ME 6401: Control Systems

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ME 6401: Advanced Mechatronics
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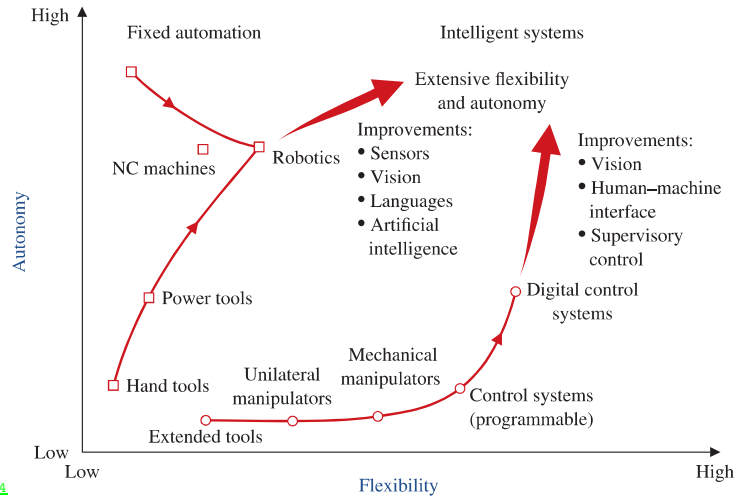
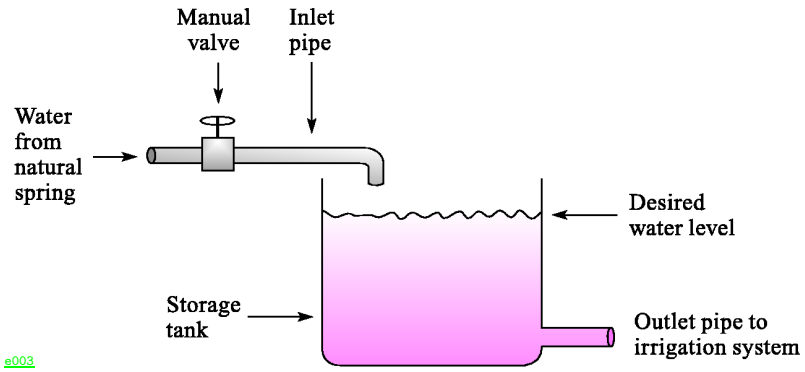


Evolution of control systems and autonomy.

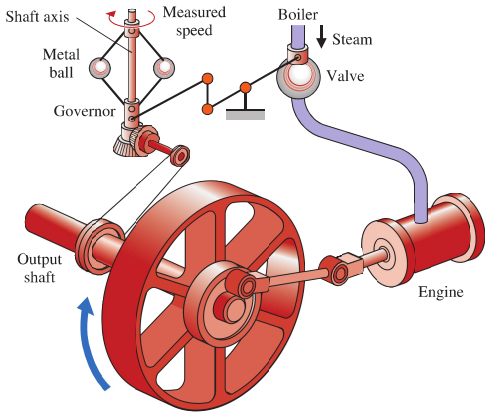
Importance

- A Control system is an interconnection of components forming a system configuration that will provide a desired system response.
- Primary Reasons
  - Power amplification
  - Remote control
  - Convenience of input form
  - Compensation for disturbances
- Important Outcomes
  - Increased productivity and lower product cost
  - Better and more uniform quality of product
  - Greater safety for operating personnel

Example: Manual Control System



Example: Automatic Mechanical Control System



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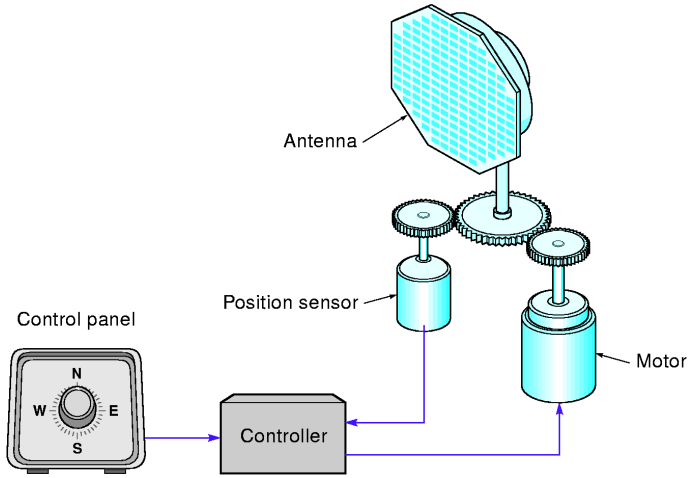
Watt's fly-ball mechanical governor

Example: An Antenna Positioning System



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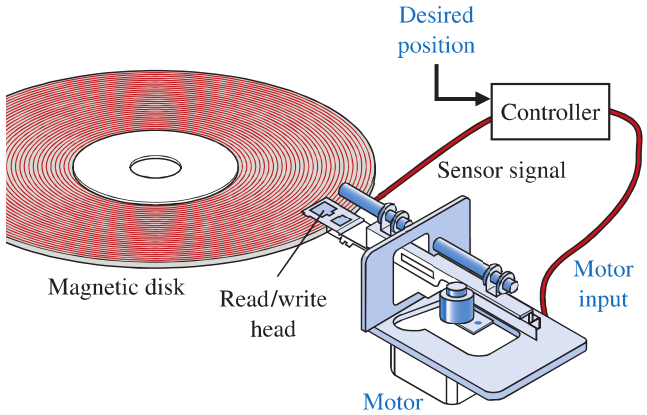
Example: Hard-disk Control System



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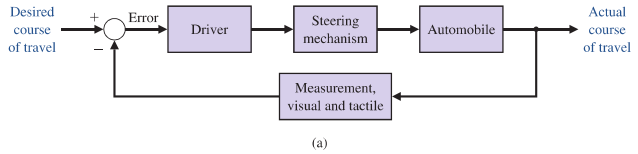

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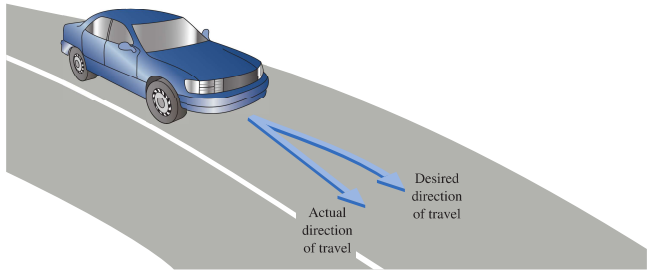

