PE 2019
Designing highly accurate power amplifiers

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1931 Congrescentrum 's-Hertogenbosch

POWER ELECTRONICS 2019

Agenda

- Speaker affiliation and roles
- ASML
- Designing power electronics in general
- Designing power amplifiers in lithography tools
  - Amplifier in mechatronics position loop
    - basic position loop
    - loop sensitivities
    - amplifier error gain
    - link amplifier errors to system performance
    - example
- Pareto
- Conclusion

ASML

CL Power and High Voltage Electronics

TU/e

TU/e Fellow (Electromechanics & Power Electronics)

Movie intro ASML: machines to make chips

ASML's tools are critical to realize Moore's law

ASML machines print pattern into photoresist (lithography)

Moore's law:

transistor count

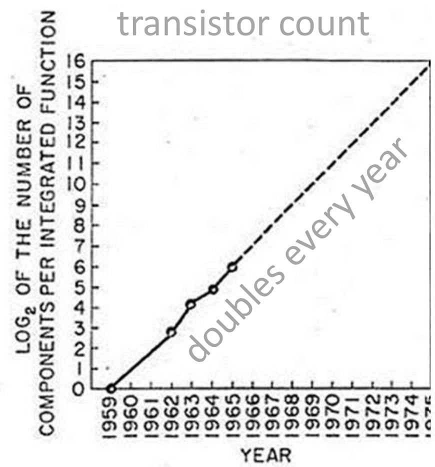
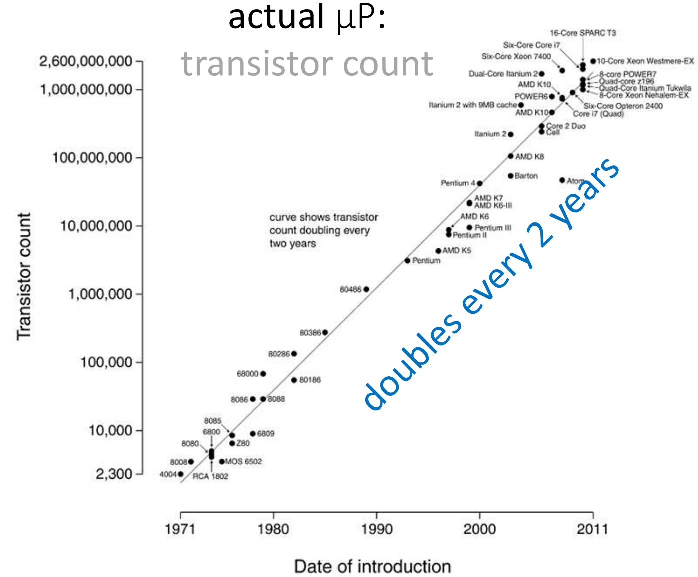


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

actual μP:

transistor count



- at present $10^{10}/chip$

(Apple A12X)

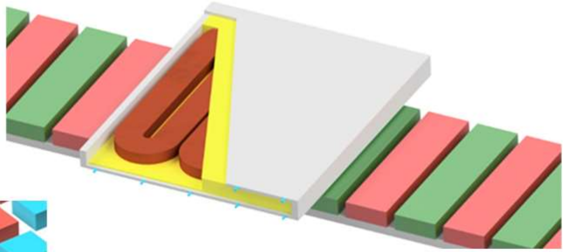
Power electronics design…

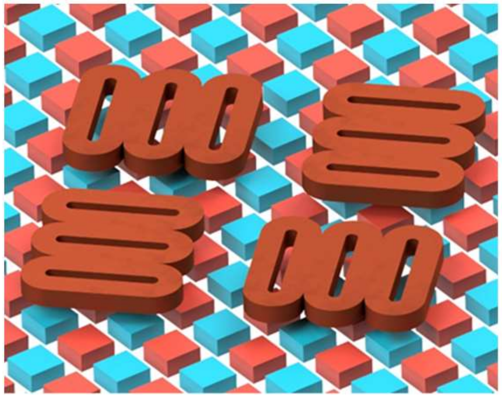
nteresting topic in electronics engineering …

… power electronics always serve an **application**.

