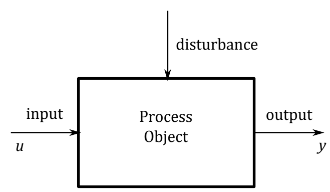
Process control

Management levels are: business management, production management, process control.

1 Goals



Goals: to bring process to the desired state.
Meet the requirements:

1. Ensure the output values with certain conditions (operates at design specifications, satisfying predetermined dynamic performance)

   value y, deviations $\pm\Delta y$, condition, etc.

   Regulatory problem - reducing the impact of the disturbances;

   Servo/tracking problem - track the changing set point;

   Not to keep as close as possible, but within permitted limits.

2. The fight against disturbances and environment/ object changes

   operability, robustness, safety, etc.

3. Process information administration and communication

   Where: production management, quality monitoring and control, business administration, asset management.

   How: local area networks, databases.

The most common problem in industry is to keep steady operation around the setpoint when disturbances are happening. Role of the controller is to react and recover the desired plant operation in a smooth manner.

Setpoint tracking arises in processes where output variable (quality or quantity) varies. A smooth and rapid transition between changes of the setpoint is expected.

General guidelines [2]

1. Keep control as simple as possible.

   Everyone involved should understand the system.

2. Use feedforward control to compensate for large, frequent and measurable disturbance.

3. Use override control to avoid constraints.

4. Avoid lags and deadtimes in feedback loops.

   Keep them inside loop as small as possible;

   Sensors should be located close to manipulated variable.

5. Eliminate minor disturbances by using cascade control systems when it is possible.

6. Avoid control-loop interaction if possible, otherwise make sure the controllers are tuned to make entire system stable.

   MIMO control.

7. Check control system for potential dynamic problems during abnormal conditions.

   Flexibility: work well over a range of conditions;

   Startup and shutdown situations.

8. Avoid saturation of the manipulated variable.

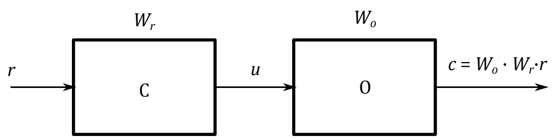
   Use override control.

9. Avoid "nesting" control loops if possible.

   Operation of the external loop depends on the operation of the internal loop.

2 Basic concepts

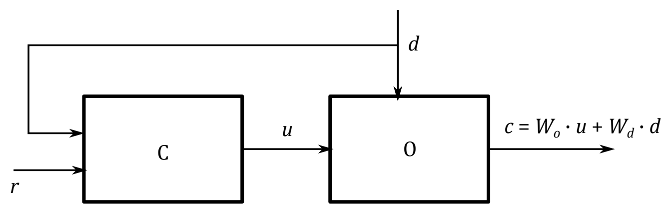
Two concepts: an open system, closed system.



2.1 Open system

from the condition $c = r$ it follows $W_r = W_o^{-1}$ $(K_r = 1/Ko, F_r() = F_o^{-1}())$ Is it realizable?

If we could detect disturbance influencing the process, we will be able to correct it before it upsets the process. Feedforward control configuration measures the disturbance (load) directly and takes a preemptive control action to eliminate its impact on the process [2, 3].



Consider disturbances d, if the disturbance is measurable its impact can be compensated.

$$(c = r) \text{ follows } W_r = W_o^{-1} \cdot (r - W_d \cdot d)$$

Feedforward control could be a perfect control mechanism, but we should consider the following problems to understand its opportunities better.
Problems:

- inaccurate model O: $W_o \pm \Delta W_o$
- non-measurable disturbances d
- non-realizable controller W_o^{-1}

An open system is one possible solution, which has its own characteristics.

Advantages	Disadvantages
Acts before the disturbance hits the process	Must identify and measure all disturbances
Cannot cause instability	Fails for unmeasured disturbances
Good for slow process dynamics	depends on the availability of process models
	Fails if process behavior varies
	No indication of control quality

[3]

Feedforward control is widely used in industry processes that include boilers, evaporators, solids dryers, direct fired heaters and waste neutralization plants [4].

Liquid level control in a boiler drum

The feedforward control can provide better control of the liquid level. If we measure the steam flow rate, feedforward controller will adjust the feed water flow rate so, that it balances the steam demand Figure 1. Alternatively we can measure pressure instead of steam flow rate.