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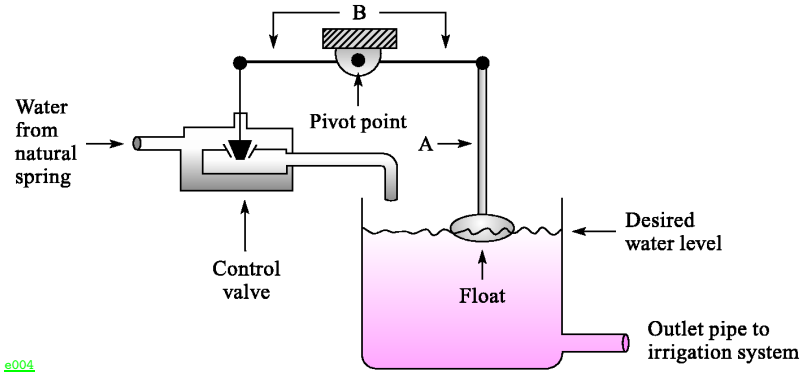
(b)

Example: Automatic Control System



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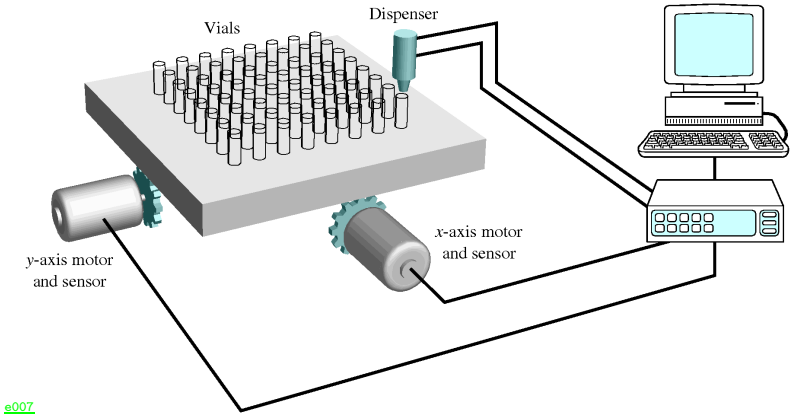
Example: Computer Based Control System



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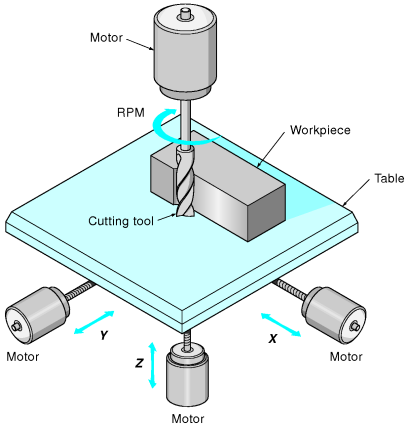
Automatic table and dispenser

Example: Servomechanism



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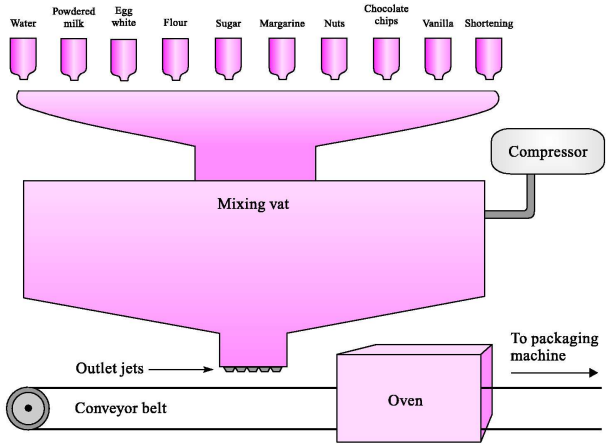
Numerical control milling machine

Example: Batch Processes in Cookie Machine



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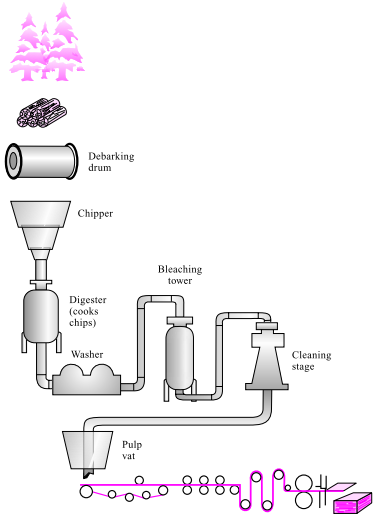
Example: Continuous Process Control in Paper Mill



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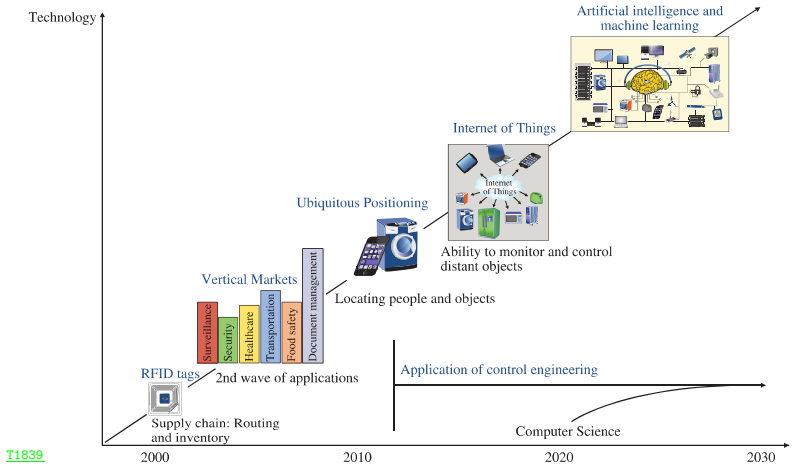
Classifications

- Open-Loop System - output has no effect on control action.
- Closed-loop System - maintains a prescribed relationship between the output & some reference input by comparing them and using the difference as a means of control.
- Servomechanism - a feedback control system to control motion.
- Process Control Systems - a feedback control system where one or more process variables such as temperature, flow, liquid level etc are controlled.
- Batch Process - is a sequence of timed operations executed on the product being manufactured.
- Continuous Process - one or more operations are being performed as the product is being passed through a process.



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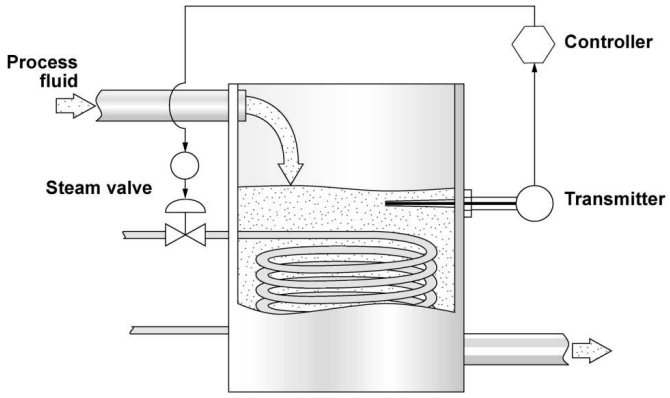
Technology roadmap to the Internet of Things enhanced with artificial intelligence with applications to control engineering.