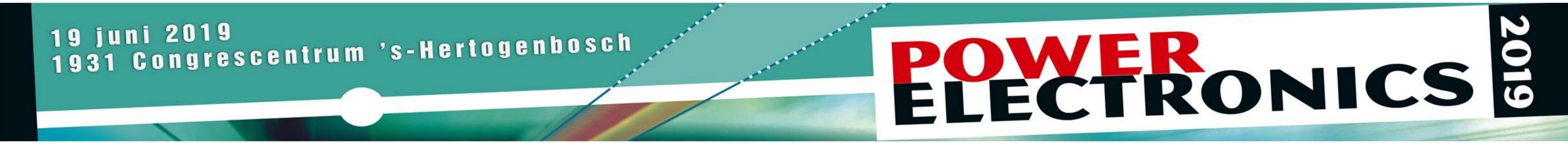
Power amplifiers in lithography tools

- sub-nanometer accurate dynamic positioning of moving stages





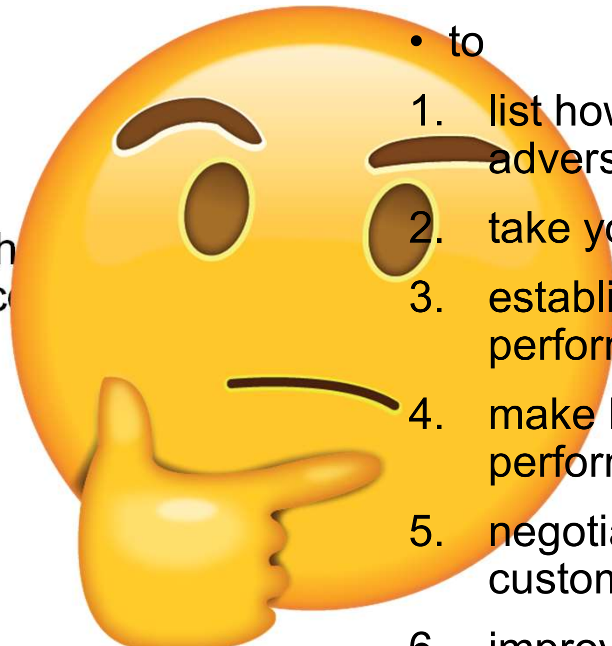
including levitation



Generic approach to design power electronics for any demanding application

- from

1. ask for specifications
2. make design
3. find out it's not what th customer needed or c gotten

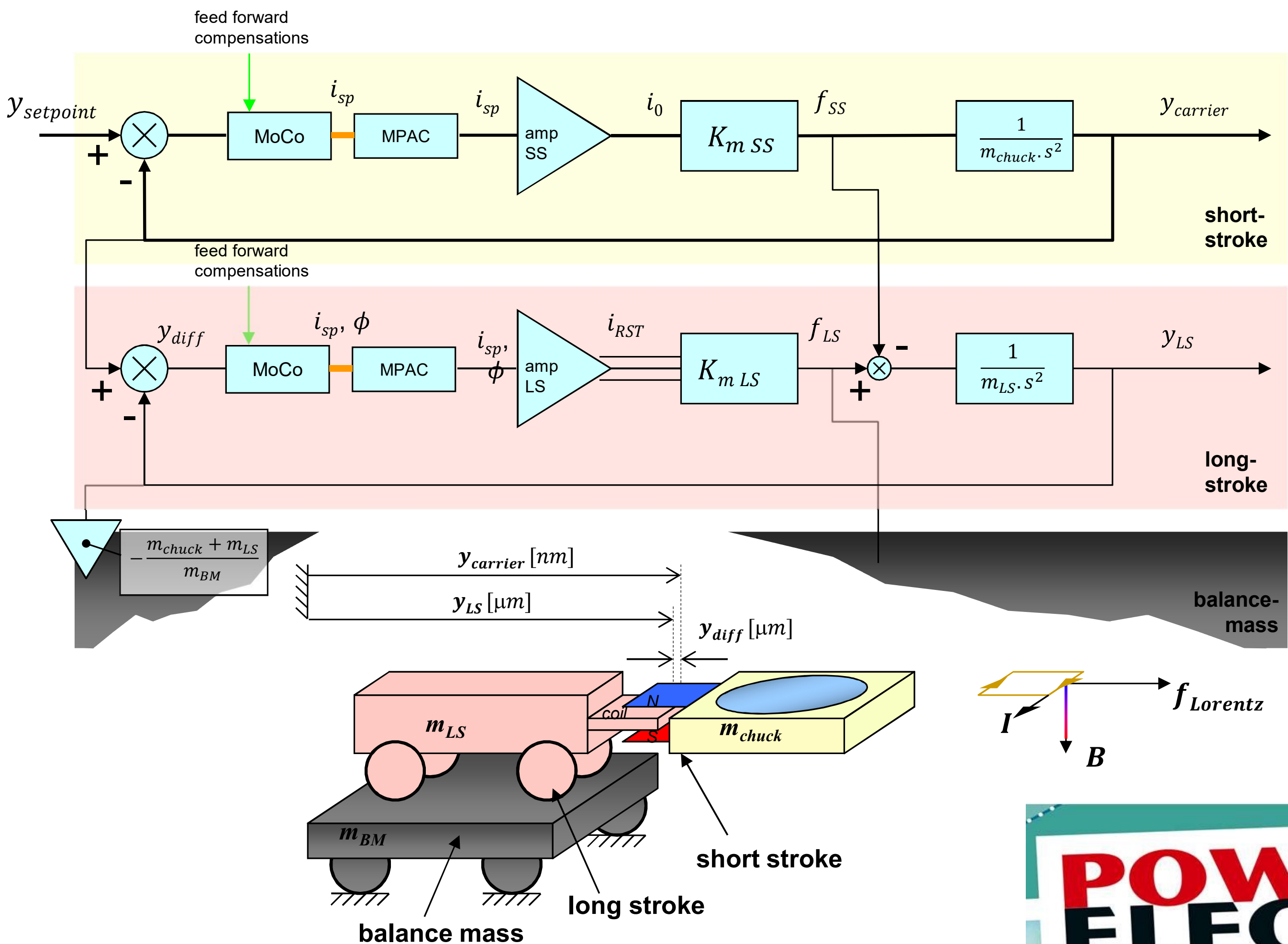


- to

1. list how your power electronics could (yes, adversely) affect the application it enables
2. take your time to make the list exhaustive
3. establish sensitivities from every list item to performance perceived by end-customer
4. make Pareto of biggest contributors to performance reduction
5. negotiate with (people representing) end-customer
6. improve biggest contributors as required