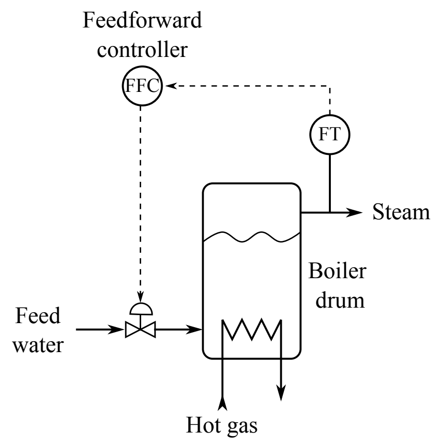


Figure 1: FFC of the liquid level i a boiler drum

2.2 Ratio Control

Ratio control is a special type of ffc that can be used in industry applications. Its objectives to maintain the ration of two process variables at specified value. The two variables are usually flow rates, a manipulated variable u and disturbance d.

$$R = \frac{u}{d} \tag{1}$$

Thus, the ration is controlled rather than individual variables.

Typical applications of ratio control include

1. Specifying the relative amounts of components in blending operations;
2. Maintaining a stoichiometric ratio of reactants to reactor;
3. Keeping a specified reflux ratio for a destination column;
4. Holding the fuel-air ratio to a furnace at the optimum value.

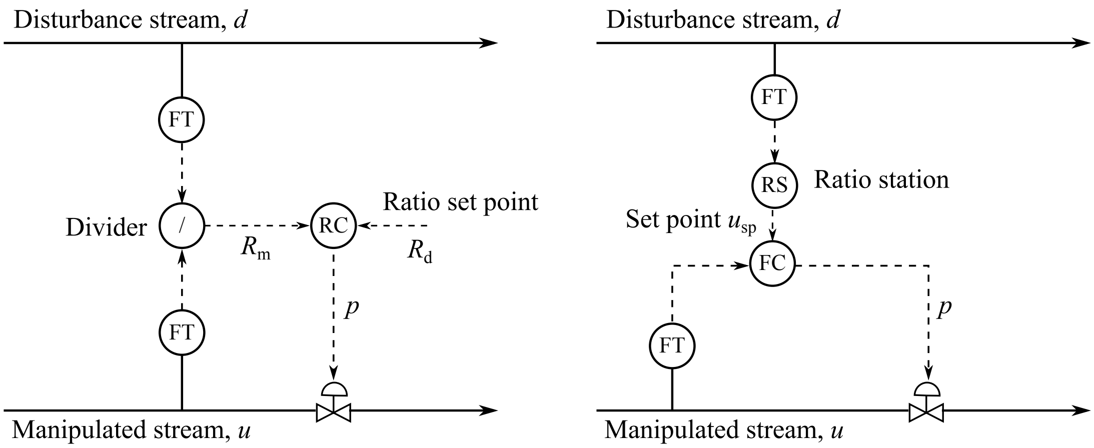


Figure 2: Ratio control

Ratio control can be implemented be two basic methods, see Figure 2. Advantage of the Method I is that measured ratio R_m is calculated. The main disadvantage is that divider element must be included in the loop and this element makes the process gain K_r vary in nonlinear way.

$$K_r = \left(\frac{\mathrm{d}R}{\mathrm{d}u}\right)_d = \frac{1}{d}.$$

The key advantage of the Method II is that process gain remains constant.

The design of the feedforward controller requires knowledge of how the controlled variable responds to changes in the control law (manipulated variable) and disturbance variables. This knowledge is usually represented as a process models [4].

Regardless of how ratio control is implemented, we must scale process variables. For that purpose spans of the two flow transmitters should be taken into account.

$$K_r = R_d \frac{S_d}{S_u},$$

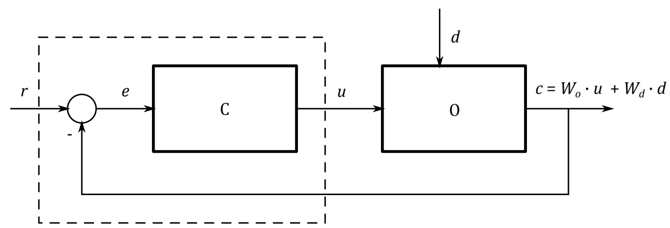
where R_d is a desired ratio, and S_u, S_d are the spans of the flow transmitters for controlled and disturbance streams, respectively.