Feedback Control



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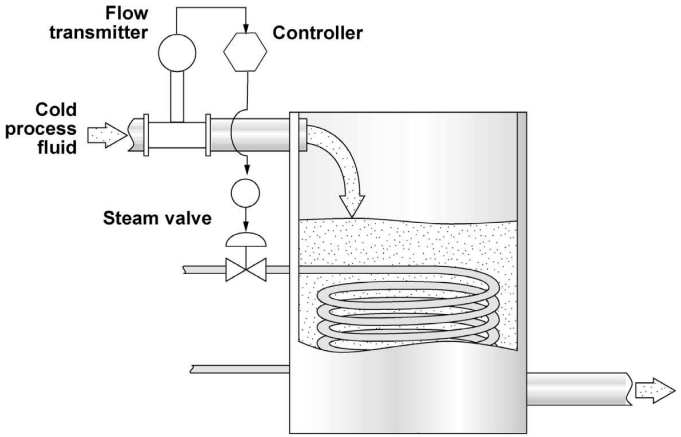
Feed-forward Control



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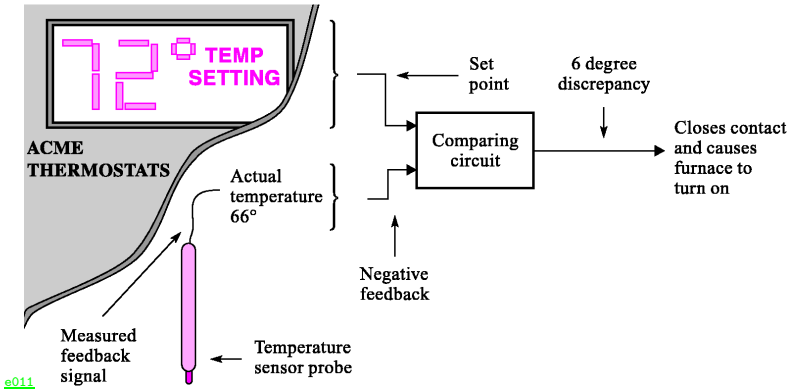
Example: Industrial Negative Feed-back Control



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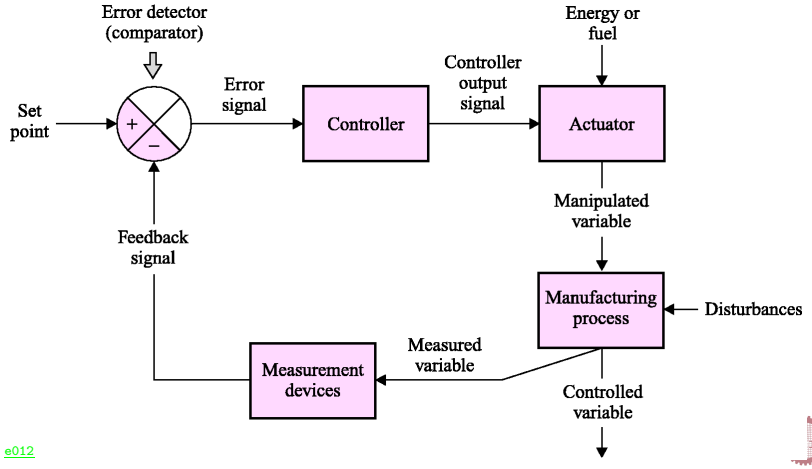
Elements of Closed-loop Control System



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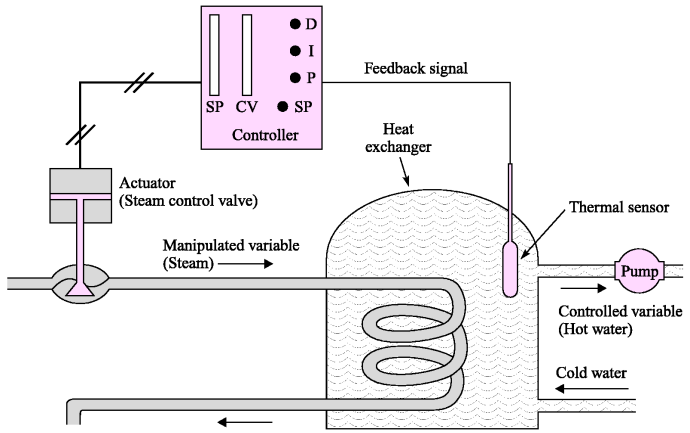
- Controlled Variable is the actual variable being monitored and maintained at a desired value in the manufacturing process.
- Measured Variable is the condition of the controlled variable at a specific point in time.
- Measurement Device senses the measured variable and produces an output signal that represents the status of the controlled variable.
- Feedback Signal is the output of the measurement device.
- Setpoint is the prescribed input value applied to the loop that indicates the desired condition of the controlled variable.
- Error Detector compares the setpoint to the feedback signal.
- Error Signal is the output of the error detector.

- Controller is the "brain" of the system. It receives the error signal (for closed-loop control) as its input, and develops an output signal that causes the controlled variable to become the value specified by the setpoint.
- Actuator is the "muscle" of the system. It is a device that alters some type of energy or fuel supply, causing the controlled variable to match the desired setpoint.
- Manipulated Variable: The amount of fuel or energy that is altered by the actuator is referred to as the manipulated variable.

Example: Industrial Temperature Control System



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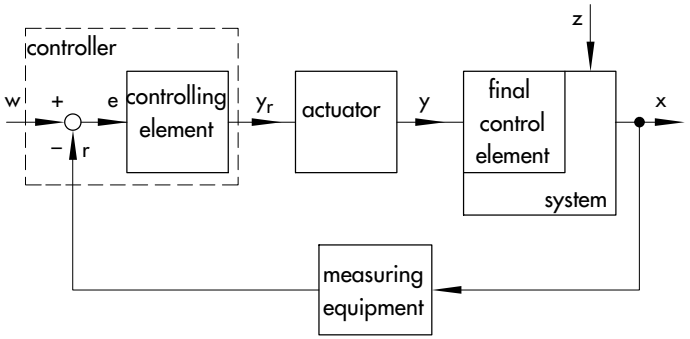
Block Diagram & Abbreviations



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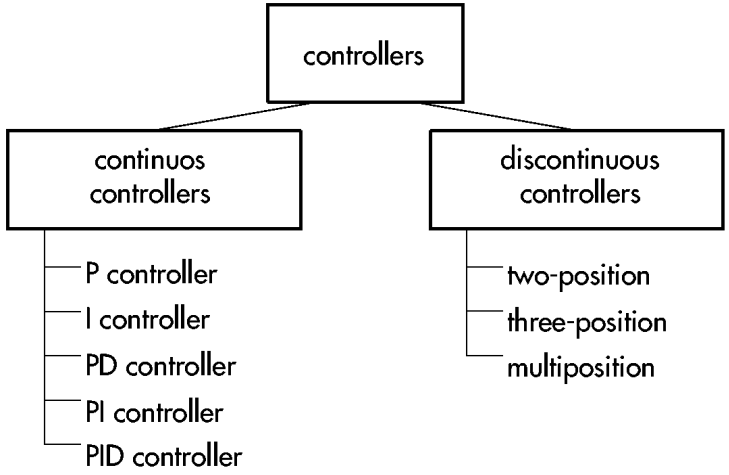
w	: reference variable	x	: controlled variable
y	: manipulated variable	z	: disturbance variable
r	: feedback variable	e	: error $(\equiv w - r)$
y_r	: controller output variable		