complex slide warning

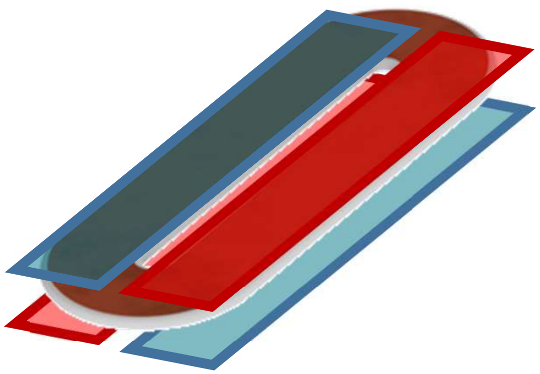
Positioning of moving stages



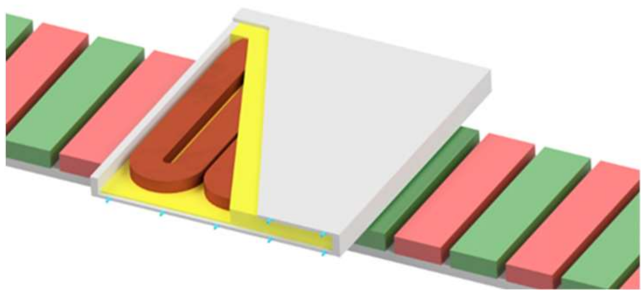
- 1 axis shown here
- in real system 6 mechanical degrees of freedom (DoF) per rigid body
- representing 12 state variables
- total ~100 interacting states
- or more if finite stiffness is considered