A disadvantage of both methods that desired ration may not be achieved as a result of the dynamics associated with the flow control loop for u.

In practice, feedforward control is combined with feedback control. For these control configurations, the feedforward controller is usually tuned before the feedback controller [4].

2.3 Closed system

The feedback control problem starts with measurement of the manipulated variable y_m. Then measured value of the controlled variable is compared with desired setpoint variable y_{sp} to generate tracking error e. The role of the feedback controller is to produce a control action based on setpoint tracking error, which applied though the manipulated variable on the process, helps the controlled variable to achieve desired setpoint. The control action is implemented through an actuator, for example some valve that regulates the flow rate of a process [3].



$$c = \left(I - W_o \cdot W_r\right)^{-1} \cdot W_o \cdot W_r \cdot r + \left(I - W_o \cdot W_r\right)^{-1} W_o \cdot W_d \cdot d \text{ - MIMO}$$

$$c = \frac{W_o \cdot W_r}{1 + W_o \cdot W_r} \cdot r + \frac{1}{1 + W_o \cdot W_r} \cdot W_d \cdot d \text{ - SISO}$$

$$out = \frac{direct}{1 + loop} \cdot inp \tag{2}$$

The most important feature of the feedback control system, that it learns the process behavior through continuous measurement of the output and feed information back to controller that commands a certain change in the manipulated variable.

Good features of the feedback

1. Reducing the impact of the disturbance d
   The goal is to compensate, not to eliminate!

   disturbances in open-loop system: $c = W_d \cdot d$

   disturbances in close-loop system: $c = S \cdot W_d \cdot d$

   $L \gg 1 \Rightarrow S \ll 1$ regulatory problem

   no disturbance d measurements needed

   no process model W_d necessary

   knows the direction of u how to change $c - d$

2. tracking the set point as close as possible $c = r$

   $L \gg 1 \Rightarrow T \approx 1$ servo problem keep within the limits $c = r + \Delta c$

3. reducing the impact of the parameters change in loop L

   $\frac{dT}{T} = S \cdot \frac{dL}{L}$ the impact of the model errors is reduced

   obtain a good system ($\frac{dT}{T} <$) from the bad components ($\frac{dL}{L} >$)

   linearization of the statical model

4. System dynamics changes

   faster in general

   stabilization of the unstable object

Drawbacks of the feedback

1. System (stable object + stable controller)

   can become oscillatory, that can cause stability reduction

2. Noise impact shows up, for the $e \ll$ it is needed $L <$.

   But this is in conflict with the requirement to reduce disturbances

   noise acts as input signal

3. Strong control signals u on the controller output

   saturation, difficult to realize

4. Difficulties with the nonminimum-phase systems (delays, RHP (Right Half-Plane), RHPZ (Right Half-Plane Zero), ...)

   imposes principle constraints on systems

   desired objectives cannot be achieved (stability, performance)

   even if exact model is known and control signals are not saturated

The feedback loop is influenced by three external signals: the reference r, the load disturbance d and the measurement noise n. The control mechanism acts using the information fed back from the measurements.

What are the closed system inputs and outputs?

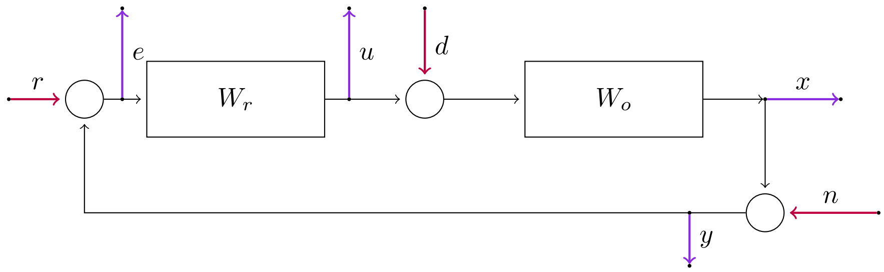


Figure 3: The pure error feedback loop

$$\begin{matrix} d \\ r \\ n \end{matrix} \rightarrow \begin{matrix} y \\ u \\ x \\ e \end{matrix}$$

In that case we have 12 transfers. If all control actions are based on feedback from the error only then the system is completely characterized by four transfer functions called *Gang of Four* [1].