Control Modes



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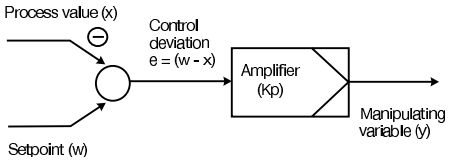
Proportional (P) Controller



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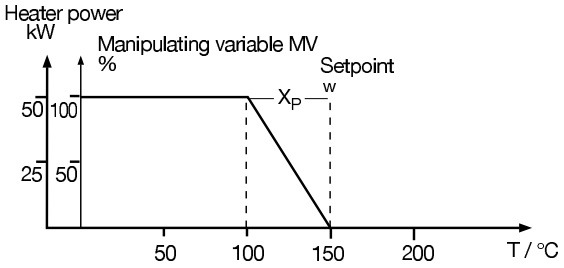
- In P mode, linear relationship between manipulating variable (MV), y and error, e exist in Proportional Band (PB), X_p:

$$y = K_p e + y_o \qquad X_p = \frac{100\%}{K_p}$$

- If error is zero, output is a constant equal to y_o.
- In case of error, for every 1% of error, a correction of K_p% is added or subtracted from y_o, depending on error sign.
- Narrower the X_p, a small deviation will cause the full manipulating range, i.e. gain increases as X_p is reduced.

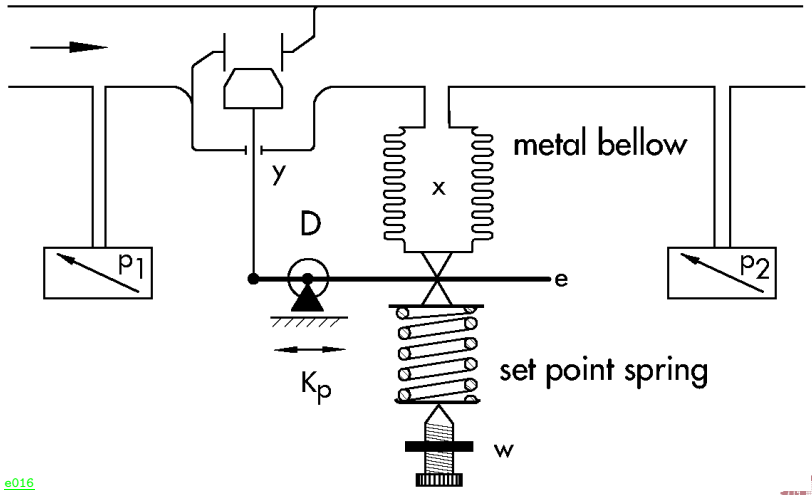
Proportional Band



e210

- MV is only proportional to error within PB, beyond which output is saturated at 0% or 100%,
- Within X_p, the controller travels through the full manipulating range, y_h, so the K_p can be determined as:

$$K_p = \frac{y_h}{X_p} = \frac{\text{Maximum manipulating range}}{\text{Proportional Band}}$$



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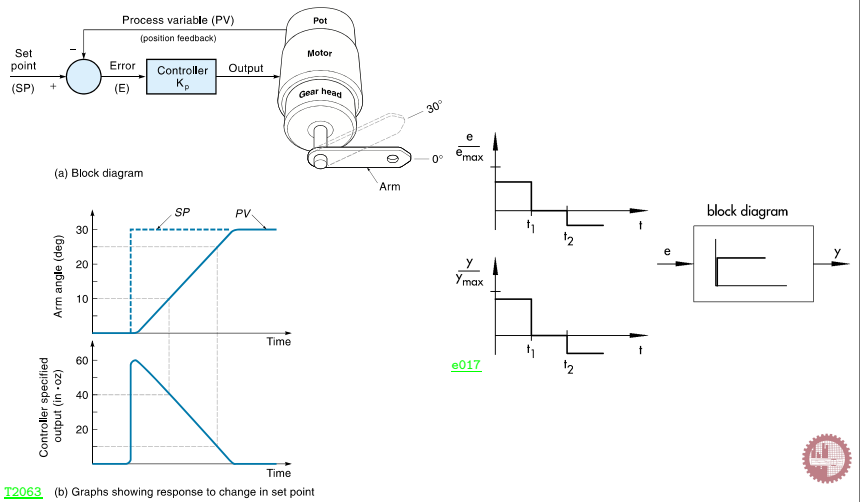
Dynamic Behaviour of a P Controller



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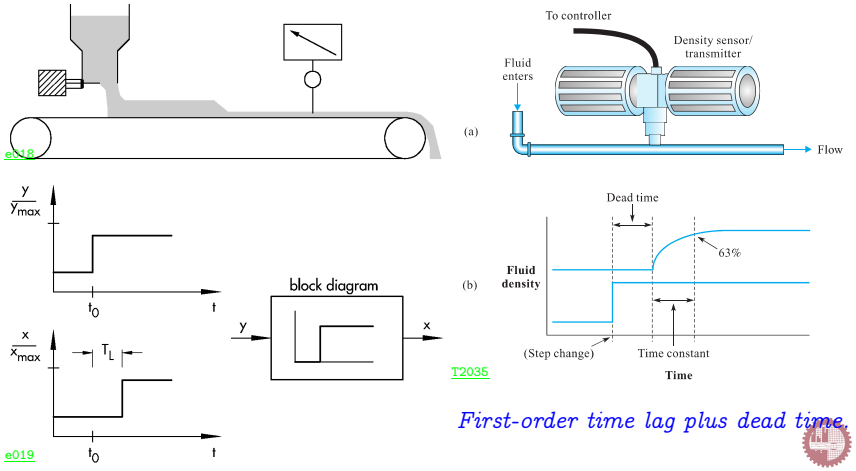
T2063 (b) Graphs showing response to change in set point

Controlled system with dead-time



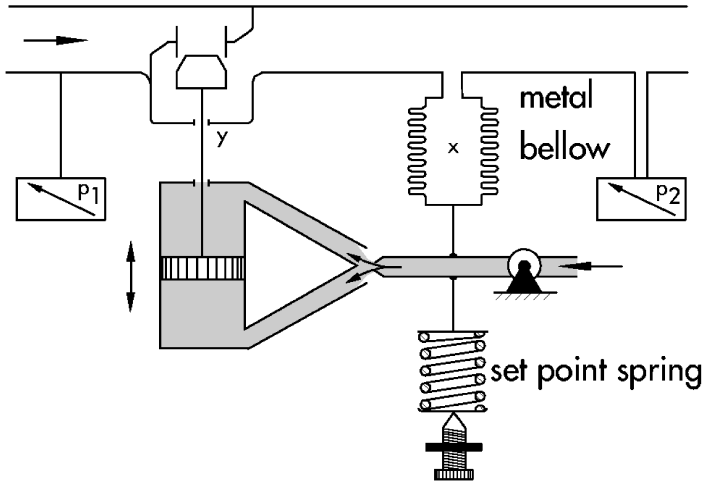
First-order time lag plus dead time.