Role of power amplifiers: supply currents for linear actuators

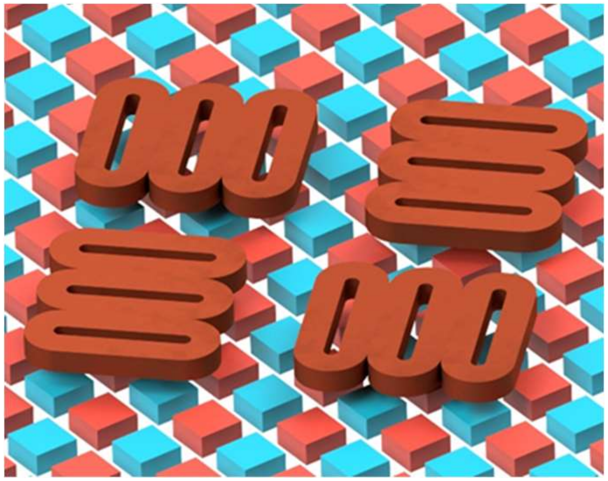
linear – short stroke



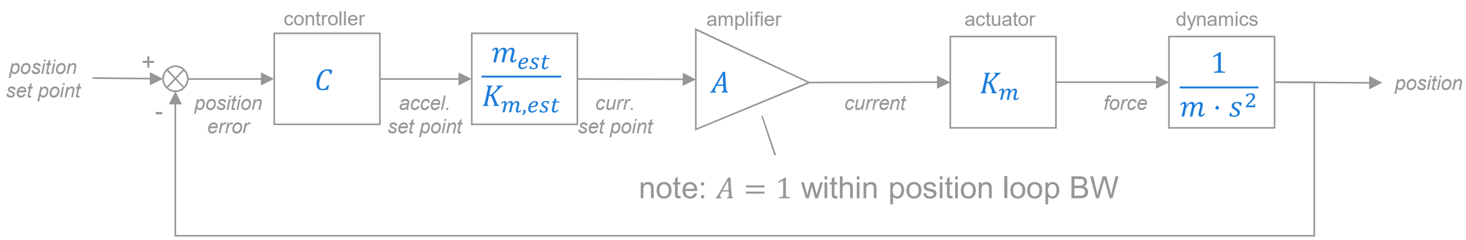
linear – long stroke



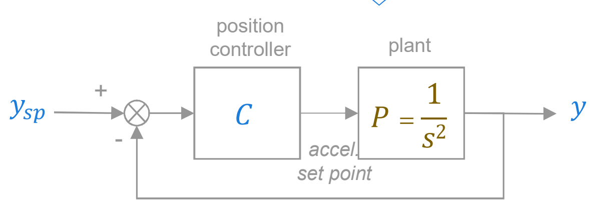
planar



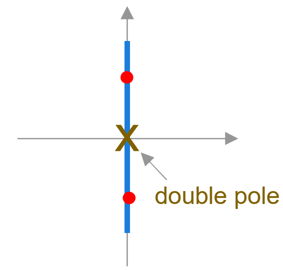
Basic 1-DoF position loop



simplify



root locus with $C = K_p$

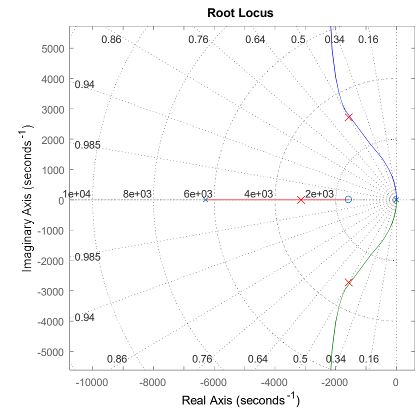


System is inherently unstable (plant has $180°$ phase shift).

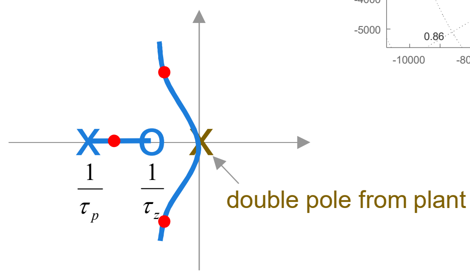
Basic 1-DoF position loop

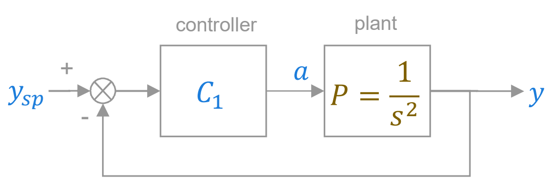
- making stable, option 1

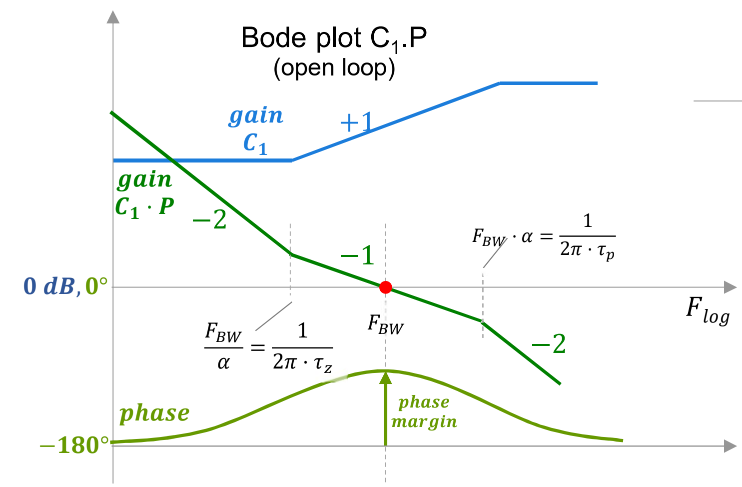
- zero/pole controller (lead/lag)
  - zero below desired BW
  - pole above desired BW
  - set gain to maximize phase margin
  - set distance zero - pole for desired phase margin



root locus $C_1 \cdot P$







$$C_1 = K \cdot \frac{s\tau_z + 1}{s\tau_p + 1}, P = \frac{1}{s^2}$$

$$|C_1 \cdot P|_{F=F_{BW}} = 1$$
$$\Leftrightarrow |K \cdot 2\pi F_{BW} \cdot \tau_z| \approx 1$$
$$\Leftrightarrow K \approx \frac{(2\pi \cdot F_{BW})^2}{\alpha}$$

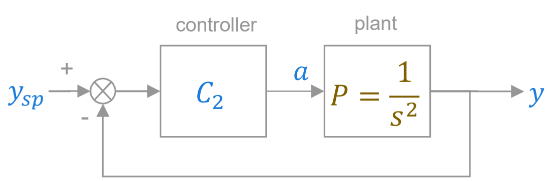
Basic 1-DoF position loop

- making stable, option 2

- PID + 2LPF filter controller
  - extra pole at 0 Hz
  - two zeroes below desired BW
  - two poles above desired BW
  - set gain to maximize phase margin
  - set distance zeros - poles for desired phase margin

more LF open loop gain
→ less sensitivity

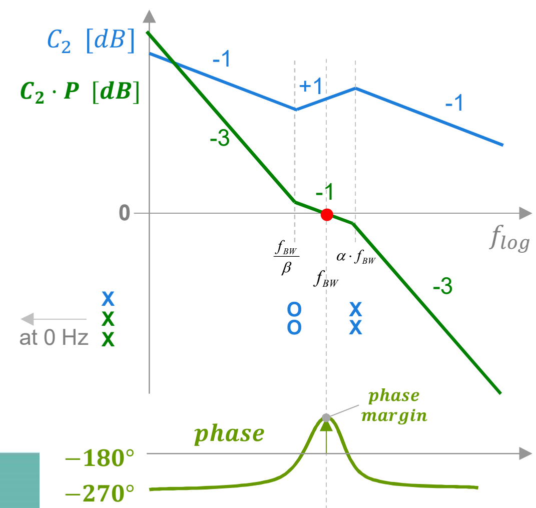
Uhm..., sensitivity?



