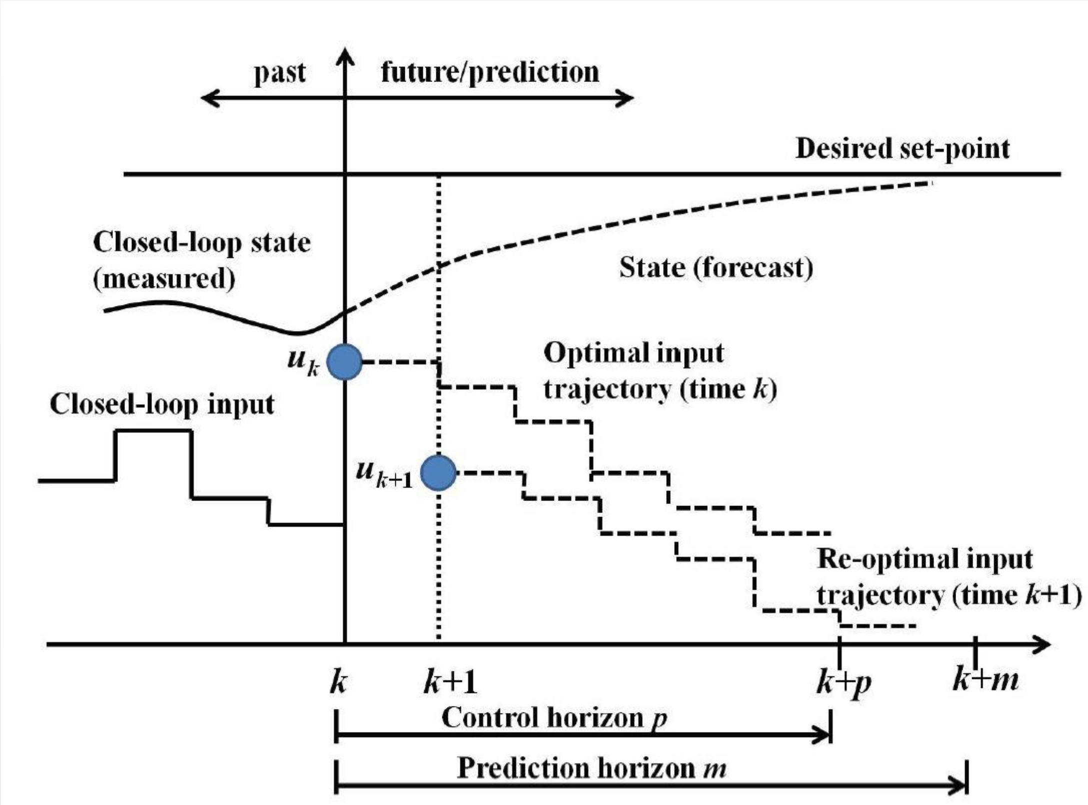
MPC principles



- MPC uses a model of the plant to make predictions about the future plant output behavior. It also uses an optimizer, which ensures that the predicted future plant output tracks the desired reference (sp).
- It solves an **optimization problem** at each time step in order to find the control action that drives the predicted plant output as close to the desired reference as possible

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Advantages of MPC

- Combines **multivariable** constraint control with process optimization.
- A generic approach that can be applied to a wide range of processes.
- Allows for more systematic controller maintenance.
- Depends on the particular process