Integral (I) Controller

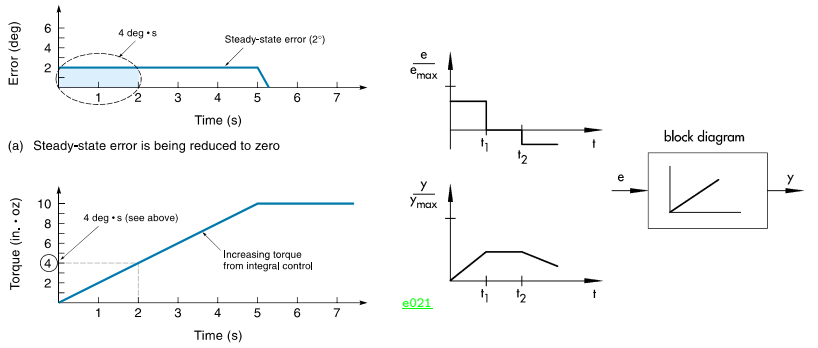
- Integral control action is used to minimise steady-state errors. As long as the error is non-zero, the integral action will cause the value of the manipulated variable to change. Control action is based on the 'history' of the system error.
- In I control mode, the value of the manipulated variable is changed proportional to the integral of the error e

$$y = K_I \int e dt + y_o \qquad \text{with :} \quad K_I = \frac{1}{T_n}$$

- The higher the integral action coefficient K_I, the greater the integral action of an I controller.
  - No steady state error,
  - Sluggish response at low K_I,
  - At high K_I, the control loop tends to oscillate/may become unstable.



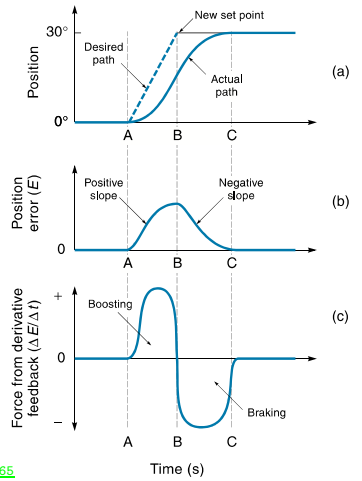
Dynamic Behaviour of a I Controller



Derivative (D) Controller

- D controllers generate the manipulated variable from the rate of change of the error and not - as P controllers - from their amplitudes.
- D controllers speeds up the transient response of the system.
- These react much faster than P controllers: even if the error is small, derivative controllers generate - by anticipation - large control amplitudes as soon as a change in amplitude occurs.
- A steady-state error signal, however, is not recognized by D controllers, because regardless of how big the error, its rate of change is zero.
- D controllers are rarely used in practice. They are usually found in combination with other control elements, mostly in combination with proportional control.

Dynamic Behaviour of D Controller



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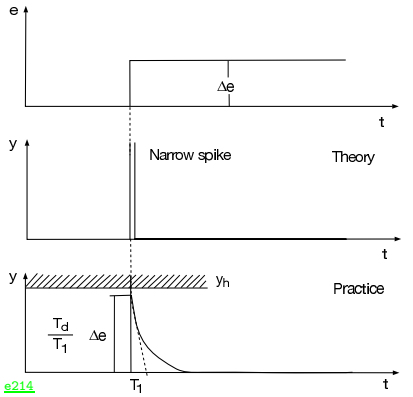

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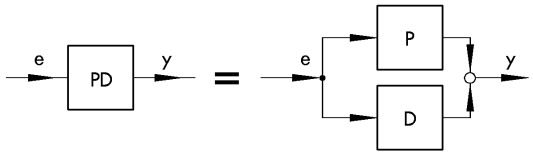
$T_1 = T_d/4$ is practical D controller time constant, and its value is specified by the manufacturer.

PD Controller

- In PD controllers with proportional-derivative control action, the manipulated variable results from the addition of the individual P and D control elements:

$$y = K_p e + K_D \frac{de}{dt} + y_o$$

- The control response for steady-state error in PD controllers is just as it occurs in P controllers. Due to the immediate control action whenever there is a change in the error signal, the control dynamics is faster than with P controllers.



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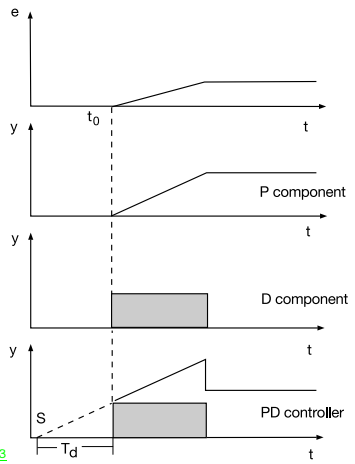
Response of a PD Controller



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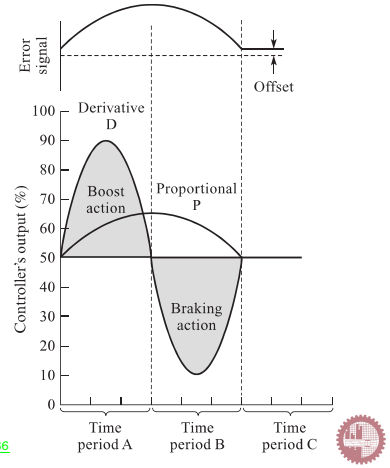

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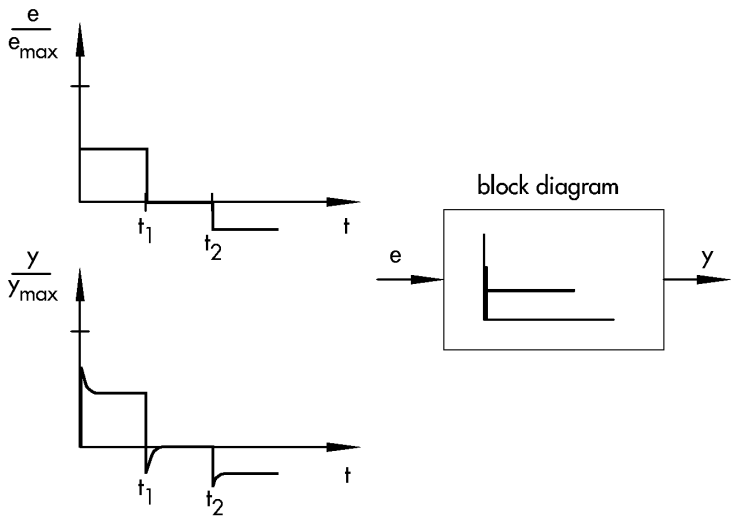

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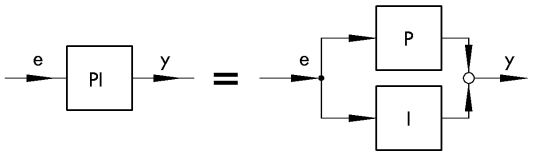
Response of a PD Controller