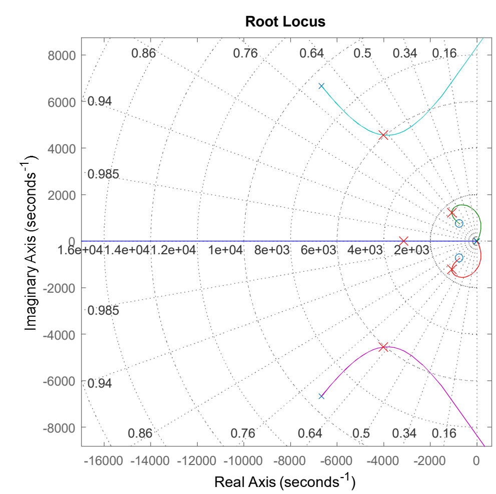
$$C_2 = C_{PID} \cdot C_{2LPF}$$

$$\Leftrightarrow C_2 = [sK_d + K_p + \frac{K_i}{s}] \cdot \frac{\omega_{LP}^2}{s^2 + s2\zeta_{LP}\omega_{LP} + \omega_{LP}^2}$$

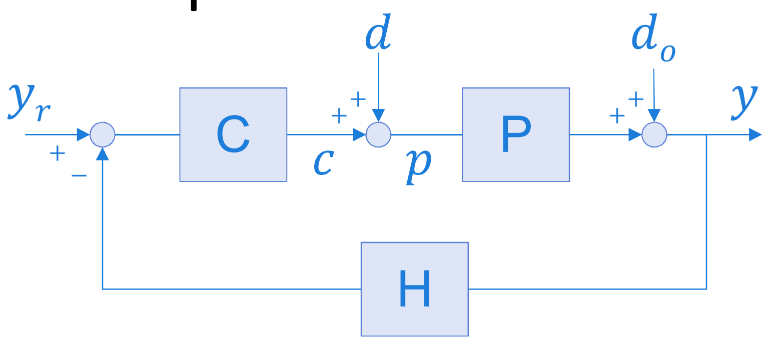
$$\Leftrightarrow C_2 = K_d \frac{s^2 + s\frac{K_p}{K_d} + \frac{K_i}{K_d}}{s} \cdot \frac{\omega_{LP}^2}{s^2 + s2\zeta_{LP}\omega_{LP} + \omega_{LP}^2}$$

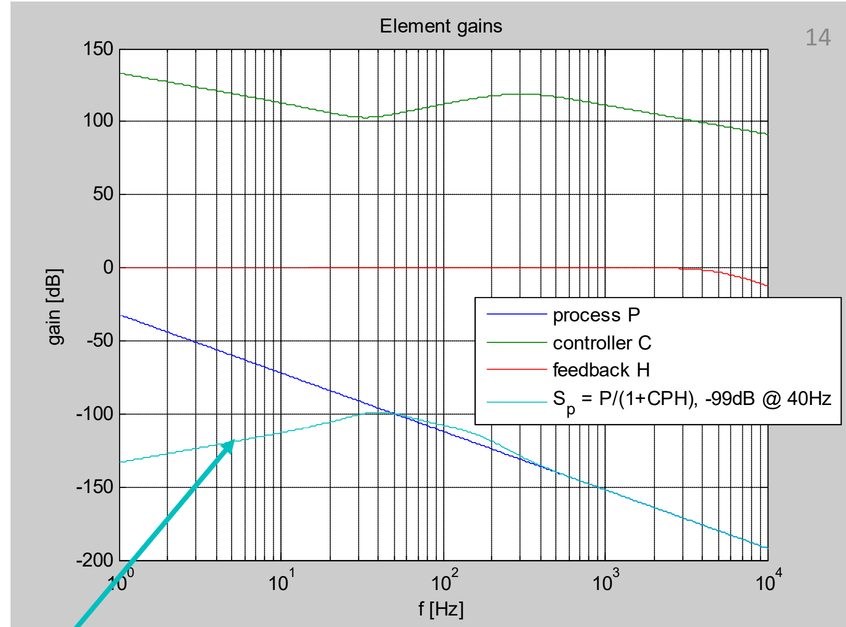


root locus $C_2 \cdot P$



Loop sensitivities





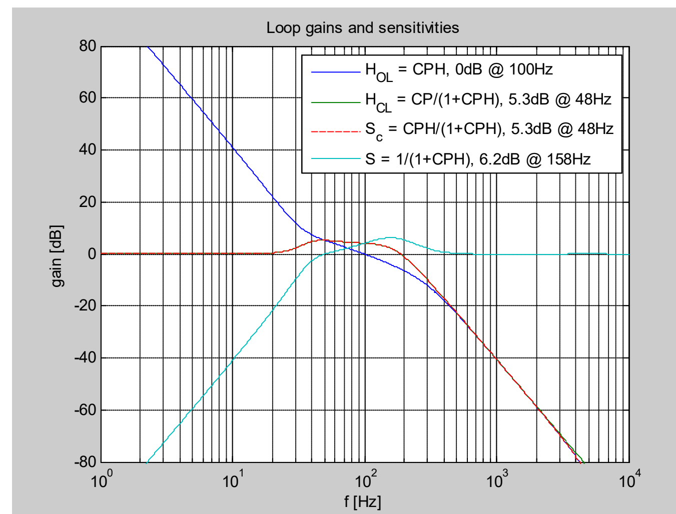
sensitivity $S = \frac{y}{d_o} = \frac{1}{1+CPH}$