$S = \dfrac{1}{1 + W_r \cdot W_o}$ sensitivity function $\frac{y(s)}{n(s)}$

$W_o S = \dfrac{W_o}{1 + W_r \cdot W_o}$ load sensitivity function $\frac{y(s)}{d(s)}$

$T = \dfrac{W_r \cdot W_o}{1 + W_r \cdot W_o}$ complementary sensitivity function $-\frac{u(s)}{d(s)}$

$W_r T = \dfrac{W_r}{1 + W_r \cdot W_o}$ noise sensitivity function $-\frac{u(s)}{n(s)}$

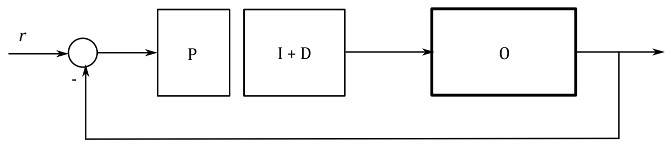
System is stable if Gang of Four is stable.
System is stable if bounded input signals (d, r, n) generate bounded outputs (y, u, x, e) (internal stability).

- If object W_o is stable then the only requirement is $W_r \cdot S = \dfrac{W_r}{1 + W_r \cdot W_o}$ should be stable;
- If object W_o is unstable then closed system can be made stable, requires all four transfers to be stable;
- It is possible to use unstable controller W_r.

Feedback changes open-loop system features. How poles are changing then controller's (C) gain is changed - root locus

Cancelation of the object pole by a controller's zero

- object stable pole (RHP) can be eliminated by the controller's zero (PI controller)



$$W_r = K_p(1 + \frac{1}{T_i \cdot s}) \quad W_o = \frac{K_o}{1 + T_o \cdot s}$$

$$W_l = W_r \cdot W_o = \frac{K_p(1 + T_i \cdot s)}{T_i \cdot s} \cdot \frac{K_o}{1 + T_o \cdot s}$$

if $T_i = T_o$, then $W_l = K/T_i \cdot s$ and closed system $W_s = 1/1 + T_s \cdot s$, where $T_s = 1/K$

in case of imprecise $T_i \approx T_o$ (some problems)

- unstable poles should not be eliminated by zero (severe problem)

There are principle limits (not all is impossible)

aim: stable closed-loop system

freedom choose the controller gain, zeros and poles

problems delay τ and Right Half (unstable) zeros (RHZ) and poles RHP.

- limitations on frequency band ω (operating speed)

  $\omega < (0.2 \ldots 0.5 \cdot RHZ), \quad \omega < (0.4 \ldots 0.7)/\tau \quad \omega > (5 \ldots 2) \cdot RHP$

- limitations in case of multi-components

  $RHZ > (14 \ldots 7) \cdot RHP, \quad RHP < (0.05 \ldots 0.16) \cdot \tau$

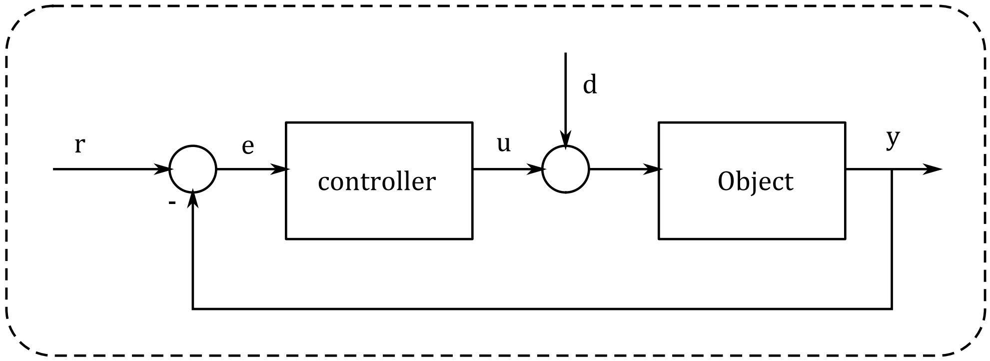
2.4 Performance

- System Requirements (objective description)
- Performance evaluation

Control loop

Control loop: $r(t), d(t) \rightarrow y(t)$ To choose a controller type your need:

1. model of the object/process or test data
2. system requirements



How to describe the desired behavior of a closed loop system? How comparable system is? What is numerical value of the system performance?
Requirements(goals)→ actual (results)

- what is changing $r(t), d(t), W_o, \ldots$ - reason
- how is changing (step, random,...)
- what is observed $y(t), e(t), \ldots$ -conclusion
- how to evaluate the change by numeric value (max, standard deviation, integral,...)