PI Controller

- PI controllers are often used in practice. If properly designed, they combine the advantages of both controller types (stability and rapidity; no steady-state error), so that their disadvantages are compensated for at the same time.
- The manipulated variable of PI controllers is calculated as follows:

$$y = K_p e + K_I \int e dt \qquad \text{with :} \quad K_I = \frac{K_p}{T_n}$$



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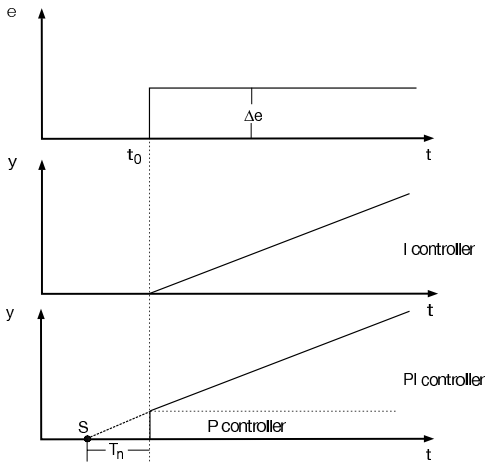
Step Response of a PI Controller



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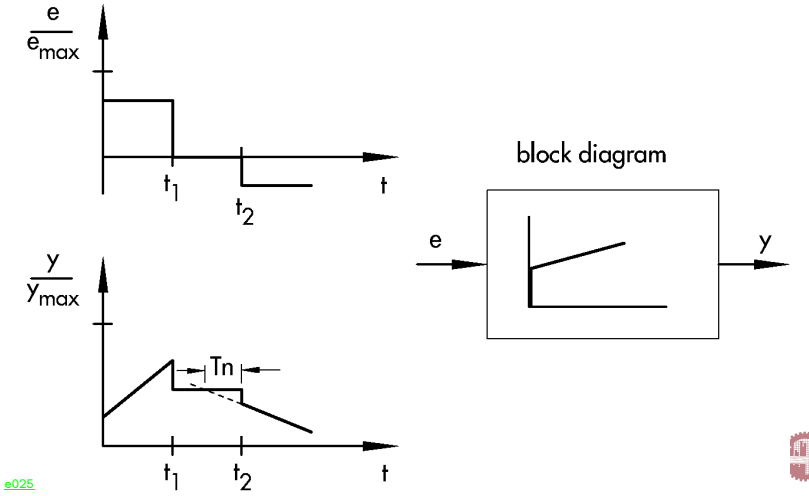
Dynamic Behaviour of an PI Controller



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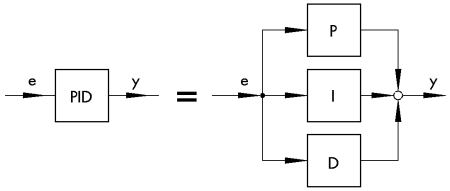
PID Controller

- If a D component is added to PI controllers, the result is an extremely versatile PID controller. If properly tuned, this controller causes the controlled variable to reach its set point more quickly, thus reaching steady-state more rapidly.
- The manipulated variable of PID controllers is calculated as follows:

$$y = K_p e + K_I \int e dt + K_D \frac{de}{dt}$$



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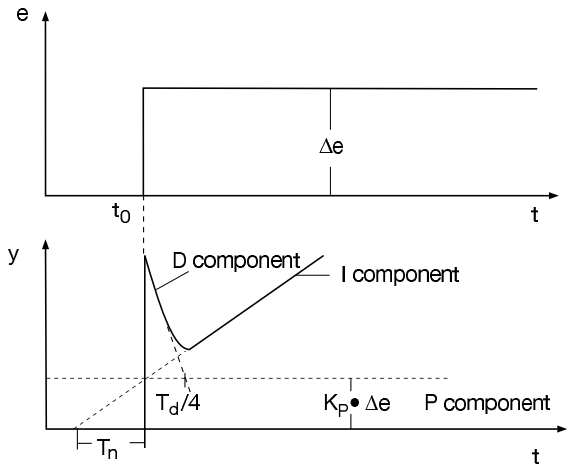
Step Response of a PID Controller



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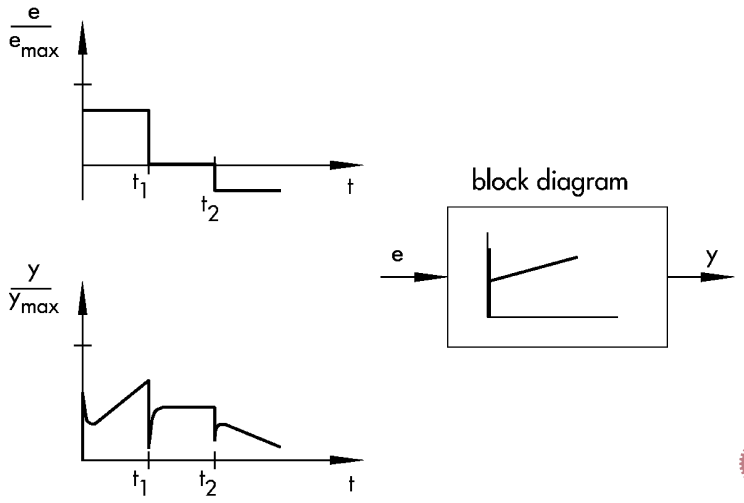
Dynamic Behaviour of an PID Controller



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Comparison of Controller Types & Configurations

Mode Combinations	Function	Applications
Proportional (P)	To provide gain	For small setpoint or small load changes
Proportional-plus-Integral (PI)	To eliminate offset	For large and slow setpoint or load changes
Proportional-plus-Derivative (PD)	To speed up response and minimize overshoot	For sudden setpoint or quick load changes in a slow-response system
Proportional-Integral-Derivative (PID)	To speed up response, minimize overshoot, and eliminate offset	For large and sudden setpoint or load changes in a slow-response system

T2040

	Permanent deviation		No permanent deviation	
	P	PD	PI	PID
Temperature	simple process for low demands	simple process for low demands	suitable	highly suitable
Pressure	mostly unsuitable	mostly unsuitable	highly suitable; for processes with long delay time I controller as well	suitable, if process value pulses not too much
Flow	unsuitable	unsuitable	suitable, but I controller frequently better	suitable
Level	with short dead time suitable	suitable	suitable	highly suitable
Conveyor	unsuitable because of dead time	unsuitable	suitable, but I controller mostly best	nearly no advantages compared with PI

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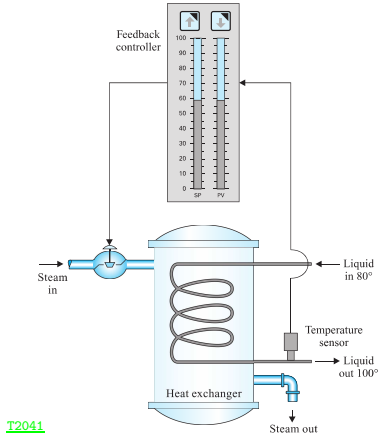
Other Controller Configurations