- equal
- dimensionless

input sensitivity $S_i = \frac{p}{d} = \frac{1}{1+CPH}$

process sensitivity $S_p = \frac{y}{d} = \frac{P}{1+CPH}$

defines sensitivity of position loop for power amplifier errors

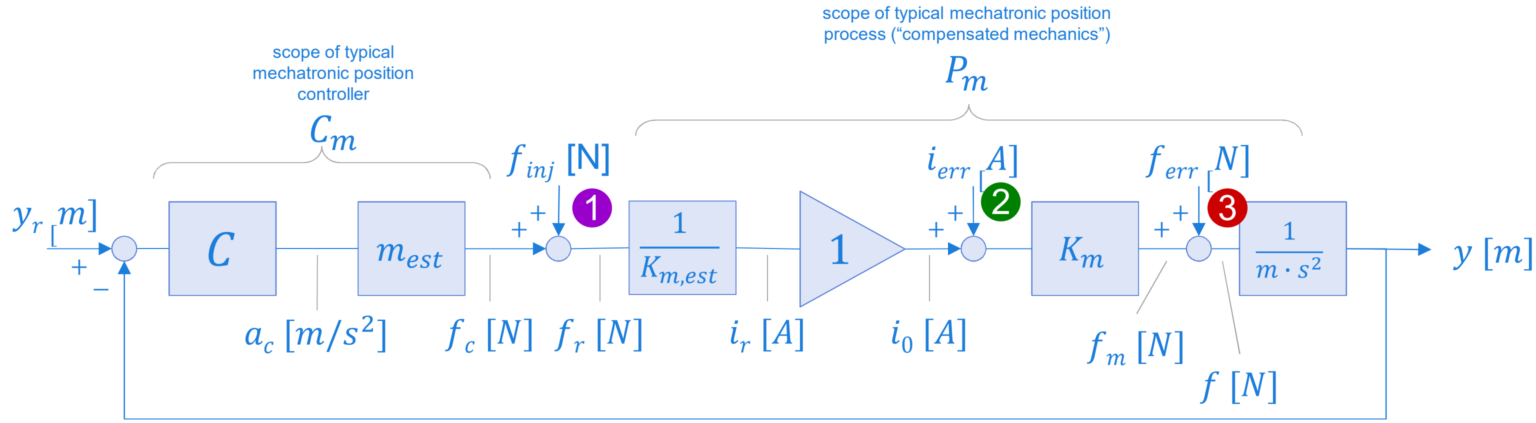


Note:

open loop gain $H_{OL} = CPH = \frac{1}{S} - 1 = \frac{-c}{p} = \frac{d-p}{p} = \frac{-c}{c+d}$

Mechatronic position loop

and relevant sensitivities



Relevant process sensitivities:

1. injected force gain $S_{p,\,force} = \dfrac{y}{f_{inj}} = \dfrac{P_m}{1+C_m \cdot P_m}\,[m/N]$

2. amp noise gain $S_{p,\,amp} = \dfrac{y}{i_{err}} = \dfrac{K_m \cdot P_m}{1+C_m \cdot P_m}\,[m/A]$

3. error force gain $\approx$ 1 (for frequency $F < F_{BW,\,amp}$)

defines sensitivity of position loop for power amplifier errors

Amplifier "noise" gain

defined by motor constant K, mass m and pos. loop bandwidth F_{BW}

amplifier noise gain =

$$C_{ANG} = \frac{y_\varepsilon}{i_\varepsilon} = \frac{\frac{K_m}{m \cdot s^2}}{1 + C \cdot \frac{m_{est}}{K_{m,est}} \cdot H_{ampCL} \cdot \frac{K_m}{m \cdot s^2}} \quad [m/A]$$