What system features are important?

Requirements must be: measurable, unambiguous, understandable.

Performance requirements

1. Requirements in time domain
   Overshoot
   Overshoot is formally defined for the case where the process makes a transition from one operating level to another, see Fig. 4.

$$\sigma(\%) = \frac{y_{max} - SP}{SP} \cdot 100\% \tag{3}$$

   Decay Ratio
   The decay ratio reflects the rate of decay of the sinusoidal component of the response. The decay ratio is the ratio of the second peak overshoot b to the first peak overshoot a (see Fig. 4)

$$\psi = \frac{b}{a} \tag{4}$$

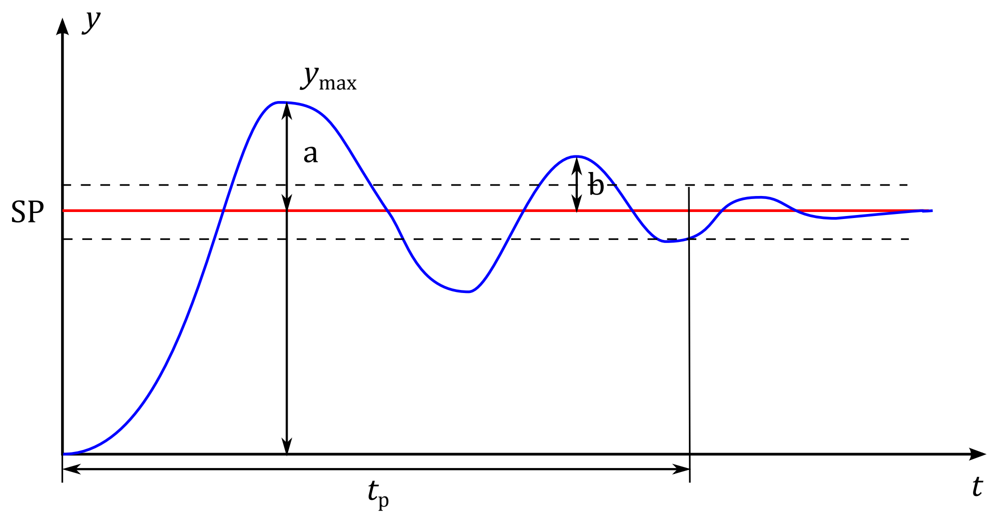


Figure 4: Control criteria

In process control, the decay ratio is the most commonly applied performance measure. Furthermore, the preferred value is almost always 1/4. The term "quarter - wave damping" is sometimes used to refer to responses whose decay ratio is 1/4. This response will have a significant first overshoot, followed by a small second overshoot.

Settling time
Settling time t_p is the time required for the system to attain equilibrium after a change in one or more of its inputs. To quantify the settling time numerically, one has to introduce a tolerance for a variable to be considered as having attained its equilibrium value. When the input is a step change in the set point, the tolerance is typically 2% or 5%. As indicated in Fig. 4, the tolerance introduces a band about the final value. The settling time t_p is the time required for the response to come within that band and to remain within that band thereafter.

The integral criteria

An integral criterion is a performance measure that is based on the integral of some function of the control error and on possibly other variables (such as time).

The three most commonly used integral criteria are as follows:

- Integral of the absolute error (IAE);
- Integral of the square error (ISE);

- Integral of time and absolute error (ITAE).

The smaller the value of the integral criterion, the better the performance of the control loop. Thus, when used as the basis for tuning a PID controller, the objective is to determine the values of the tuning parameters K_c, T_i, T_d that minimize the selected integral criterion.

2. Requirements in frequency domain

   poles placement, dominant pole (pair), amplitude and phase margins

3. Requirements to robustness

   actual parameters are not accurately known (model errors) or changed (aging, repair, cleaning, ...) and different from the calculated ones.

- Requirements are contradictory (speed $\leftrightarrow$ overshoot)
- Different requirements give different solutions

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