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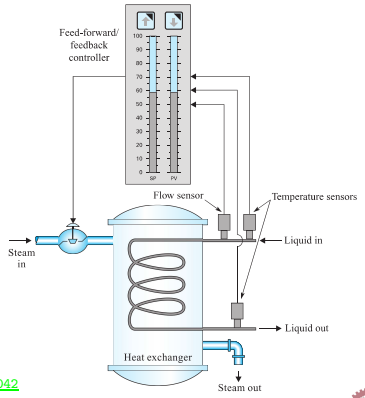
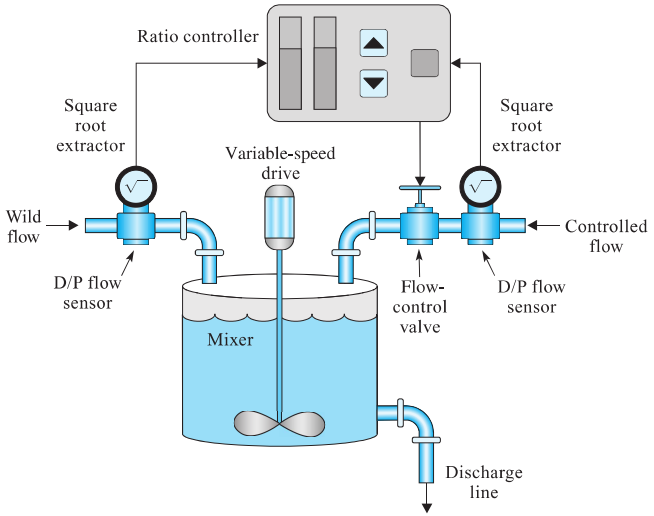
Feedback control system



T2042

Feed-forward control system

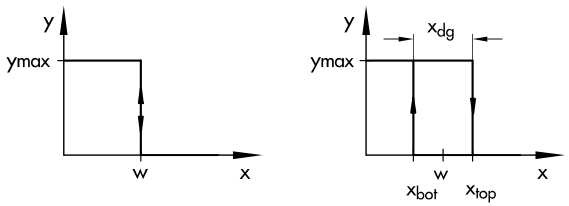


T2066

Ratio-control mixing process

Two-position (ON/OFF) Controller

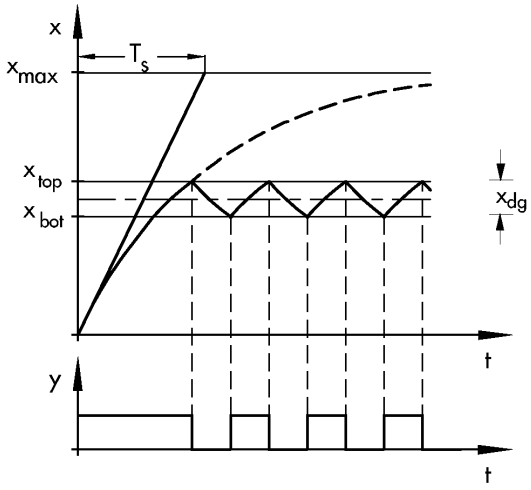
- The two-position controller has only two different output states, for instance 0 and y_{max}.
- For a simplest two-position controller, chatter is a practical problem as output oscillates back-and-forth when the controlled variable is close to the set point.



T2068

Switching characteristics of the two-position controller (without and with a neutral zone of width x_{dg}

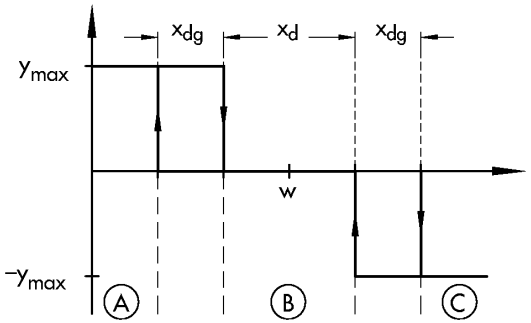
Response of an ON/OFF Controller



e028

Three-position Controller

Three-position controllers can assume three different switching states. In a temperature control system, these states are not only 'off' and 'heating' as in a two-position controller, but also 'cooling'.



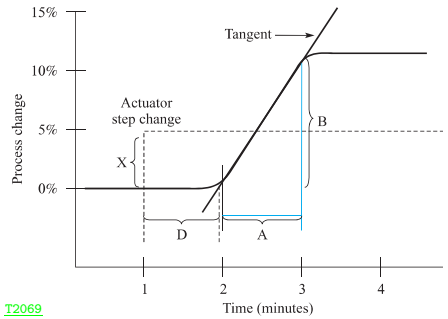
e029

Ziegler-Nichols Tuning Rules

$$G_{PID}(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) = K_p + \frac{K_I}{s} + K_D s$$

- Method 1: reaction-curve method (open-loop method): feedback loop is opened, and the controller is manually directed to output a small step function to the actuator. The system response is used to calculate K_P, K_I and K_D.
- Method 2: continuous-cycling method:, analyse the process response by forcing the controlled variable to oscillate by adjusting the proportional setting. The time period is ultimate period (T_c), and proportional setting causing the oscillation is the ultimate proportional gain value (K_u). These values are used to calculate K_P, K_I and K_D.

Method 1



T2069

$\Rightarrow R = \frac{B}{A}$

$\Rightarrow R_I = \frac{R}{X}$

- A = Time in minutes
- B = % of the process change
- X = % of the actuator change

- Effective delay (D): the time from when the step change is made until the process variable begins to react. This delay is caused by the process lag, dead time, or both.
- Process reaction rate (R): defined as how much the process changes per unit of time. This value is obtained by calculating the slope of the process reaction curve.
- Unit reaction rate (R_I): a measure of how much the process reacts for each percent of actuator change. To determine this value, the size of the step change must be taken from the graph. The size is read as a percentage of the actuator's span.