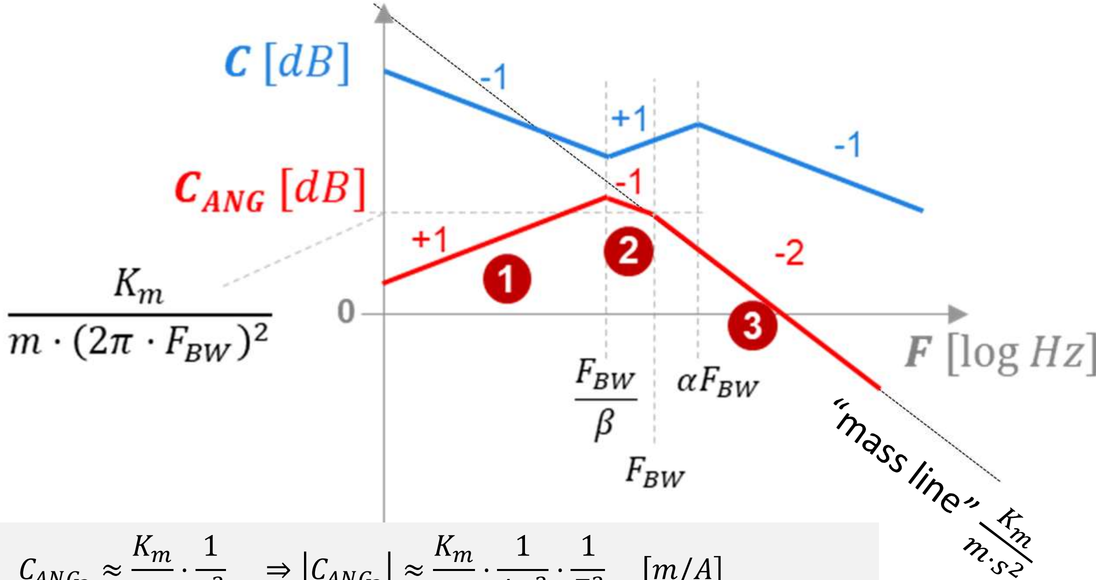
$\Leftrightarrow C_{ANG} \approx \frac{K_m}{m} \cdot \frac{1}{s^2 + C}$ for $F \leq 10 \cdot F_{BWposloop} \rightarrow H_{ampCL} \approx 1$

3 $F > F_{BWposloop} \rightarrow |C_m P_m| \ll 1 \Leftrightarrow \left|\frac{C}{s^2}\right| \ll 1 \Leftrightarrow |C| \ll |s^2|$

$$\Rightarrow C_{ANG_3} \approx \frac{K_m}{m} \cdot \frac{1}{s^2}$$

1, 2 $F < F_{BWposloop} \rightarrow |CP| \gg 1 \Leftrightarrow \left|\frac{C}{s^2}\right| \gg 1 \Leftrightarrow |C| \gg |s^2|$

