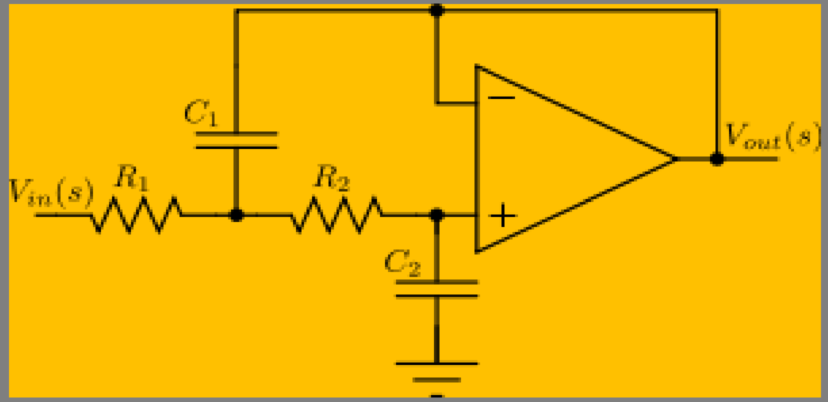
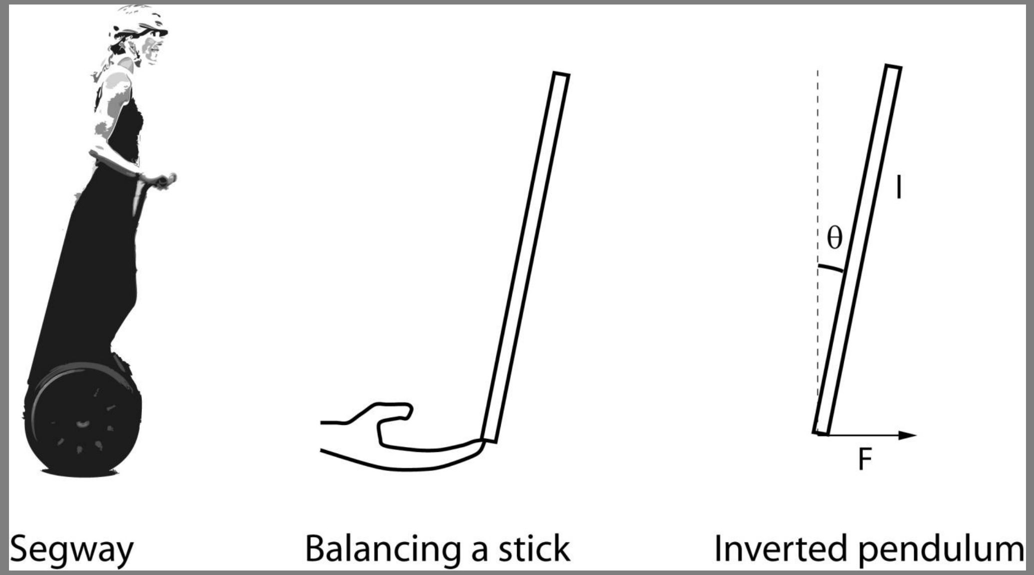
EEE304

Week 5: Feedback Systems





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Week 5: Feedback Systems

Learning Objectives:
-Develop a general understanding of
  -the feedback control problem and its objectives
  -how to determine inputs and outputs of a control system
  -loop shaping principles to define specifications for the closed loop system
-Tune PI controllers for simple plants for some common types of control problems

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Lecture 5.1: Feedback Generalities

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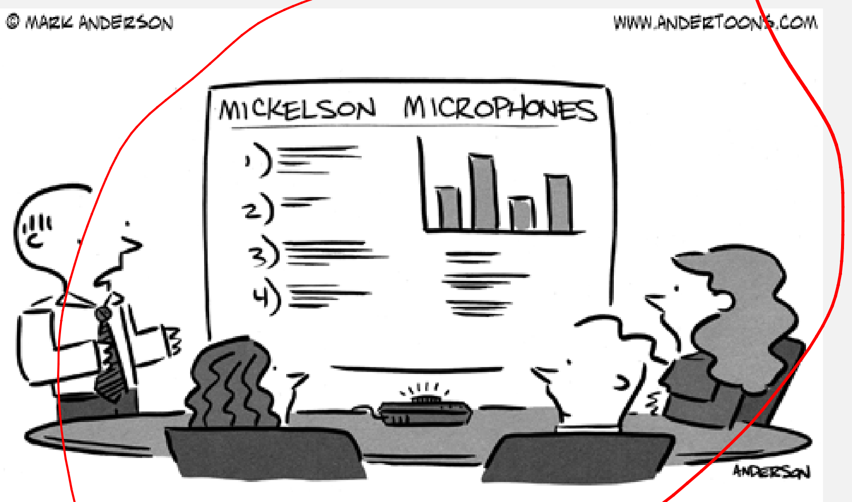
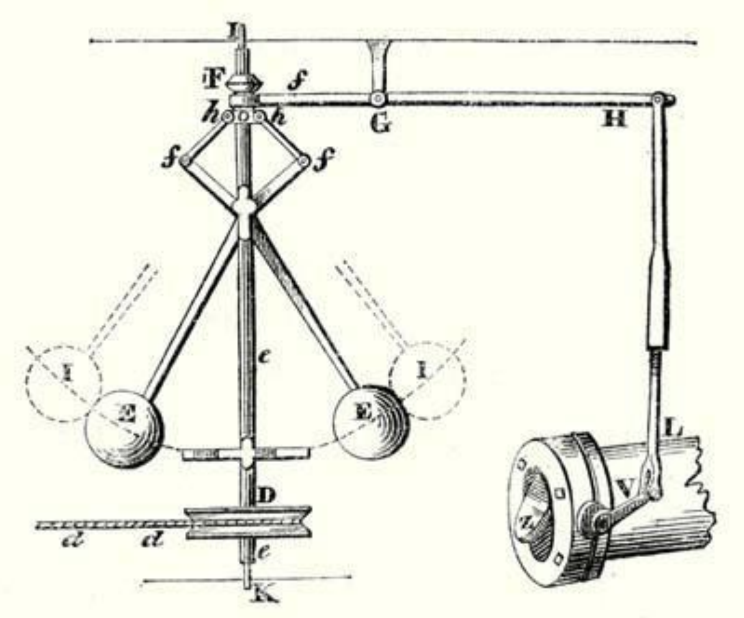
Feedback Systems

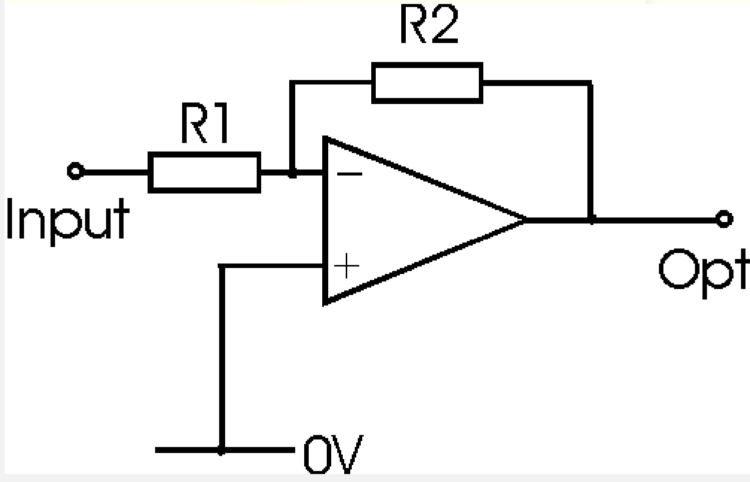
- Feedback systems are ubiquitous
  - Biology, Industrial Processes, Flight, Driving (human-in-the-loop or autonomous), financial, social
- Antiquity (Ktisivios water clock) to Watt regulator
- Bode, Nyquist and Electronic Amplifiers for communications (telephony)



"The good news is we're getting a lot of feedback. The bad news is we're getting a lot of feedback."

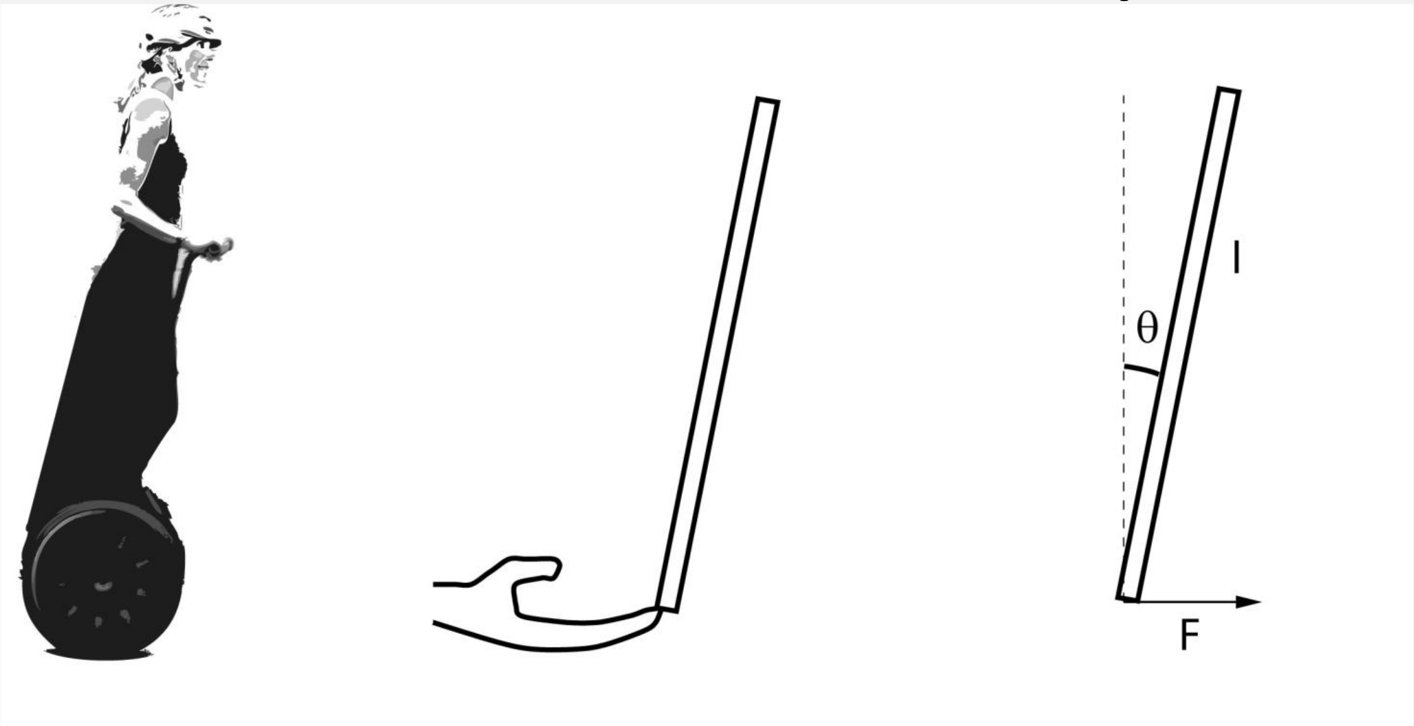
- Op-amps and electronic circuits, Motor speed/position control
- Aerospace and multivariable control
- Complex Systems and distributed control



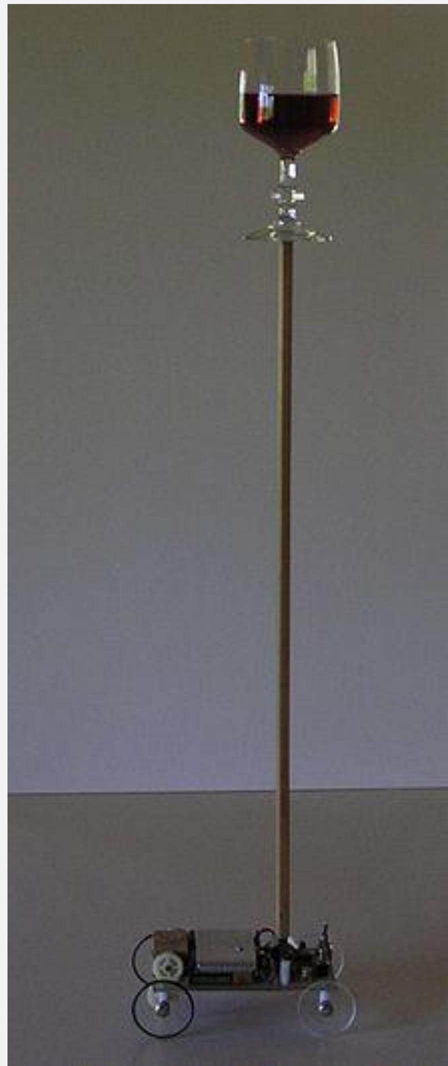


Feedback systems

- Why Feedback?
  - The purpose of feedback is to reduce the effects of "uncertainty" (disturbances, modeling errors)
  - Feedback also changes the dynamics of the system and other objectives can include stabilization, speed-up of response etc



Segway Balancing a stick Inverted pendulum



Some Common Control Examples

- Aerospace applications
  - high performance fighter aircraft, helicopters, jet engines
- Electromechanical systems
  - robotic arms, pendulum, cart and pendulum
- Automotive
  - intelligent vehicle highway systems, platooning, traffic control
  - engine management, anti-lock brakes, active suspension
- Manufacturing processes, scheduling of operations
- Biomedical applications, prosthetics, drug administration

Feedback Systems

"need to know the future"
(accounting for uncertainty)