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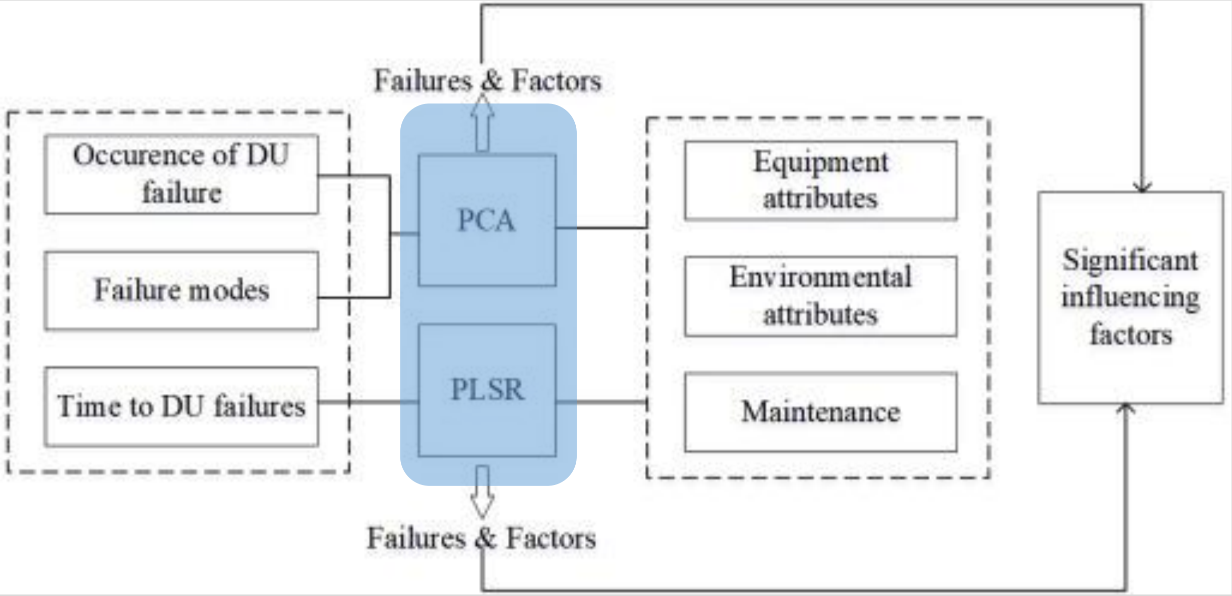
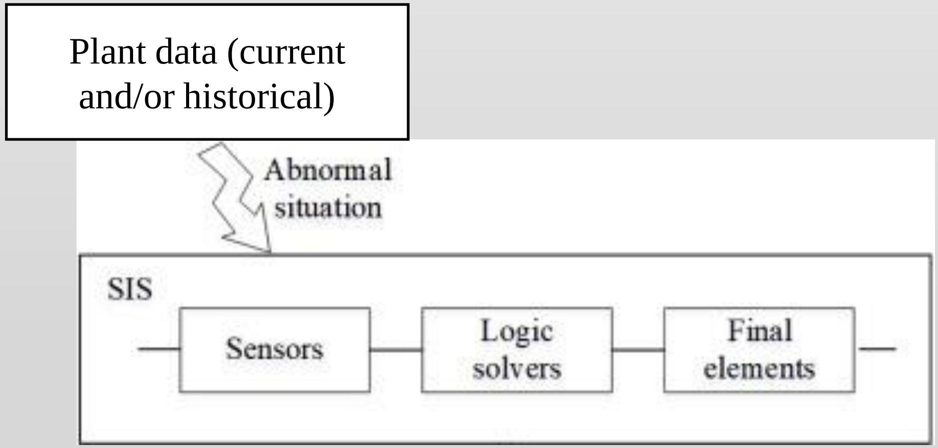
Limitations of MPC

- It is a linear method; therefore, it is not recommended for **highly nonlinear processes** (e.g., pH control).
- It does not adapt to process changes. If the process changes significantly, the MPC model must be re-identified.
- For certain cases, the economic LP may not be accurate enough. For these cases, it may be necessary to add nonlinear optimization on top of the LP.

And what about safety ?

Digitalization, in its general meaning of easily available data in large amount and related techniques for its analysis, is becoming more and more important (and applied) also in the estimation of **reliability** of safety-critical components and in the **early detection** of abnormal situations that may lead to uncontrolled (dangerous) plant operations





Conclusions and discussion

	Can greatly enhance	**May be useful**	**Can give a little help**
Standard FB PID			
Cascade			
Inferential			
Feed-forward			
Ratio			
Scheduled tuning			
Dyn decoupling			
MPC			
Safety			
Batch processing			
Others ?			

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