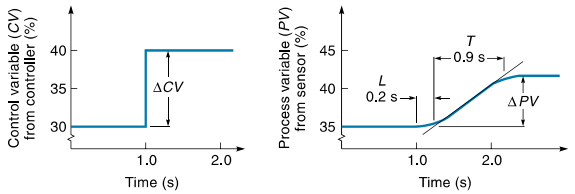
Ziegler-Nichols Reaction-Curve Formulas

Controller Mode	Proportional Gain K_c	Proportional Band PB	Reset Time T_i (Minutes per Repeat)	Reset Rate T_r (Repeats per Minute)	Derivative Time T_d
P	$K_c = 1/R_1D$	PB = $100R_1D$	N/A	N/A	N/A
PI	$K_c = 0.9/R_1D$	PB = $110R_1D$	3.33D	0.3/D	N/A
PID	$K_c = 1.2/R_1D$	PB = $83R_1D$	2D	0.5/D	0.5D

T2070

$$G_{PID}(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) = \frac{0.6}{sR_I}\left(s + \frac{1}{D}\right)^2$$

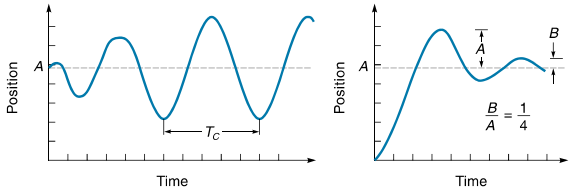
Example: ▷ Estimate K_P, K_I and K_D using data in figure below:



T2072

[7.7, 19.275/s, 0.77 s]

Method 2: Oscillation Method of Ziegler & Nichols



T2071

(a) System as forced into oscillation (b) Resulting response after tuning

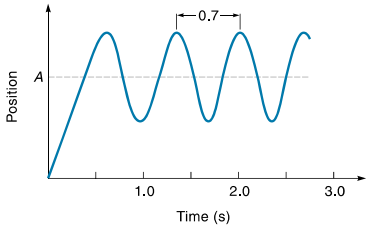
1. Reduce any I and D action to their minimum effect.
2. Gradually begin to increase K_P to K_u while providing periodic small disturbances to the process until system performs undamped oscillations of constant amplitude.

Controller	K_p	T_i	T_d
P	$0.5K_u$	∞	0
PI	$0.45K_u$	$T_c/1.2$	0
PID	$0.6K_u$	$T_c/2$	$T_c/8$

	Rise time	Overshoot	Settling time	Steady-state error
Increasing K_P	Decrease	Increase	Minor change	Decrease
Increasing K_I	Decrease	Increase	Increase	Eliminate
Increasing K_D	Minor change	Decrease	Decrease	No influence

T2074

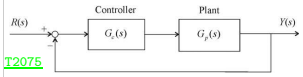
Example: ▷ Estimate K_P, K_I and K_D using $K_u = 4$ and data in figure below:



T2073

[2.4, 6.857/s, 0.21 s]

Example: ▷ Tune using ultimate-cycle method, estimate K_P, K_I and K_D.

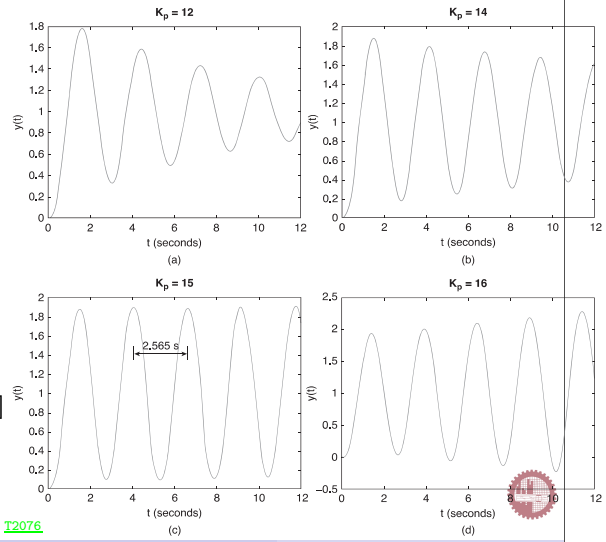


T2075

$$G_c(s) = K_p\left[1 + \frac{1}{T_i s} + T_d s\right]$$
$$G_p(s) = \frac{2}{s(s+2)(s+3)}$$

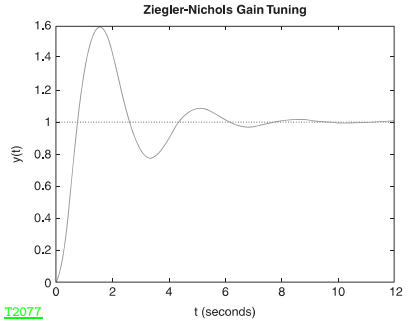
$\Rightarrow K_u = 15,\ T_c = 2.565$ s

[9, 7.02/s, 2.886 s]

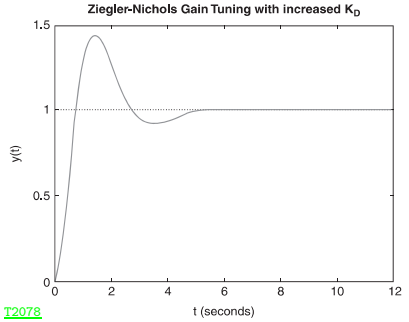


T2076

... contd.



T2077

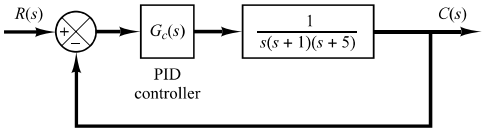


T2078

$K_p = 9,\ K_I = 7.02/s,\ K_D = 2.886$ s $\quad K_p = 9,\ K_I = 7.02/s,\ K_D = 4.0$ s

Design Problem: PID Controller

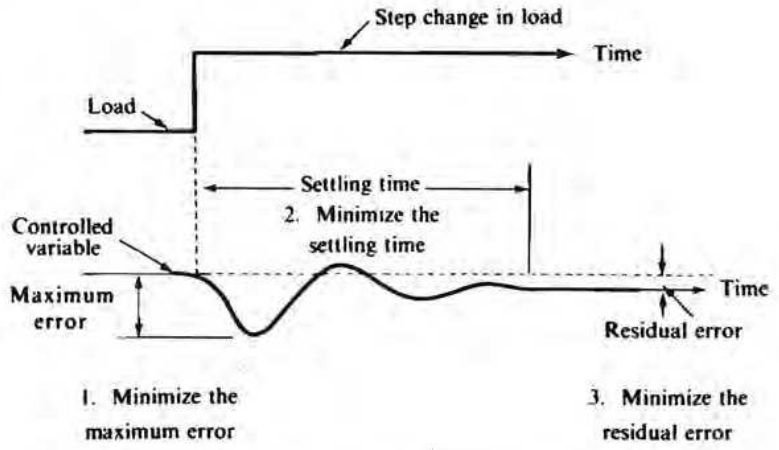
Example: ▷ Find PID tuning parameters



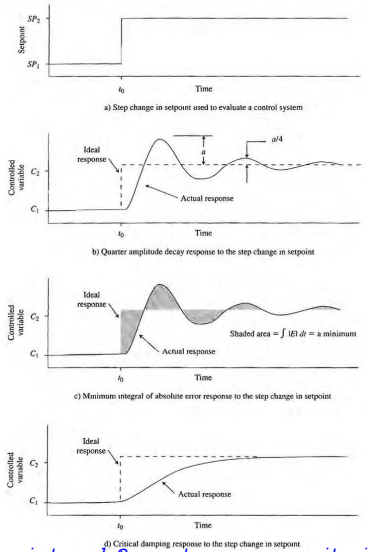
T2079

$[K_u = 30,\ T_c = 2.81,\ K_p = 18,\ T_i = 1.405,\ T_d = 0.35124]$

3 Objectives of a closed-loop control system



T2080



T2081

Step change in set-point and 3 most common criteria of a good control