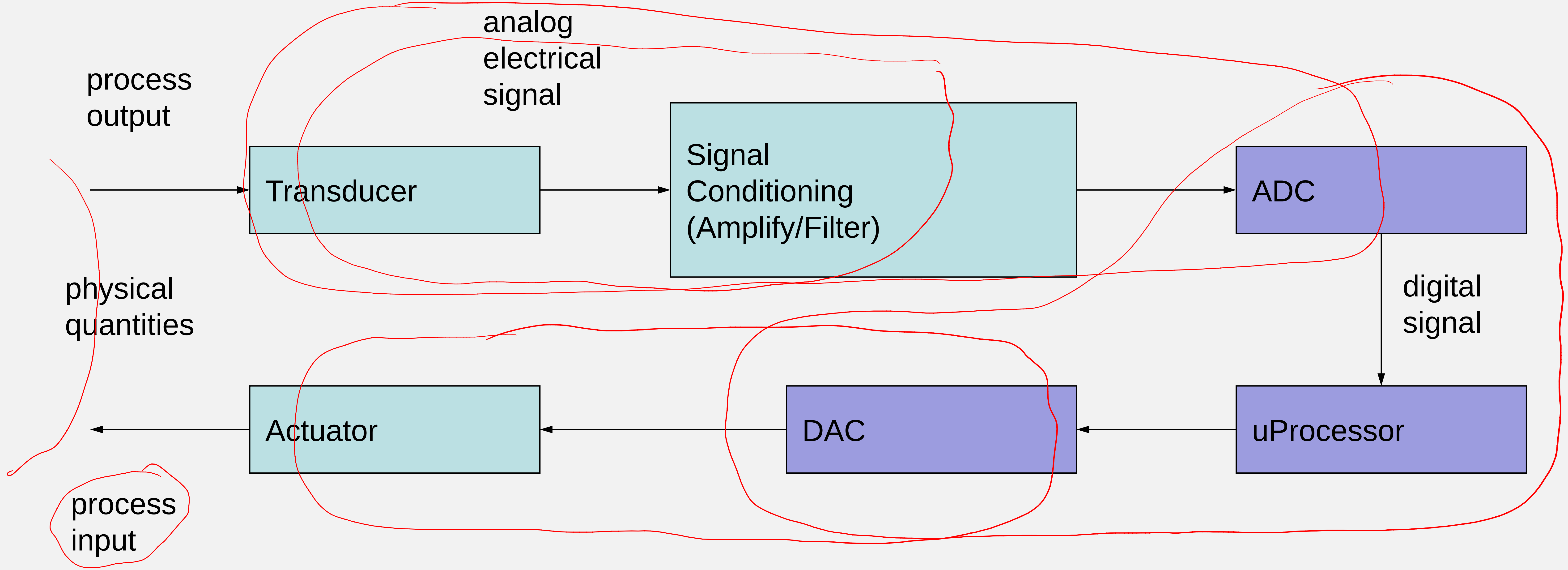
Design Issues:

- I/O Process description
  - Sensors and actuators (to define inputs and outputs and enable modeling of the dynamic effect of manipulated/input variables to process/output variables)
  - First-principles modeling $\frac{dy}{dt} = f(y, x)$, System identification $\{x_i, y_i\}_{i=1:N} \mapsto H : y = H[x]$
- Control Objectives and Specifications
  - Match a target system, Minimize input-output energy
- Controller design (algorithm and structure), parameter "tuning"
  - PID, Lead-Lag, Linear Quadratic, Multivariable, Model Predictive Control

COMPLEXITY
COMPUTATION
PERFORMANCE

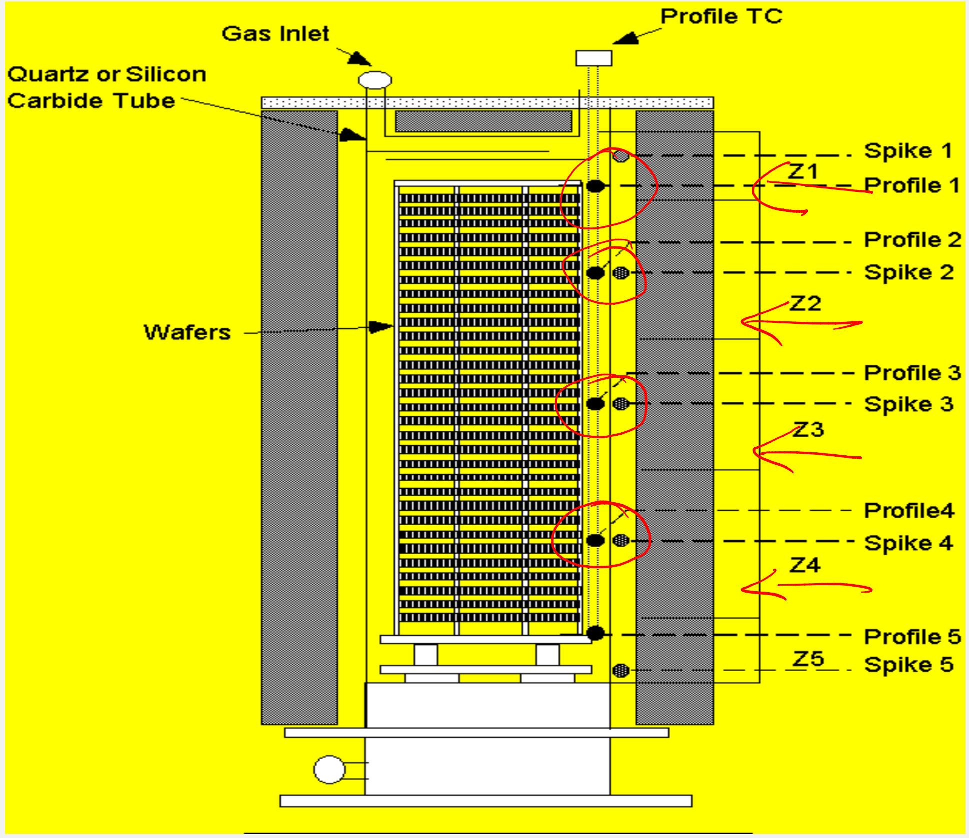
- Implementation (analog, digital-controller discretization)
- Auxiliary functionality (monitoring, different modes of operation)

Typical Configuration of a data acquisition and control system

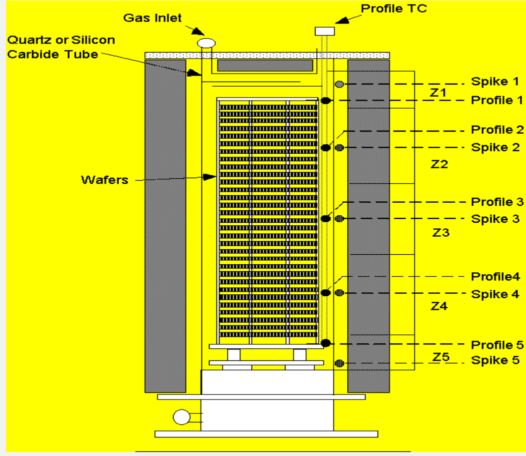


Diffusion Furnace Temperature Control

- Multivariable system, approximating distributed sensing and actuation
  - Measure temperatures at different points inside the tube (profile) and outside of the tube, near the heating element (spike)
  - Apply heating power through SCR actuating modules roughly in the same zones
  - Accuracy is essential



Diffusion Furnace Temperature Control



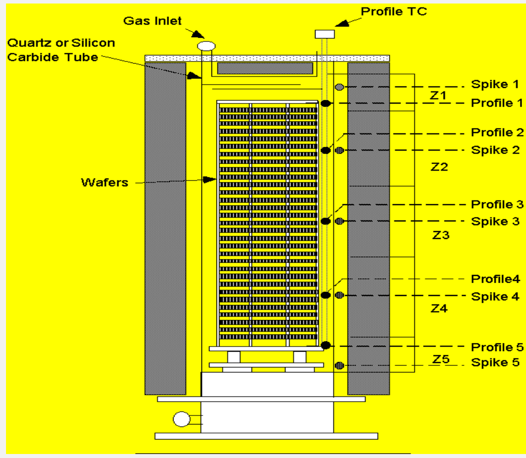
- Modeling:
  - Basic heat balance equation

$$
\begin{aligned}
m c_p \dot{T} &= H_{in} - H_{out} \\
&= q - hA(T - T_{ambient}) - \sigma F A(T^4 - T_{ambient}^4)
\end{aligned}
$$

    - m = mass, c_p = specific heat, T = absolute Temperature, h = heat transfer coefficient (convection), A = surface area, s = Boltzmann constant (radiation), F = view factor, q = externally supplied heat
  - Lumped Model (Linearized) $\dfrac{\delta T(s)}{\delta q(s)} = \boxed{\dfrac{1/mc_p}{s + (hA + 3\sigma F A T_0^3)/mc_p}}$
  - Apply to differential volumes and obtain a PDE model

Diffusion Furnace Temperature Control

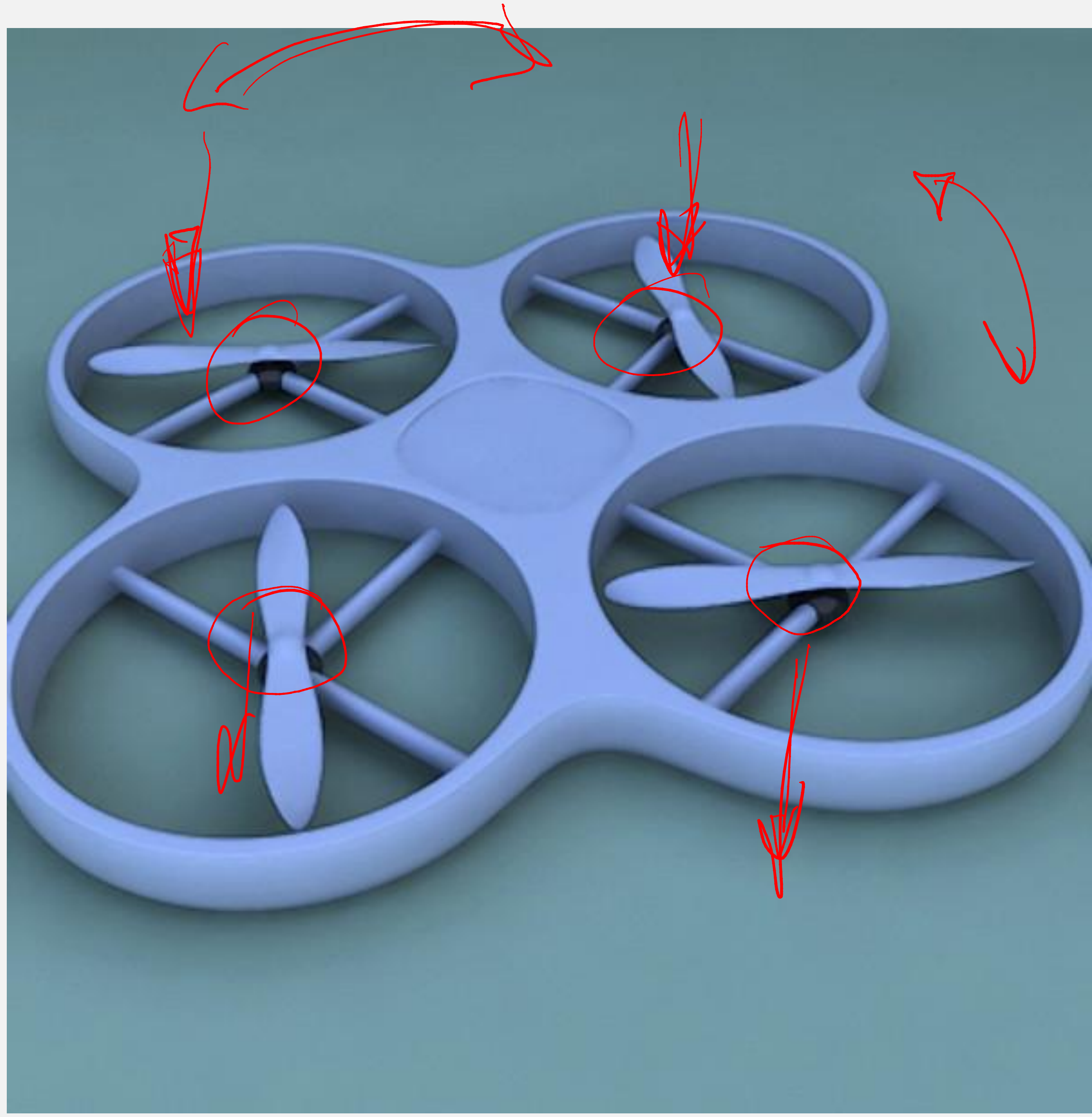
- Sensors: Thermocouples for high temperatures (some operations above 1000deg.C). Pyrometry is another option for single wafer reactors.
  - Issues: Cold-junction compensation, amplification, and table look-up linearization. RF interference may appear from SCR application of electrical power
- Actuators: SCR modules
  - Issues: resolution - switching transient trade-off



- Need for elaborate and precise controllers
  - Newer furnaces have more (5) heating zones for more resolution and improved uniformity (temperature coupling is higher than in the older 3-zone furnaces)
  - Radiation Nonlinearity and coupling for wide range of operations; more pronounced in single-wafer rapid thermal processors (RTP)

Control of Quad-helicopter

- 4 independent propellers, differential thrust to control roll and pitch
- Sum of all to control up-down acceleration
- New cheap and small accelerometer sensors to provide output measurements



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Lecture 5.2: Control Objectives and Specifications

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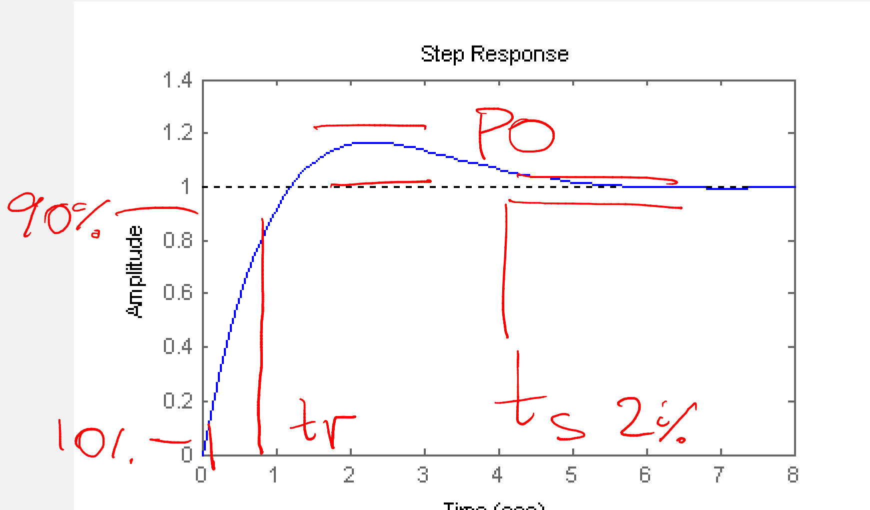
Objectives and Specifications in Feedback Systems

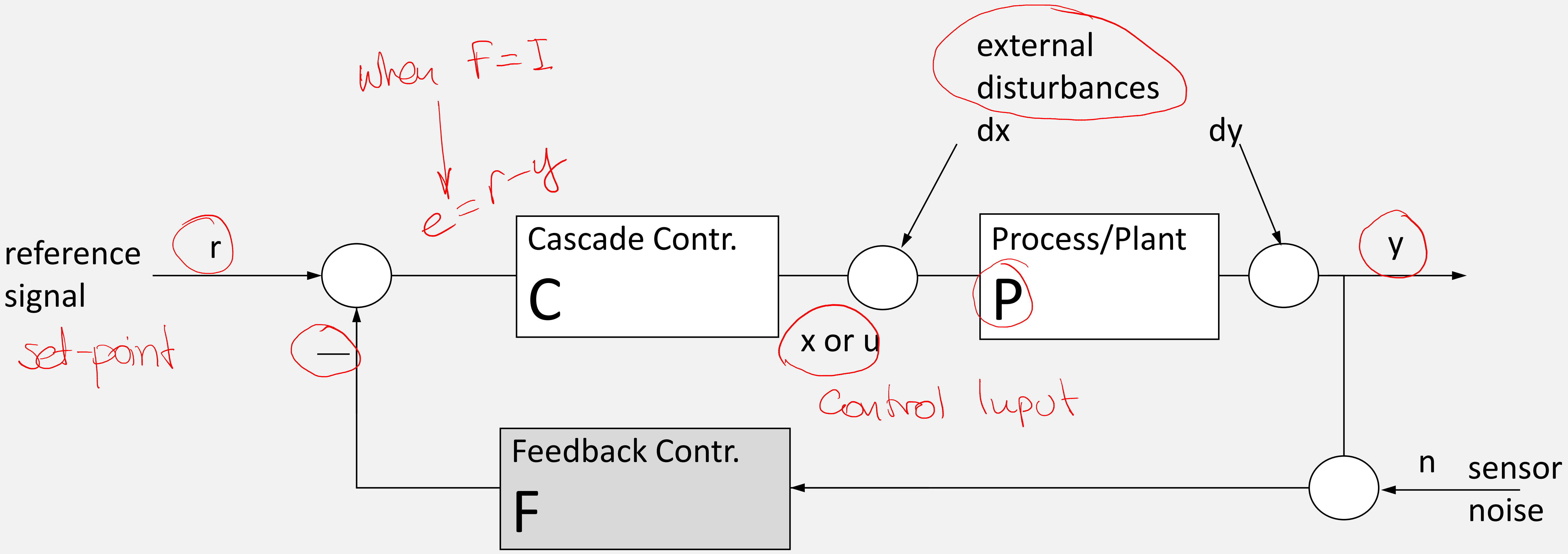
- The control objectives are (should be) defined in terms of disturbance rejection or uncertainty reduction capabilities of the closed loop system.
    - E.g., op-amp gain is 100 regardless of temperature and load; chamber temperature reaches target steady-state in 5min regardless of loads.
- Control objectives are given in terms of more detailed specifications on the closed-loop response or the closed-loop transfer function
    - E.g, Settling time, Rise time, Bandwidth, Percent Overshoot, Damping Ratio, Steady-state errors etc.

Damping ratio
ζ for dominant pole pair
$s^2 + 2\zeta\omega_0 s + \omega_0^2$

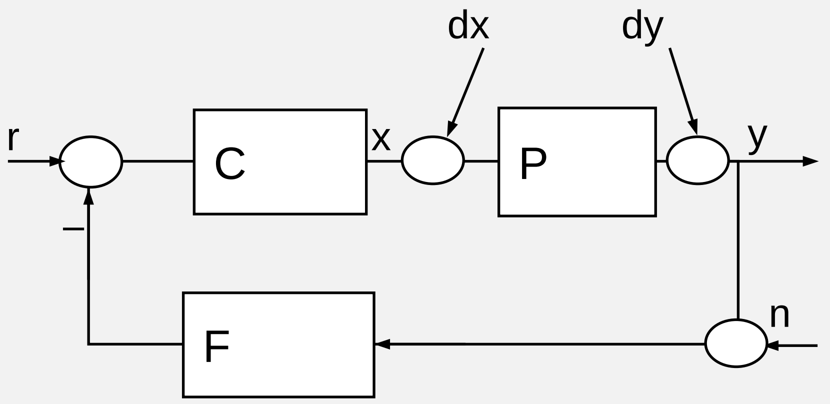


Block Diagram of a Feedback System

- On the controller design: We first need to understand and be able to computate of the transfer function(s) relevant to the "controller".
- General controller structure and signal flow:



A simple example: Motor speed control



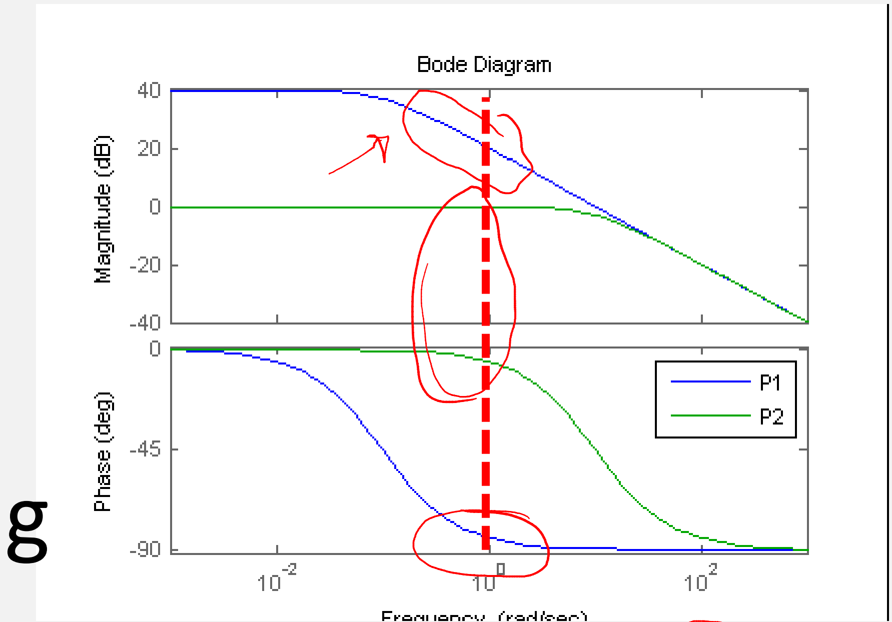
- A simplified description of motor angular velocity (F = ma):

ANG VELOCITY

CURRNT

$$J\frac{d\omega}{dt}+\varepsilon\omega=ci,\quad \text{or}\quad \dot{y}+ay=kx \Leftrightarrow \frac{Y(s)}{X(s)}=\boxed{P(s)=\frac{k}{s+a}}$$

where: J is the moment of inertia, ε is the friction coefficient and ci is the torque generated by the applied current

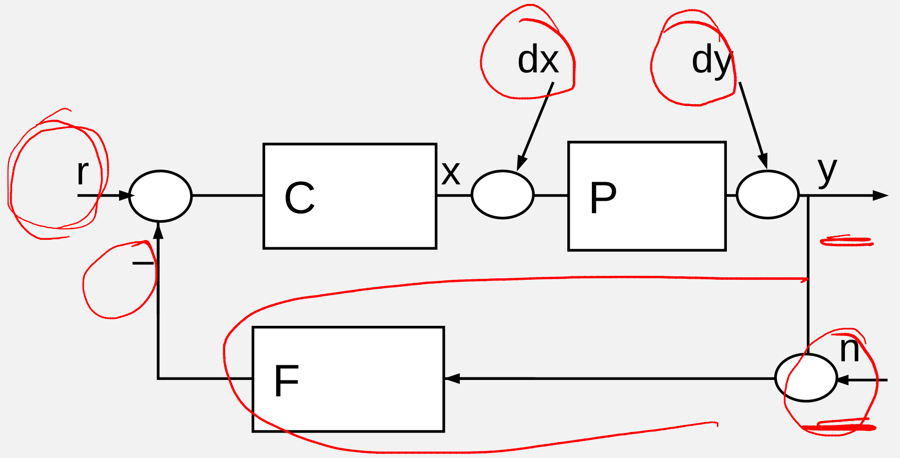


$$P_1(s)=\frac{10}{s+0.1}$$

$$P_2(s)=\frac{10}{s+10}$$

- There are two modes of operation of such motors, depending on the relation between the open loop bandwidth and the closed loop bandwidth (assume 1rad/s):
  - Integrator $P_1(s)\approx\frac{10}{s}$
  - Constant $P_2(s)=1$
- We want to study how such a choice affects the design of a controller and the properties of the loop.

Controller Specifications: A little algebra



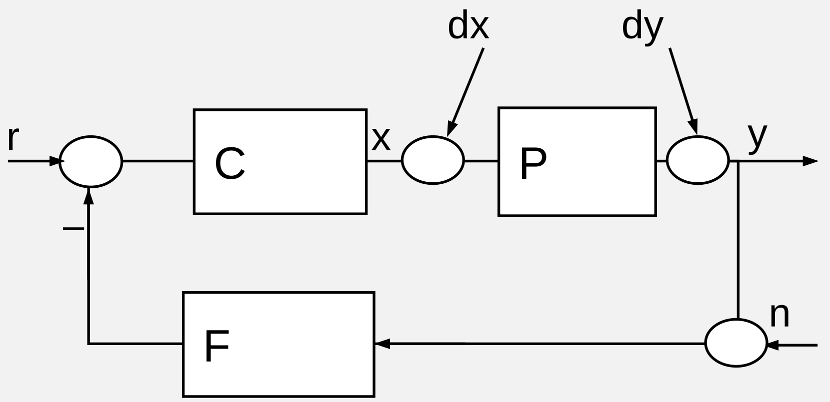
- The system is linear, so the output will be the superposition of outputs from every external input.
  - Quick rule: The transfer function x → y is the transfer function of the direct path divided by 1+Loop-transfer function. For unity feedback (F=1),

$$\boxed{d_y \mapsto y} : y = d_y + Px = d_y + PC(0-y) \Rightarrow (1+PC)y = d_y \Rightarrow y = Sd_y \qquad \frac{y}{d_y} = \frac{1}{1+PC}$$

$$n \mapsto y : y = Px = PC(0-(n+y)) \Rightarrow (1+PC)y = -PCn \Rightarrow y = -Tn \qquad \frac{y}{n} = \frac{-PC}{1+PC}$$

- S is called the Sensitivity transfer function and T is called the Complementary Sensitivity or Co-Sensitivity (because $\boxed{S + T = 1}$). These are the two important transfer functions in a closed loop system because they define the most fundamental trade-off between performance to disturbances (|S| << 1) and insensitivity to measurement noise (|T| << 1).

More Block Diagram Computations



- Feedback control objective: Reduce the effect of disturbances on the output

$$y = d_y + P[x + d_x] = d_y + PC[r - F[y+n]] + Pd_x$$
$$= Sd_y + SPCr - SPCFn + SPd_x$$

where : $L = PCF$ (Loop Transfer function)

S+T=1

$S = (1+PCF)^{-1}$ (Sensitivity), $T = PCF(1+PCF)^{-1}$ (Complementary Sensitivity)

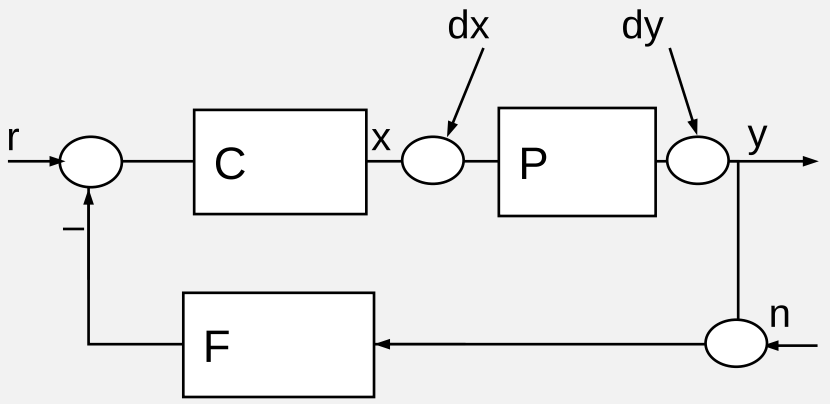
- Typically, the disturbance has power at low frequencies, so we should choose S is small and CF large there, or CF should contain an integrator. That choice will also guarantee zero steady-state error to step disturbances.

From FVT of Laplace

- The noise has power at high frequencies so T and CF should be small there, or CF should/could contain a low-pass filter.

- Other important Sensitivities are dx → x describing the effect of disturbances on the control input and possible saturating elements

Translating into Specifications



- Feedback control objective: Reduce the effect of disturbances on the output. For a unity feedback loop

$$y = r + \{Sd_y - Sr - Tn + SPd_x\}$$

we can ask for S to have a zero at DC to eliminate constant errors, and specify a metric on the bandwidth of S or T to ensure a speedy response.

- Settling time is not easily managed, but

  Rise time ~ 2/BW ~ magnitude of "dominant poles"

  Damping ratio ~ resonance peak ~ 1/Overshoot

  are more friendly.

Note: These spec's may appear to be set on the system response but they express objectives on the loop transfer function and, indirectly, disturbance rejection.

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Lecture 5.3: Loop Shaping Principles

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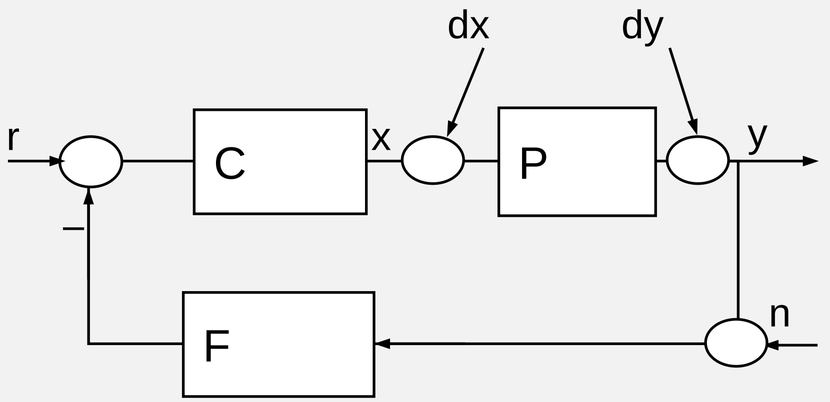
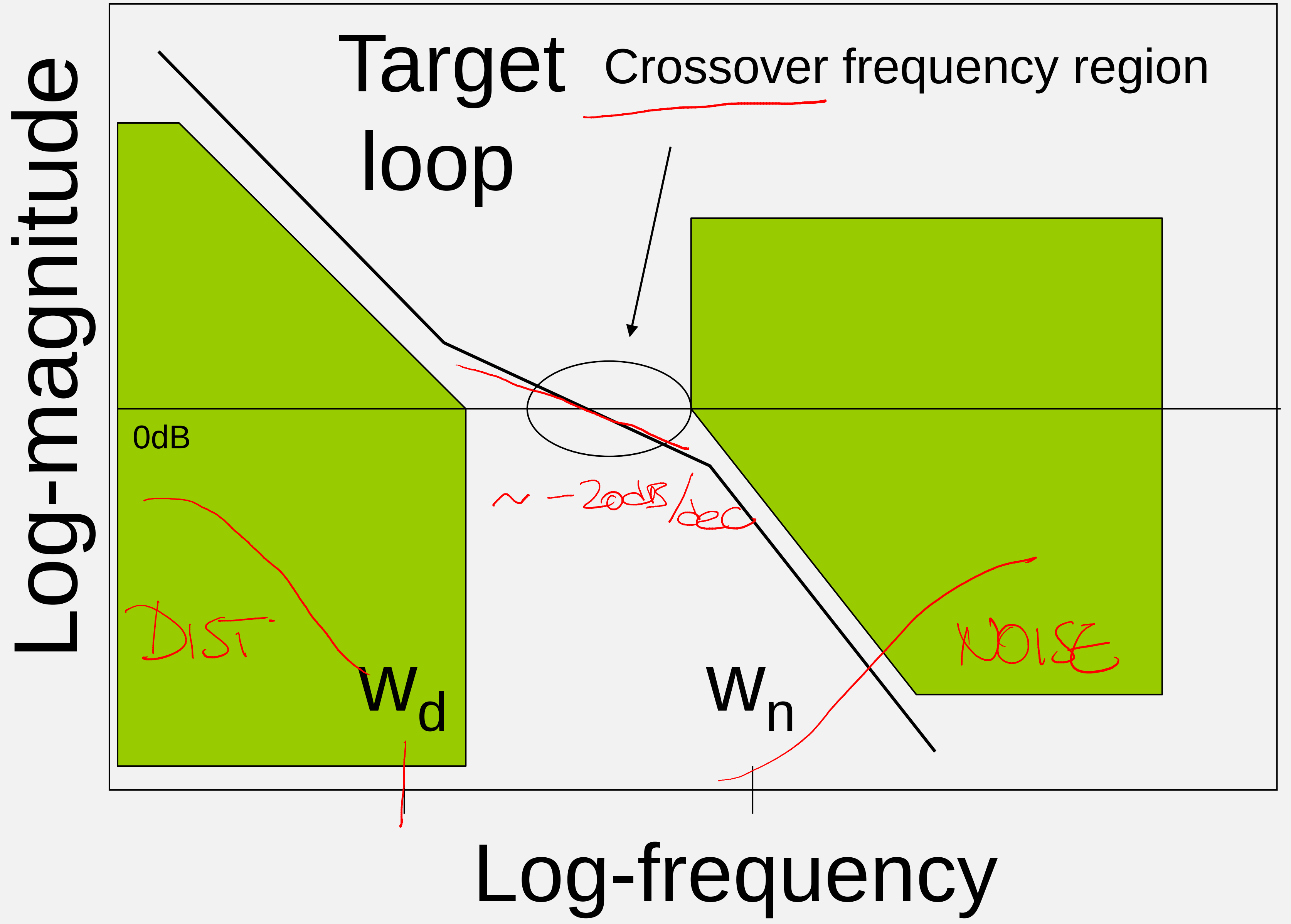
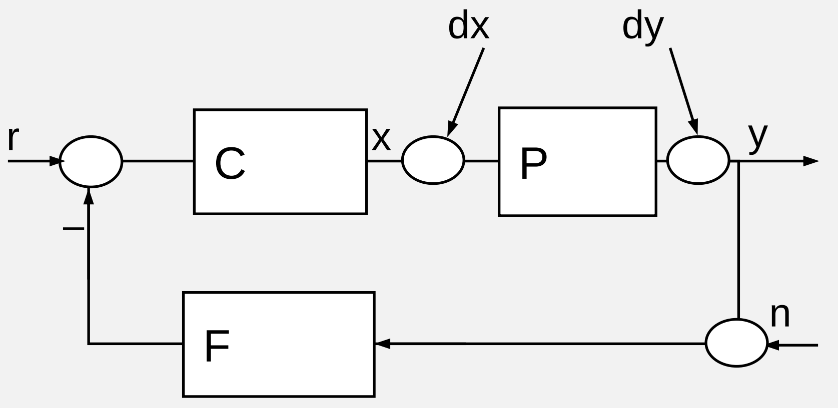
Essential Loop-Shaping



- The Loop Transfer Function L(s) should have roughly the shape shown in the figure with wd and wn being the frequency bounds for the disturbances and noise.
- The crossover frequency ($|L(j\omega_c)|=1$) should be in the interval between disturbance and noise.
- L should have a "gentle slope" around crossover to maintain small Sensitivity peaks.
- The crossover frequency should be below the magnitude of RHP zeros and above the RHP poles of P(s)
- Note: can only attenuate disturbances where the sensor information is reliable



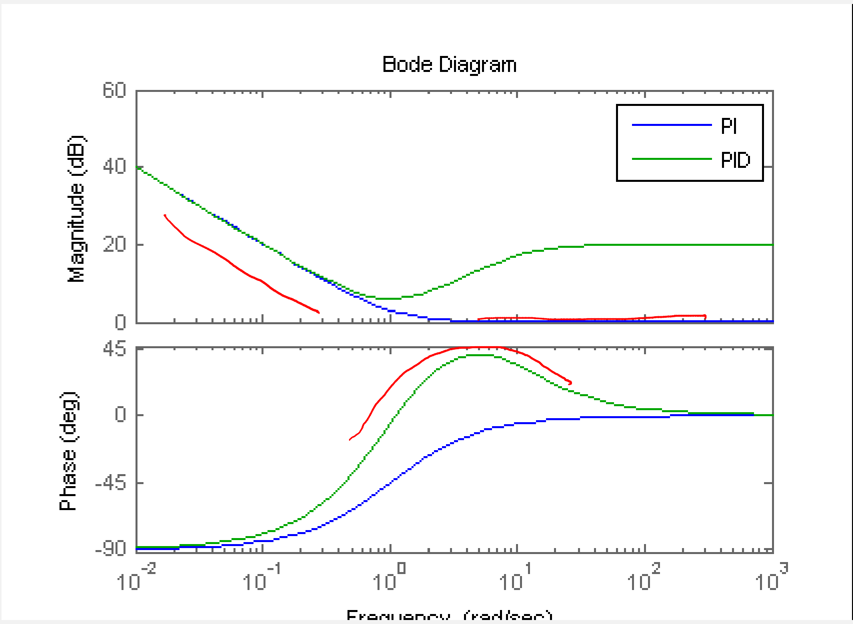
The PID Controller



- A typical controller is the so-called PID (Proportional-Integral-Derivative) is a special case of Lead-Lag and is the most widely used controller in industry.

$$PID: C(s) = K_P + \frac{K_I}{s} + \frac{K_D s}{\tau_p s + 1} = \frac{K(\tau_z s + 1)^N}{s(\tau_p s + 1)}$$

PID = double zero at $-1/\tau_z$

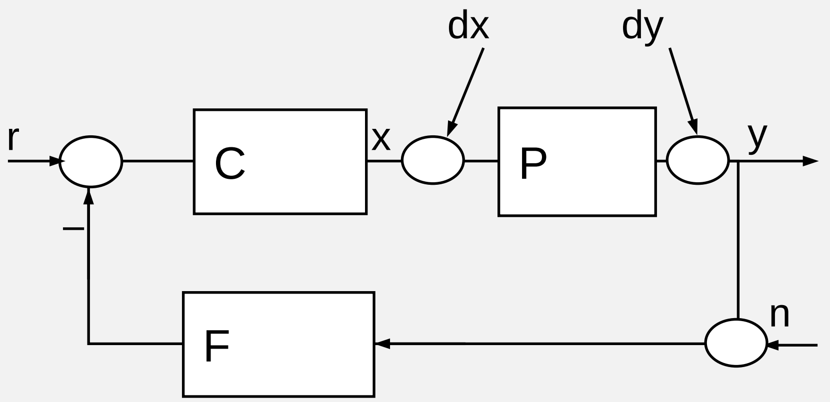


$$N = 1, \tau_p = 0, \tau_z = 1, K = 1$$

$$N = 2, \tau_p = 0.1, \tau_z = 1, K = 1$$

- The PID transfer function is expressed in various different forms, depending on usage and context. In any case, the PID has the main features discussed in Loop shaping: High gain at low frequencies, increasing phase around the intended crossover for closed-loop stability.
- Its additive form is, among others, convenient for implementation, its pole-zero form is convenient for parameter tuning.
- Commonly used: PI: $N = 1, \tau_p = 0, (K_D = 0)$, PID: $N = 2, \tau_p \sim (10\omega_c)^{-1}$
- For the PI/PID, an additional filter pole can be used to roll-off the high frequencies to reduce the effects of noise.
- For the PID, a simpler design is obtained with the choices of the pole as 10 x crossover and the zeros being the same.

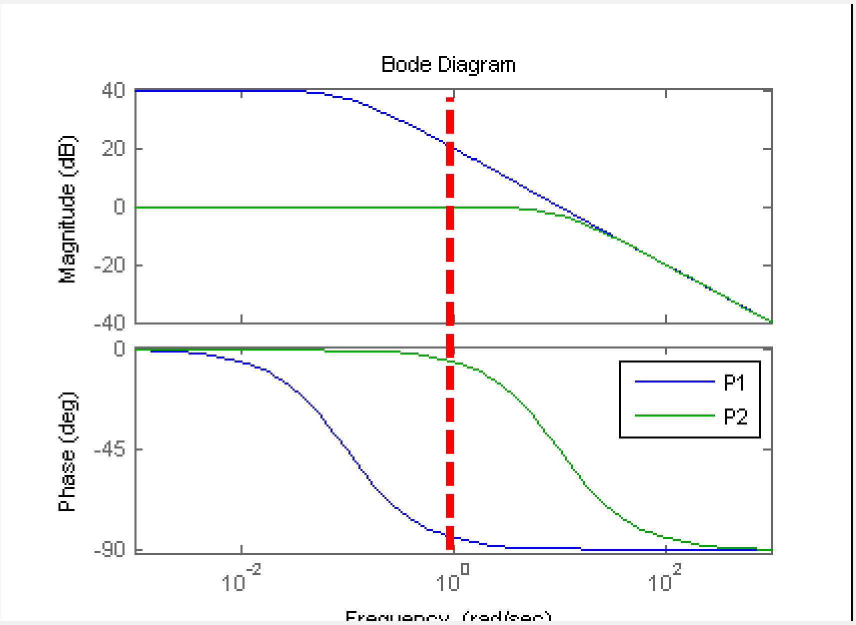
A simple example I: Motor speed PID control



- Let us consider the case of motor speed control with a motor with high friction to be controlled with a closed loop bandwidth of ~1rad/s.
- In its simplified form

$$P(s)=\frac{10}{s+10}\approx 1$$

an approximation that is valid for frequencies around 1 where we place the loop crossover frequency.

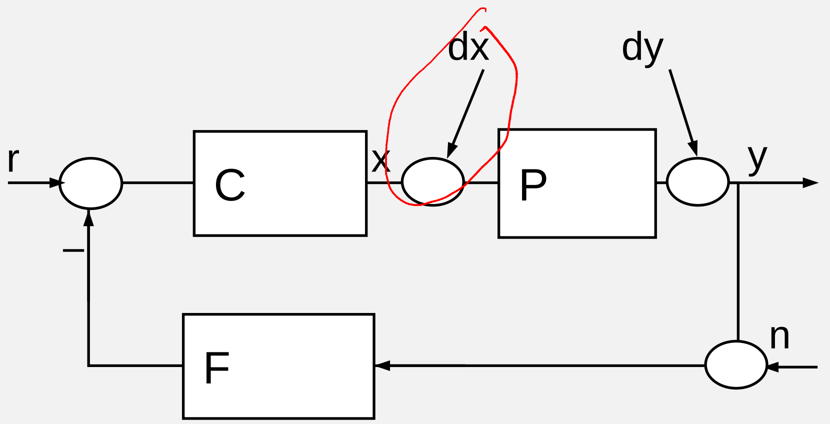


$$P_1(s)=\frac{10}{s+0.1}$$

$$P_2(s)=\frac{10}{s+10}$$

  - Note: BW ~ crossover because L << 1 => T << 1. In general, a better approximation is $BW = 1.5\omega_c \ or \ 2\omega_c$, but this is a minor detail in the context of an iterative design.

A simple example I: Motor speed PID control



- We use a PID with $C(s) = \dfrac{K(\tau_z s+1)^N}{s(\tau_p s+1)}; \quad \tau_z = 0, \tau_p = 0 \Rightarrow C(s) = \dfrac{K}{s}$
- The simplified loop becomes

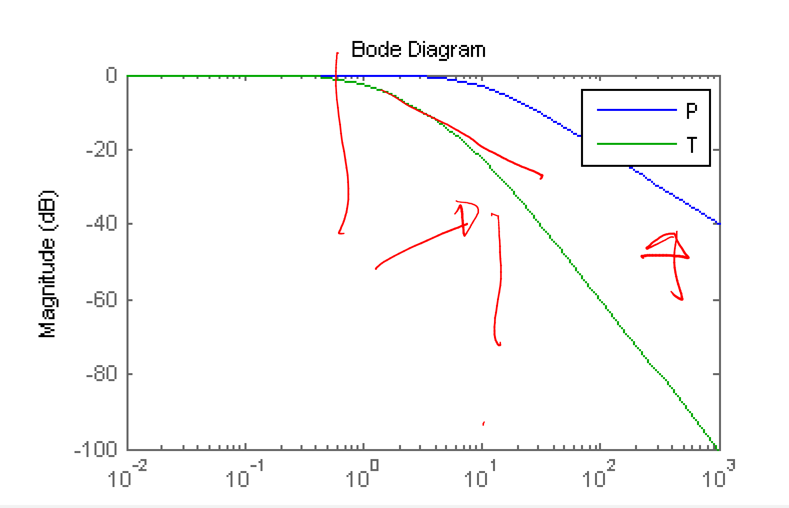
$$L(s) = P(s)C(s) = \frac{K}{s} \Rightarrow T(s) = \frac{L(s)}{1+L(s)} = \frac{K}{s+K} \Rightarrow K = 1$$

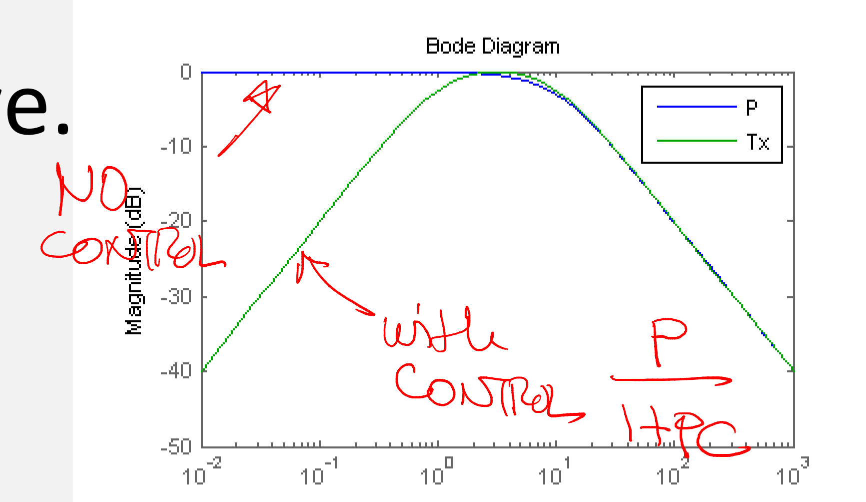
where the last selection K = 1 is to satisfy the control objective.

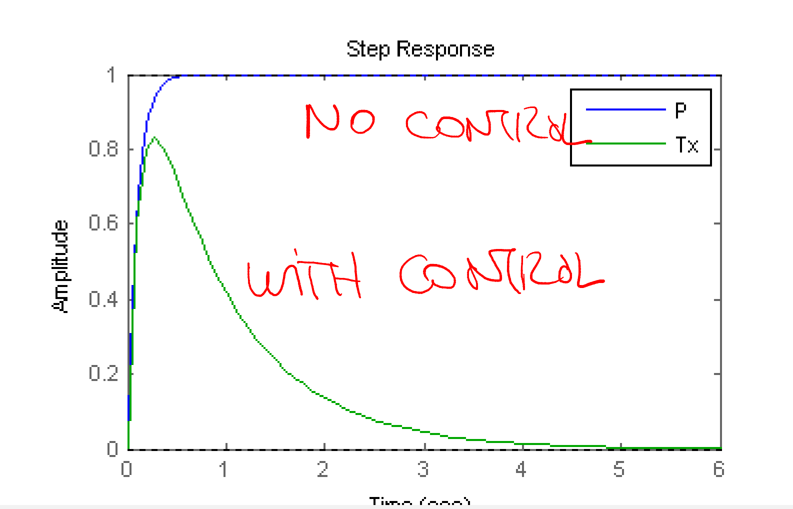
- The actual loop is

$$L(s) = P(s)C(s) = \frac{10}{s(s+10)} \Rightarrow T(s) = \frac{10}{s^2+10s+10}$$

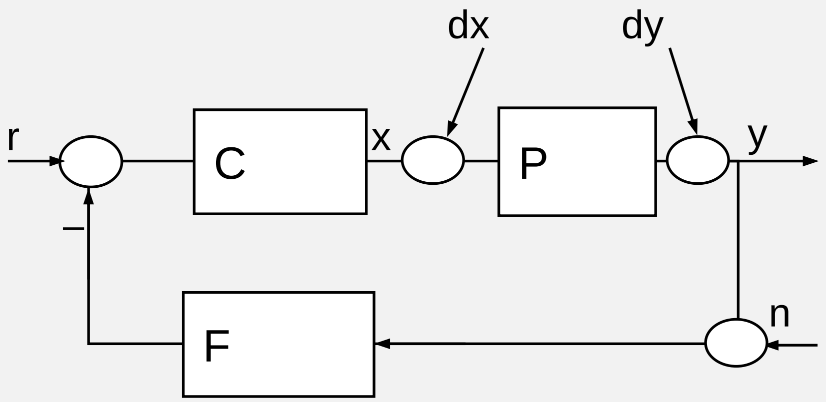
- We evaluate this design: The closed loop is slower than the open loop system, but the response to input disturbances has been improved at low frequencies (dx → y: P/(1+PC)).







A simple example II:
Motor speed PID control

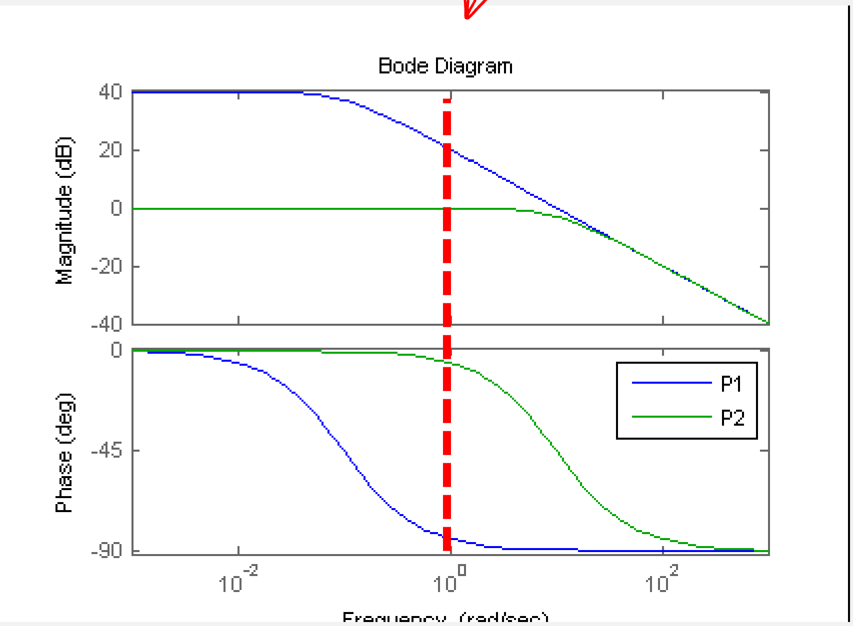


- Let us consider the case of motor speed control with a motor with low friction to be controlled with a closed loop bandwidth of ~1rad/s.
- In its simplified form

$$P(s)=\frac{10}{s+0.1}\approx\frac{10}{s}$$

an approximation that is valid for frequencies around 1 where we place the loop crossover frequency.

- This is a more difficult case and just an I-controller will not work. We need a PI (at least) but now we need to select the zero and the gain of the controller.



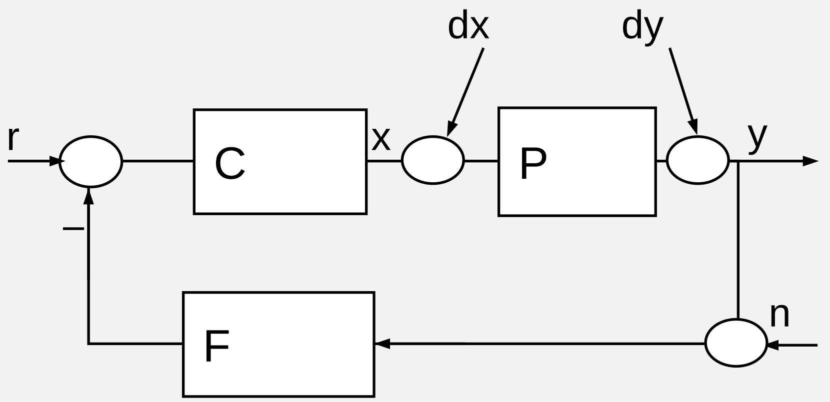
$$P_1(s)=\frac{10}{s+0.1}$$

$$P_2(s)=\frac{10}{s+10}$$

$\frac{K}{s^2}$

Closed loop $\frac{K}{s^2+K}$

A simple example II: Motor speed PID control



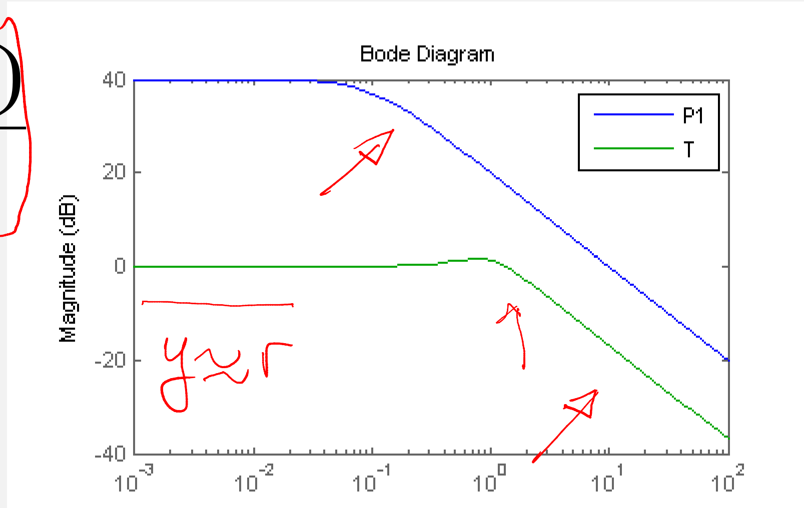
- We use a PID with $C(s)=\dfrac{K(\tau_z s+1)^N}{s(\tau_p s+1)}$; $\quad N=1, \tau_p=0 \Rightarrow \boxed{C(s)=\dfrac{K(\tau_z s+1)}{s}}$
- The simplified loop becomes

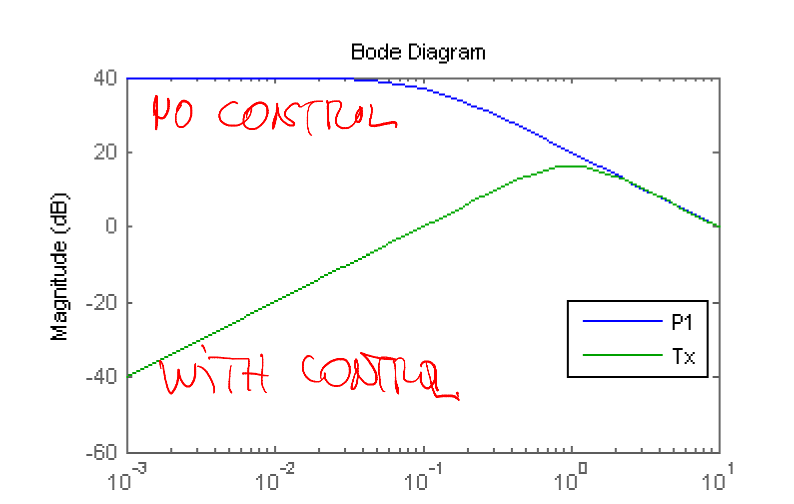
$$L(s)=P(s)C(s)=\boxed{\frac{10K(\tau_z s+1)}{s^2}} \Rightarrow \boxed{T(s)=\frac{10K(\tau_z s+1)}{s^2+10K\tau_z s+10K}}$$

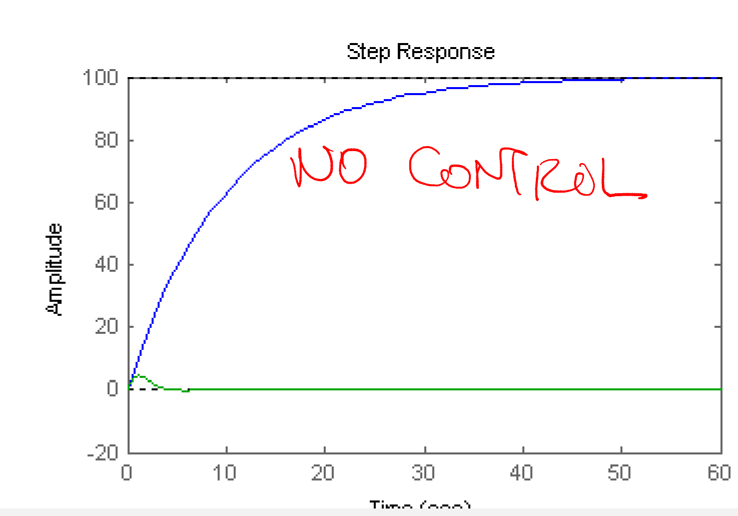
1

we now choose K = 0.1 and $\tau_z=\sqrt{2}$ to obtain a system with moderate damping $1/\sqrt{2}$ and natural frequency 1.

- The actual loop now is $L(s)=\boxed{\dfrac{1.41s+1}{(s+0.1)(s)}} \Rightarrow T(s)=\dfrac{1.41s+1}{s^2+1.51s+1}$
- We evaluate this design: The closed loop is much faster than the open loop system, BW is a little higher (2rad/s), and the response to input disturbances has been greatly improved. But why these selections worked and how can we generalize?







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Lecture 5.4: Essentials of Feedback Systems Stability

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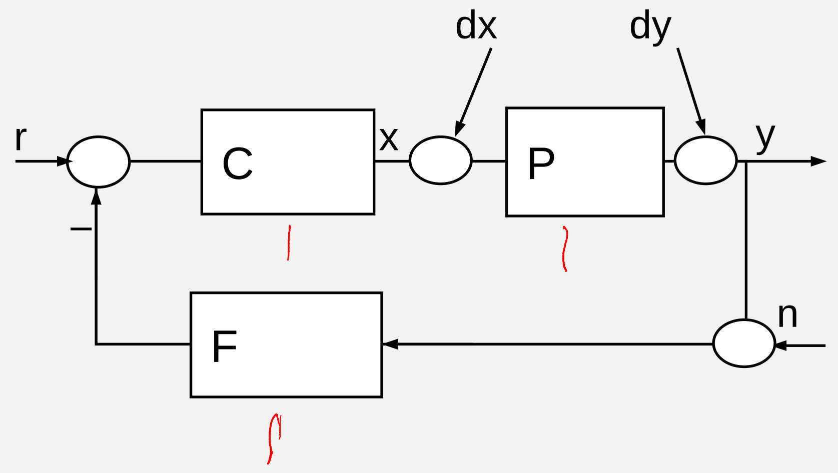
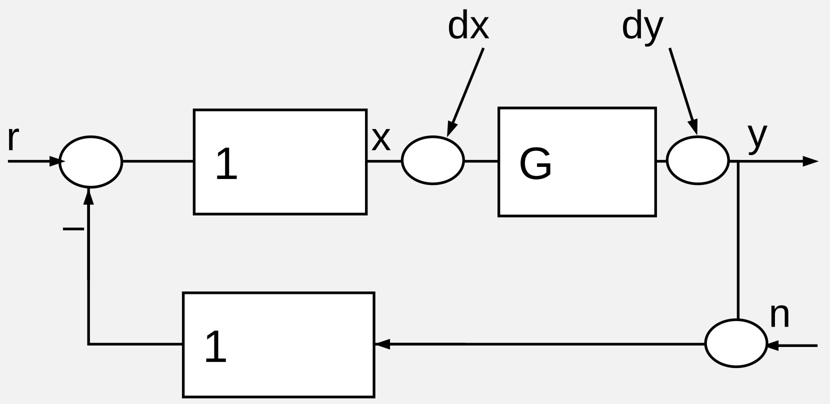
Essential Feedback Stability Theory



- Traditionally, stability of scalar feedback systems (single-input, single-output) has been discussed using tools from polynomial algebra and complex analysis. These are suitable for low to mid-complexity controller designs and that includes “most” of practical applications.
- In the feedback loop, stability is determined by the Loop transfer function L(s) alone. Here, $L(s) = n_L(s)/d_L(s)$.
- The characteristic equation for the closed loop is $1 + L(s) = 0 \Leftrightarrow n_L(s) + d_L(s) = 0$ and stability requires that all its roots are in the LHP (inside the UC for DT systems).

$\mathrm{Re}(p_i) < 0$ $|p_i| < 1$

Essential Feedback Stability Theory



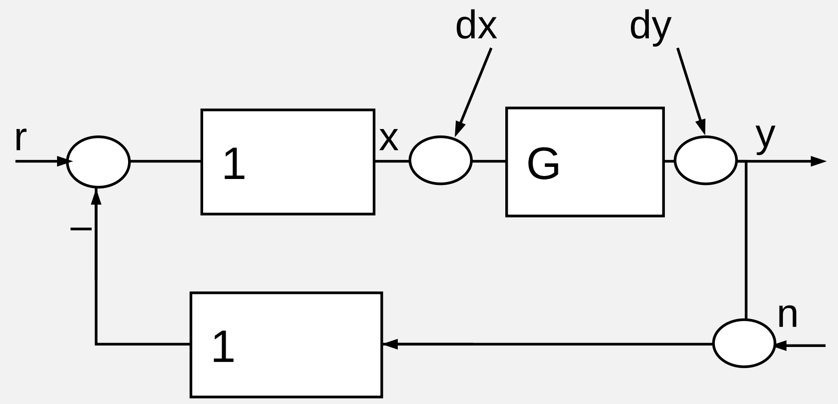
The standard tools for stability analysis are:

- Routh criterion: It derives conditions on the coefficients of a polynomial [Ki] so that its roots are in the LHP. One can then write down general stability conditions for the closed-loop characteristic equation $n_L(s;[K_i]_{i=1,2,...}) + d_L(s;[K_i]_{i=1,2,...}) = 0$ but provides little insight in the design of controllers.

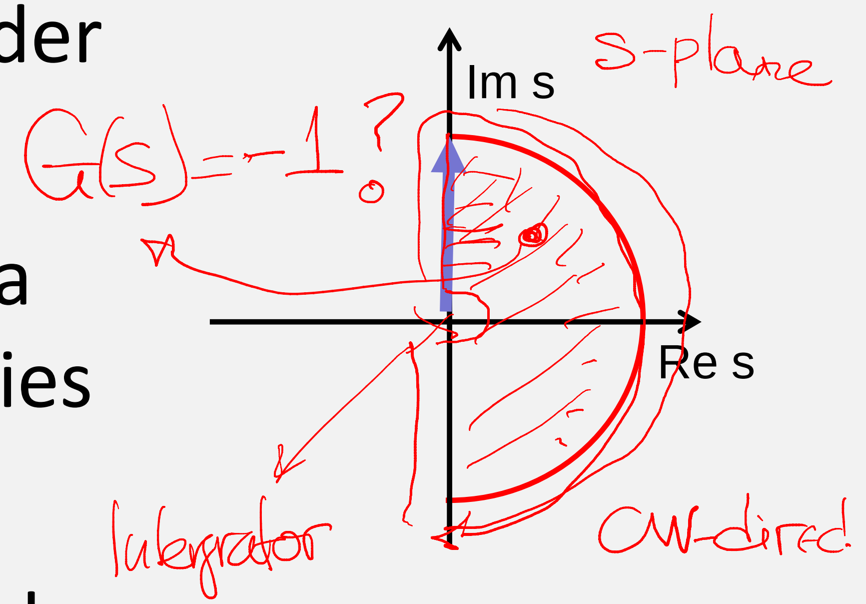
$G = K' n_L/d_L$

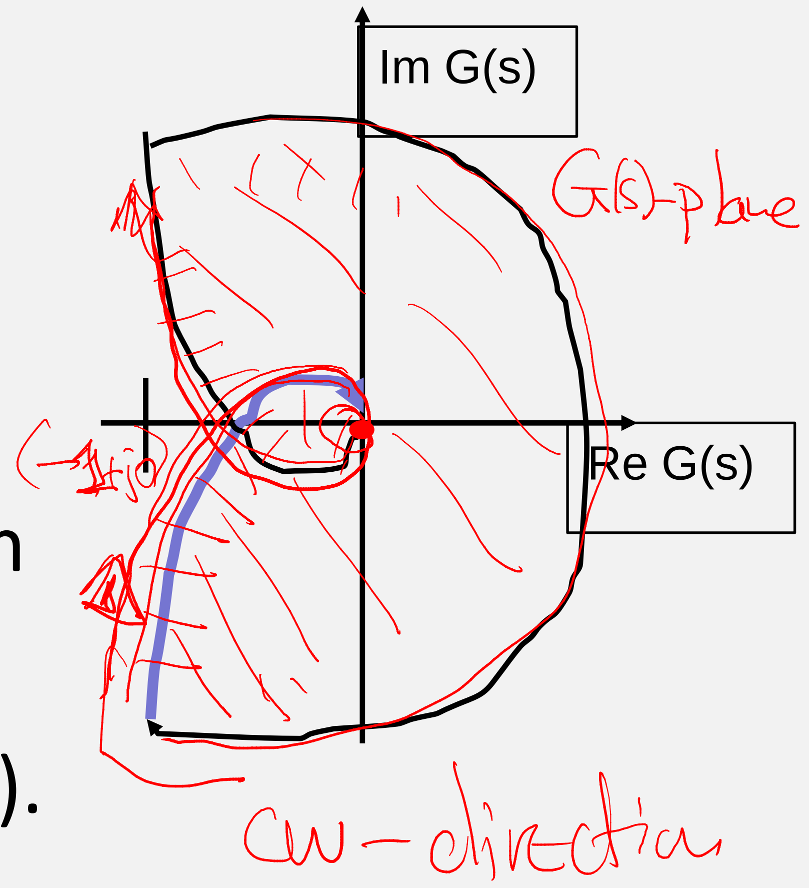
- Root-Locus: Finds the loci of the roots of $Kn_L(s) + d_L(s)$, as K ranges from 0 to infinity. It provides some insight on how to choose the controller poles and zeros and quantifies the choice of the overall gain K for stability. Usually its objectives are in the form of the properties of a dominant pole-pair.
- Frequency-domain (Bode/Nyquist): The Nyquist criterion gives conditions for the characteristic equation $1 + G(s) = 0$ to have zeros (roots) in the LHP. It provides more insight on the choice of controller structure and a system-related sense of stability margin that has proved successful in practice.

Essential Feedback Stability Theory

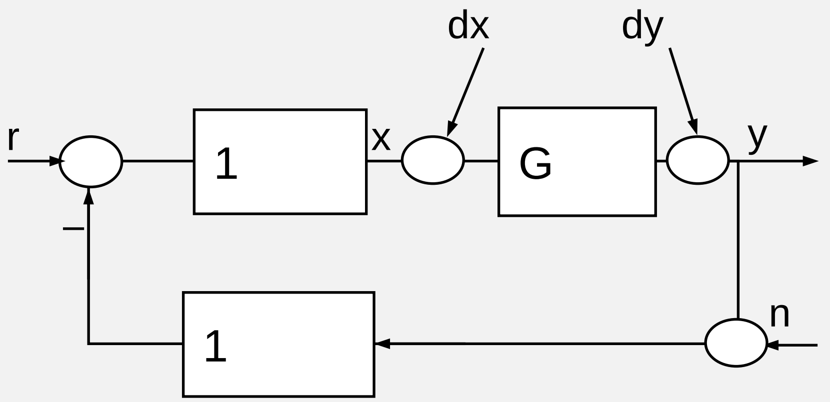


- The Nyquist criterion for closed stability examines the map of the RHP under the complex valued function G(s).
  - The RHP in the s-plane is enclosed by the “Nyquist path” (jw-axis, and a semi-circle at infinity; small semicircles are added to exclude singularities on the path.)
  - The path is mapped under G onto the G(s) plane. The jw-axis is mapped on a curved line, the negative axis maps on the complex conjugate, the semicircle at infinity maps to the origin (for strictly proper G) and semicircles avoiding singularities map to semicircles at infinity.
  - The map is conformal so it preserves angles: The Nyquist path encloses the RHP on its right and the Nyquist plot encloses the map of the RHP on its right. (Mind the direction!)
  - Then, if 1+G(s) has a root in the RHP, the Nyquist plot will contain (-1+j0).





Essential Feedback Stability Theory



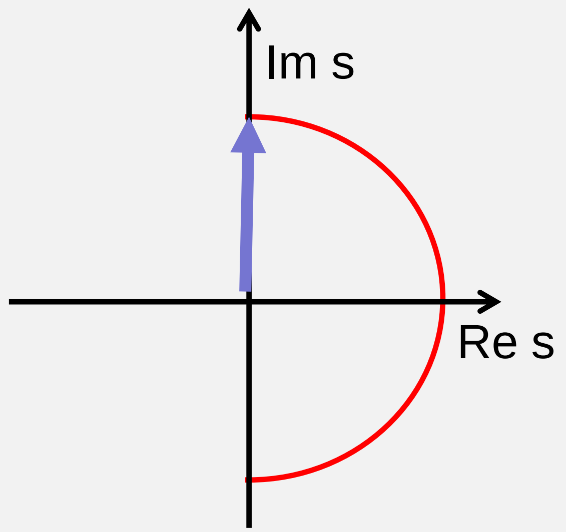
- The more precise Nyquist theorem also counts the RHP zeros of 1+G(s):

$$\boxed{Z = N + P}$$

  Z = number of zeros of 1+G(s) in RHP. (Poles of closed-loop; must be 0)

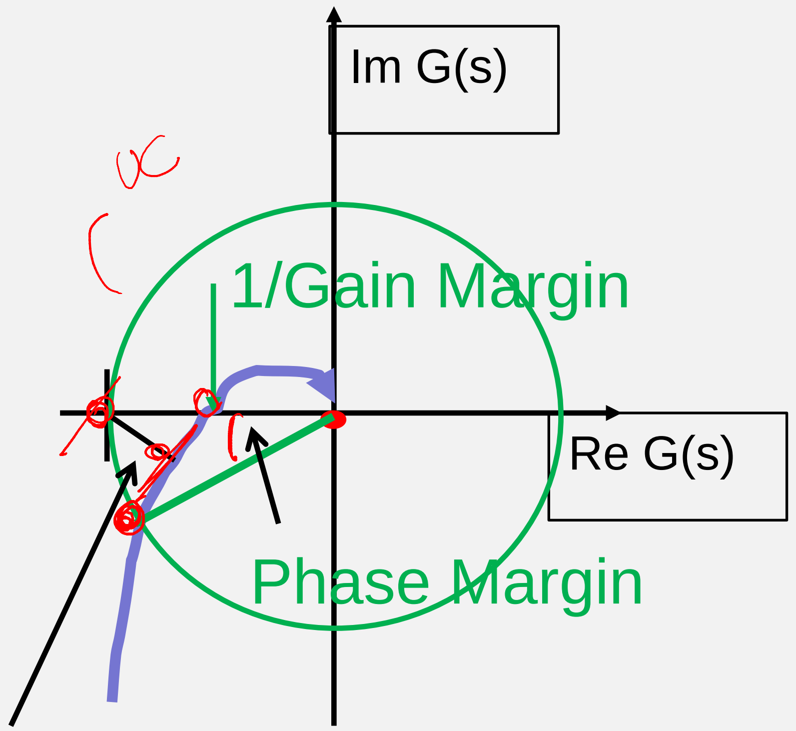
  N = number of clockwise encirclements of (-1+j0)

  P = number of poles of G(s) in RHP. (Poles of open-loop.)



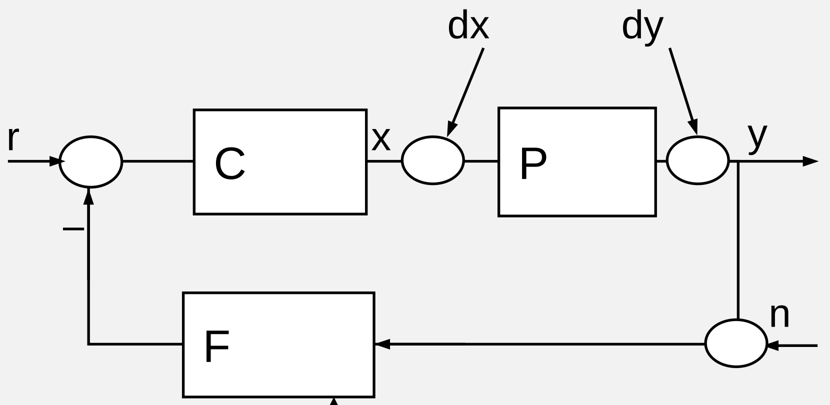
- Stability Margin: Distance from Instability, Minimum distance of G(jw) from the critical -1 point. The distance is |1+G(jw)| = 1/|S(jw)|
  - Small stability margin implies large Sensitivity peak.
- Phase Margin ~ Stability margin. Not as rigorous but easier to measure and adjust. Gain margin: still easier but not as good of a metric to represent distance from instability
- Phase margin at the gain crossover frequency. Gain margin at the phase crossover frequency.

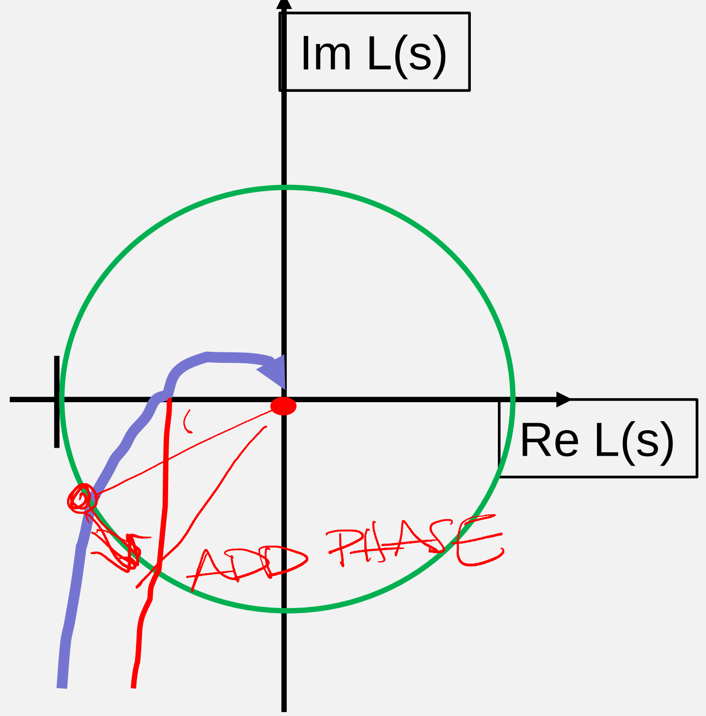
$|G(j\omega)| = 1$ $\angle G(j\omega) = -180°$



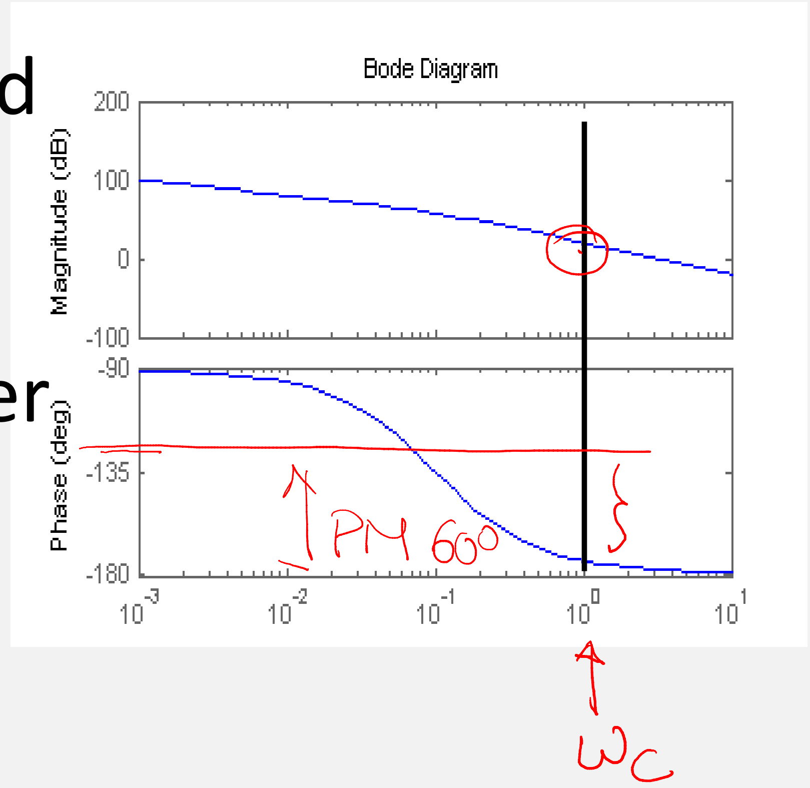
Min. Distance = |1+L(jw)|
= 1/|S(jw)|

Essential Feedback Stability Theory





- We now arrive at a compensation procedure:
- Suppose we start with a loop-shape with desirable properties for disturbance and noise attenuation. Then draw its Nyquist plot and determine the crossover point. If the Phase Margin is not adequate, add compensator phase. Determine the compensator parameters so that the crossover frequency is unchanged.
- Equivalently, we can look at the Bode plot of the shaped plant (having added the integrator) and find the phase at the intended crossover frequency. Determine the compensation phase needed to achieve the desired phase margin (i.e., the zeros). Then adjust the gain of the loop so that the crossover occurs at the desired frequency.

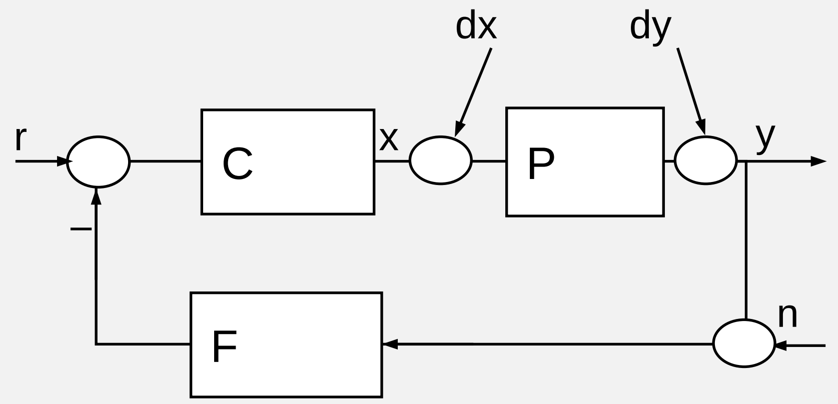


EEE304

Lecture 5.5: PI Tuning Examples

ARIZONA STATE UNIVERSITY

PID Tuning Summary



A typical PID controller tuning in the frequency domain:

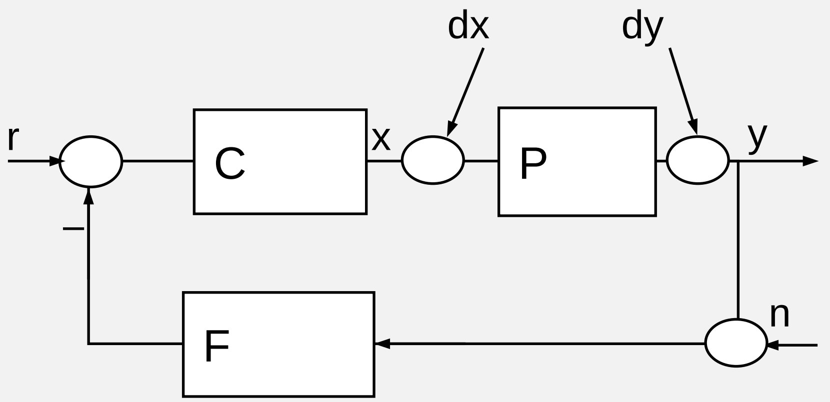
- Select the gain crossover frequency based on closed-loop bandwidth objectives. The crossover separates the frequency range of high loop gain (disturbance attenuation, reliable sensor information) and low loop gain (sensor noise attenuation, high model uncertainty). Roughly, $BW \approx 1.5\omega_c$
  - Observe fundamental limitations: RHP poles < bandwidth < RHP zeros
    - At the gain crossover frequency

$$\omega_c : |PCF(j\omega_c)| = 1, \quad \angle PCF(j\omega_c) \geq -130 \pm 10^o \Big\} \begin{matrix} 40^o\text{-}60^o \\ \text{PM} \end{matrix}$$

- - - Evaluate the closed loop system and iterate to achieve the desired bandwidth and avoid excessive peaks/resonances in S (adjust PM).

- In the first set of examples we discuss the simpler case of PI tuning

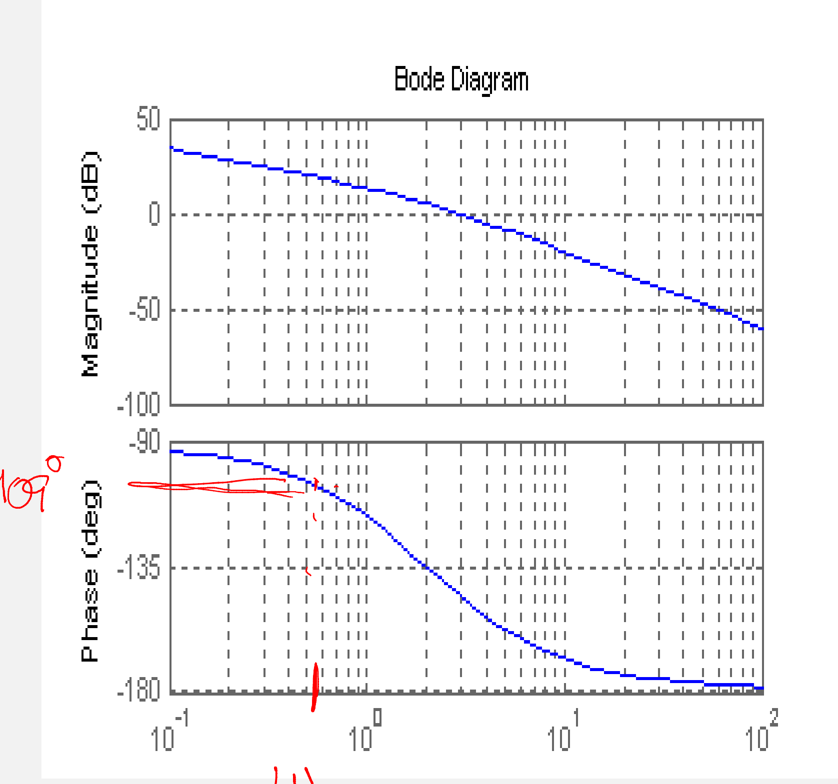
Motor speed PI control 1



- Let us consider the case of motor speed control with a motor with moderately high friction to be controlled with a closed loop bandwidth of ~1rad/s.
- The current to speed motor transfer function is given as

$$P(s) = \frac{10}{s+2}$$

Note: We take the crossover frequency to be BW/1.5



-109^o

ω_c

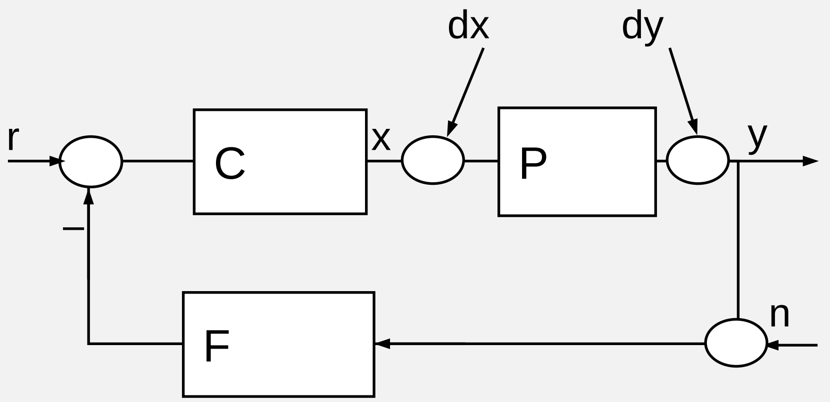
- We consider the Bode plot of the plant with the integrator and design the PI zero to achieve the objective

$> -120^o$

- At $\omega_c = 1/1.5$, $\angle PC_I = -\tan^{-1} 0.67/2 - 90^o + \tan^{-1}\tau_z\omega_c = -109^o + \tan^{-1}\tau_z 0.67 => \tau_z = 0$

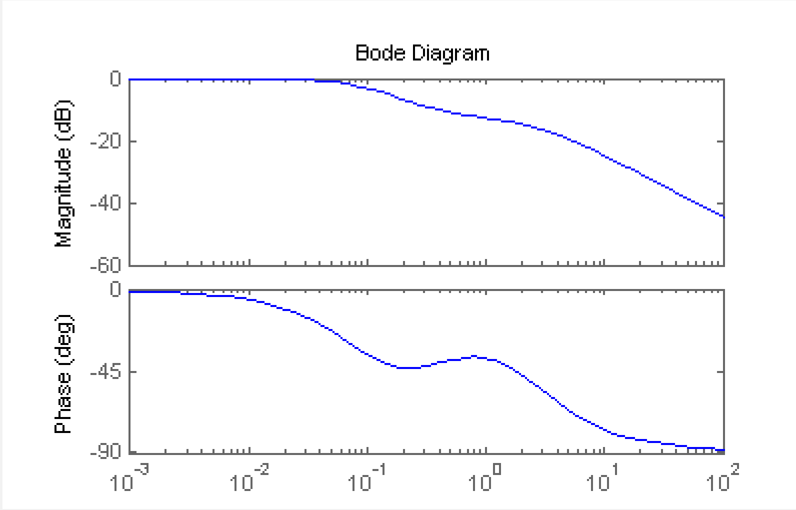
Note: with $\tau_z = 0$, PM > 60, so we do not need the zero. (Do NOT use negative τ_z!)

Motor speed PI control 1

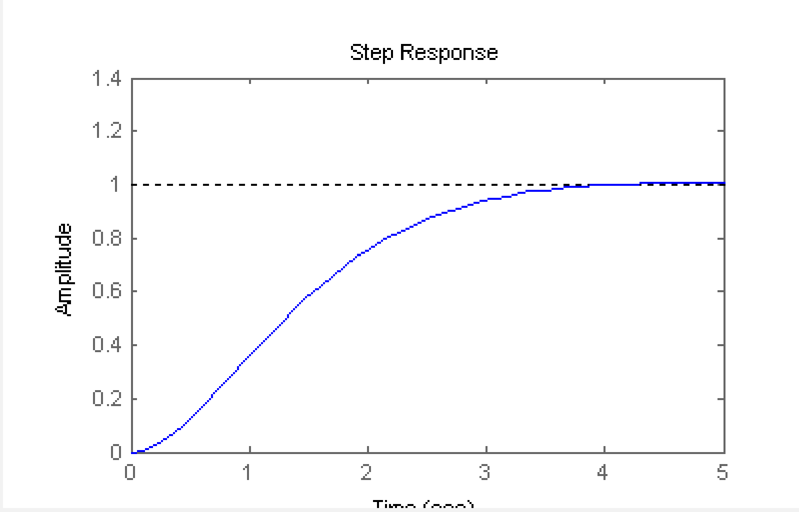


- Now compute the gain so that the crossover is at 0.67:

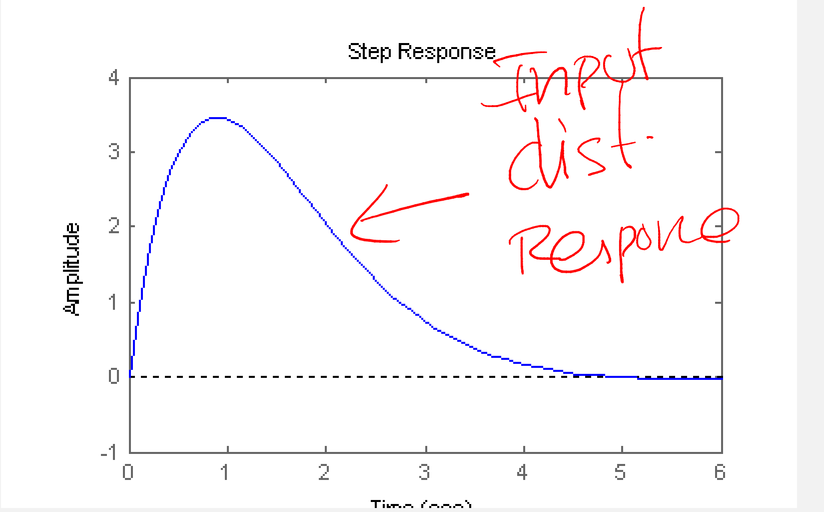
$$|P(s)C(s)|_{s=j0.67}| = \frac{10}{|j0.67+2|}\frac{K}{|j0.67|} = 1 => K = 1/7.1 => \boxed{C(s) = \frac{0.14}{s}}$$



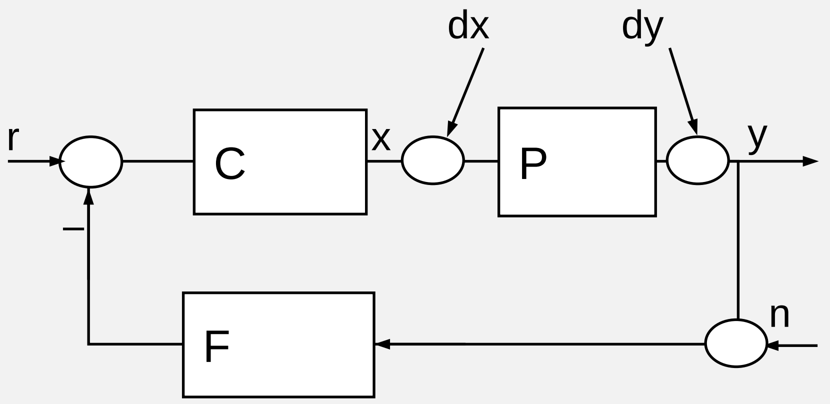
- We evaluate this design: The closed loop is slower than the open loop system, with BW = 0.97rad/s, very close to the desired one.



- The response to input disturbances has been improved at low frequencies (dx → y: P/(1+PC)).



Motor speed PI control 2



- Let us consider the case of motor speed control with a motor with moderate-low friction to be controlled with a closed loop bandwidth of ~1rad/s.
- The current to speed motor transfer function is given as

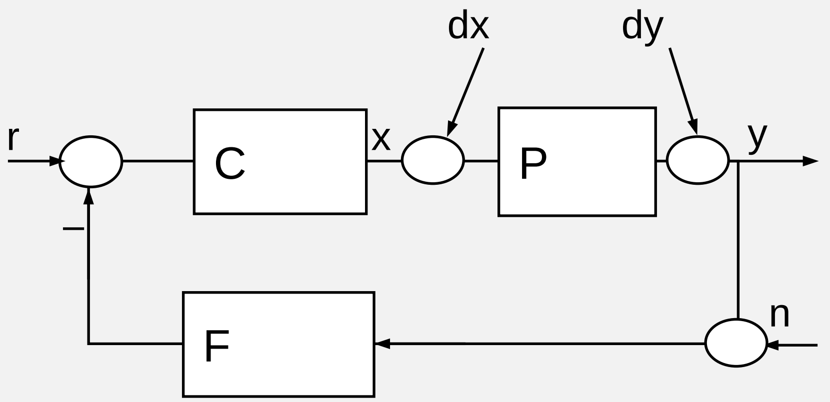
$$P(s) = \frac{10}{s + 0.5}$$

Note: We take the crossover frequency to be BW/1.5

- We consider the Bode plot of the plant with the integrator and design the PI zero to achieve the objective
- At $\omega_c = 1/1.5, \quad \angle PC_I = -\tan^{-1} 0.67/0.5 - 90^o + \tan^{-1}\tau_z 0.67 = \underbrace{-143^o + \tan^{-1}\tau_z 0.67}_{-120} =>$

$$\tau_z = \frac{\tan(23^o)}{0.67} = 0.63 \quad (s)$$

Motor speed PI control 2

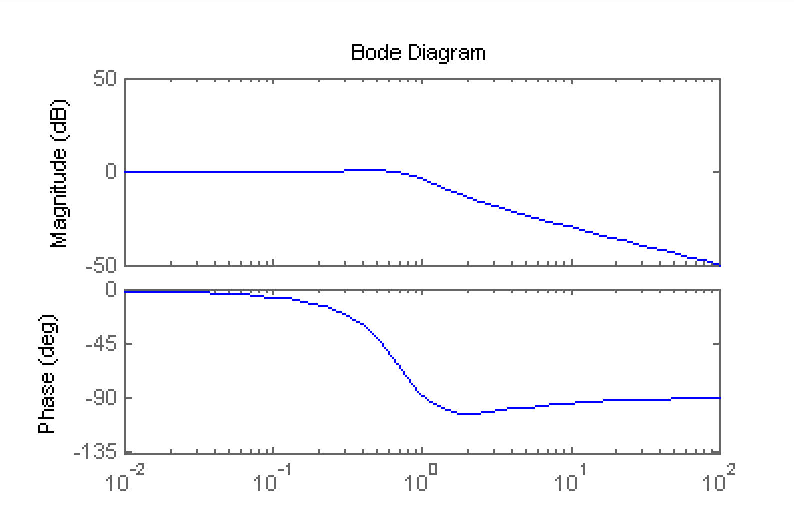


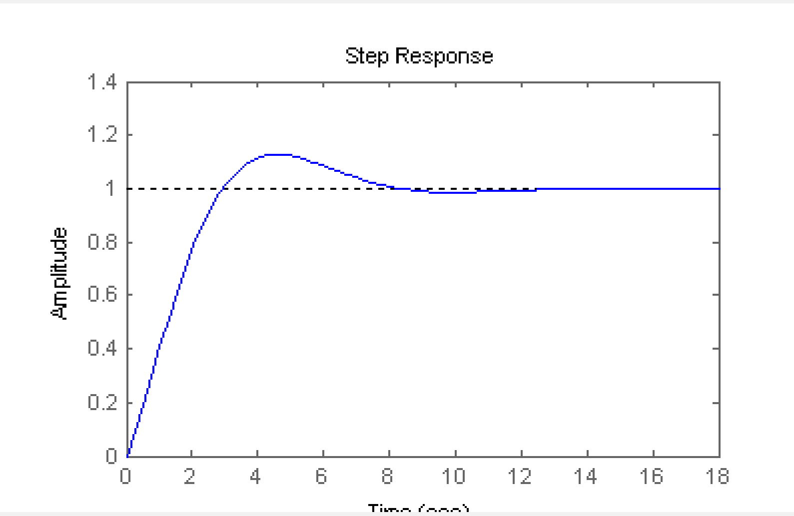
- Now compute the gain so that the crossover is at 0.67: (rad/s)

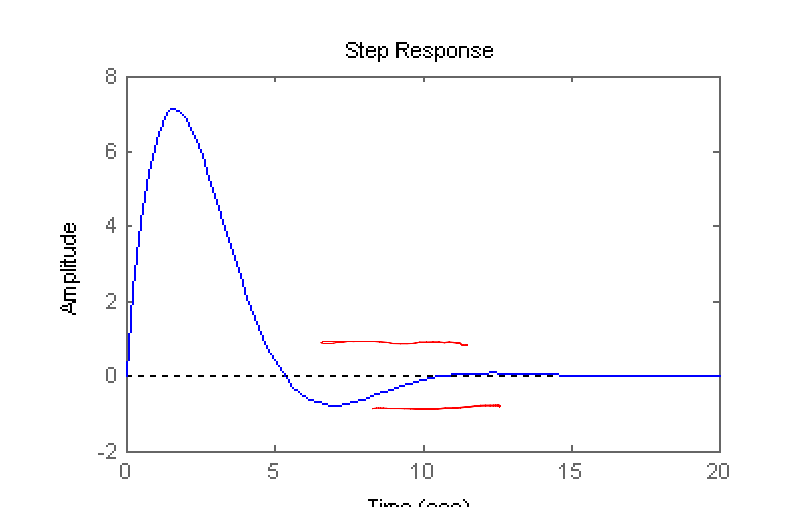
$$|\,|P(s)C(s)|_{s=j0.67}| = \frac{10}{|j0.67+0.5|}\,\frac{K\,|j(0.63)(0.67)+1|}{|j0.67|} = 1 \Rightarrow K = 1/19.5 \Rightarrow$$

$$\boxed{C(s) = \frac{0.032s+0.051}{s}}$$

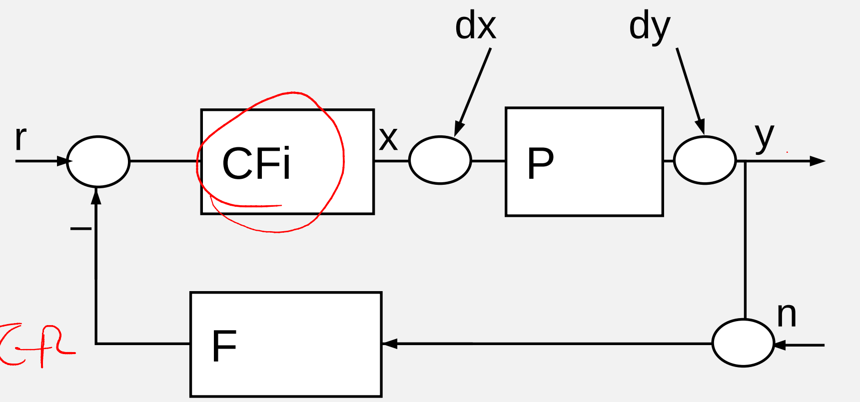
- We evaluate this design: The closed loop is faster than the open loop system, with Bandwidth 0.93 fairly close to the desired value, and has modest peak magnitude and overshoot.
- The response to input disturbances has been improved at low frequencies (dx → y: P/(1+PC)).







Motor speed PI control 2
Adjusting response to commands



PREFILTER

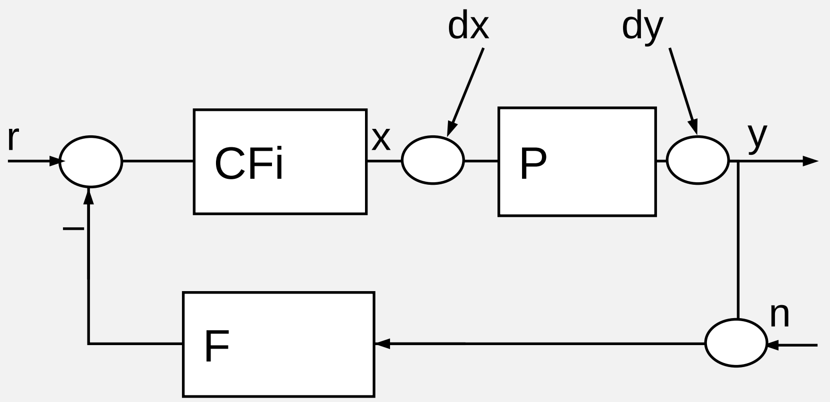
- When the PI controller increases the bandwidth of the system, the step response to commands (r) exhibits an overshoot.
- This is an undesirable effect that can be removed by using a prefilter (smoothing the command r) or by splitting the controller to a cascade and a feedback part. We address the latter case here.
- The Loop transfer function remains the same as long as the product CF is left unchanged. For example, we can define a low pass filter Fi and its inverse F:

DC = 1

$$\boxed{F_i(s) = \frac{\tau_1 s + 1}{\tau_2 s + 1},} \quad \boxed{F(s) = \frac{\tau_2 s + 1}{\tau_1 s + 1},} \quad \tau_1 < \tau_2$$

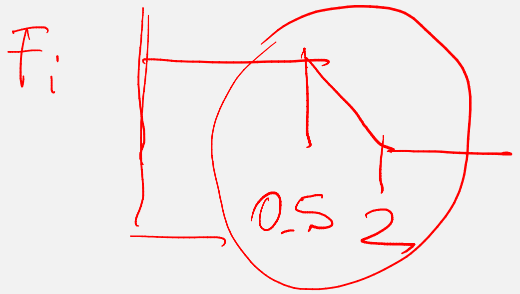
- We can then implement CFi in the forward path and F in the feedback path. This preserves the disturbance attenuation properties of our design but filters the r-to-y response by Fi.

Motor speed PI control 2
Adjusting response to commands



- We observe that the transfer function T peaks around 1 rad/s. We chose a filter with time constants around the peak magnitude frequency

$$F_i(s) = \frac{0.5s+1}{2s+1}, \quad F(s) = \frac{2s+1}{0.5s+1}$$



- Then implement the controller with

$$CF_i(s) = \frac{0.032s+0.051}{s} \cdot \frac{0.5s+1}{2s+1}, \quad F(s) = \frac{2s+1}{0.5s+1}$$

- We evaluate the response of the controller and find that the overshoot to steps has been virtually eliminated. (In general, some trial and error may be necessary; more systematic methods to tune filters like this exist but they tend to be fairly complicated.)