$$\Rightarrow C_{ANG_{1,2}} \approx \frac{K_m}{m} \cdot \frac{1}{C}$$

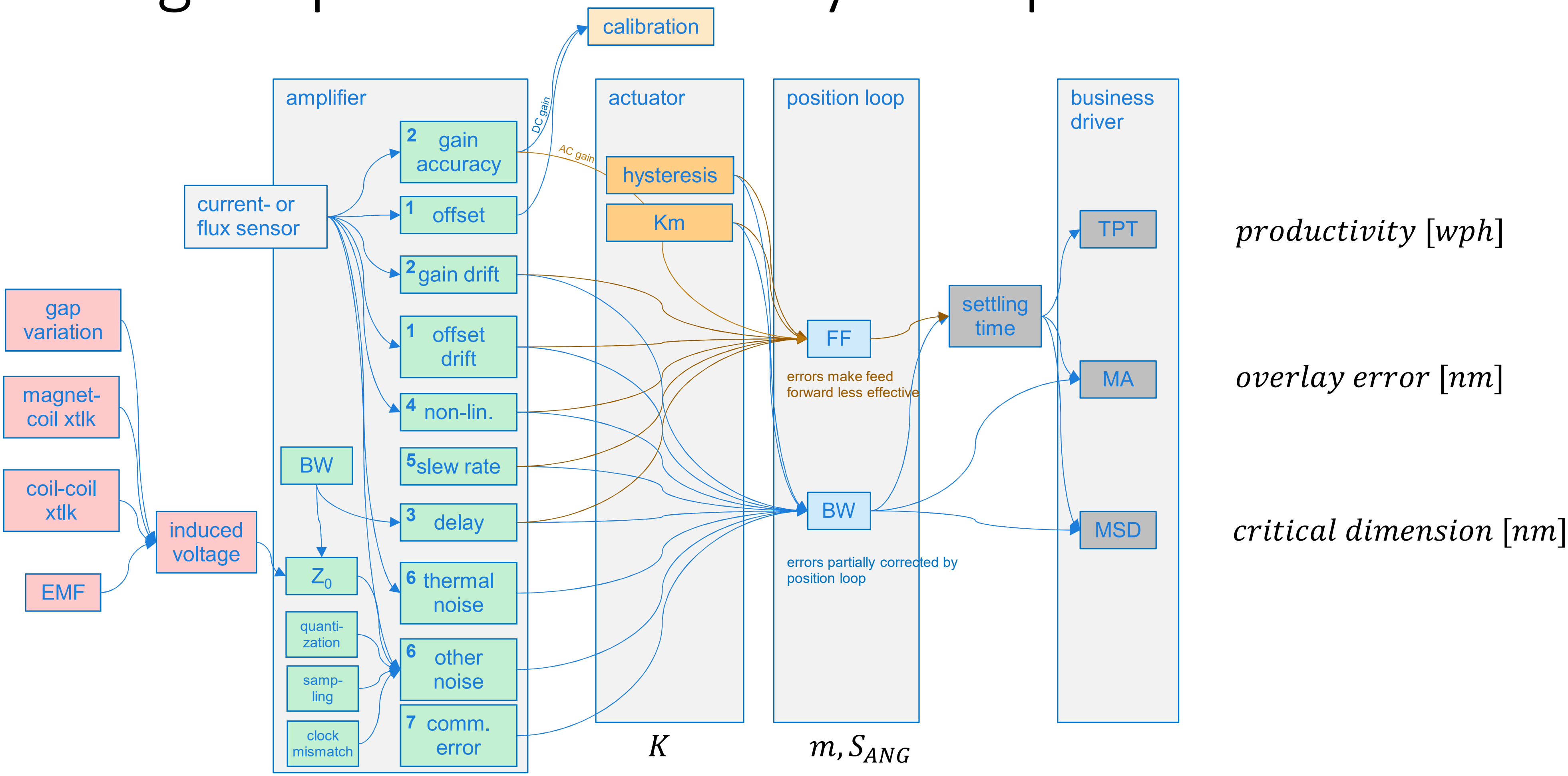


3 $C_{ANG_3} \approx \frac{K_m}{m} \cdot \frac{1}{s^2} \quad \Rightarrow |C_{ANG_3}| \approx \frac{K_m}{m} \cdot \frac{1}{4\pi^2} \cdot \frac{1}{F^2} \quad [m/A]$

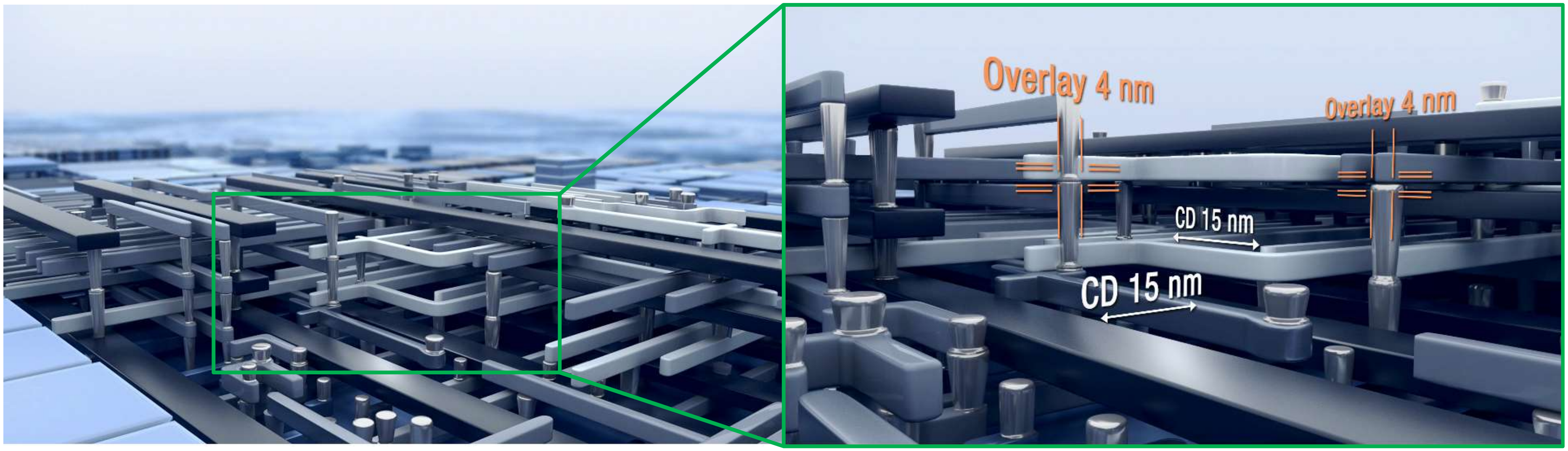
2 $C_{ANG_2} \approx \frac{K_m}{m} \cdot \frac{1}{C} \quad \Rightarrow |C_{AN\ 2}| \approx \frac{K_m}{m} \cdot \frac{1}{4\pi^2 \cdot F_{BW}} \cdot \frac{1}{F} \quad [m/A]$

1 $C_{ANG_1} \approx \frac{K_m}{m} \cdot \frac{1}{C} \quad \Rightarrow |C_{AN\ 1}| \approx \frac{K_m}{m} \cdot \frac{1}{4\pi^2 \cdot BC \cdot F_{BW}{}^3} \cdot F \quad [m/A]$

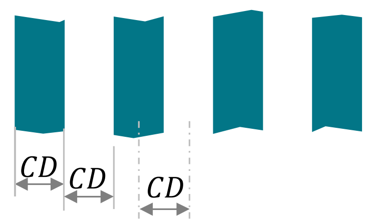
linking amplifier errors to system performance



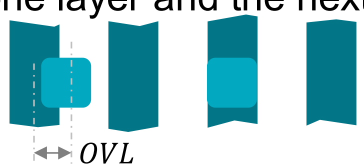
Critical dimension CD, overlay OVL



CD is smallest feature size (line width, isolation width, half pitch)

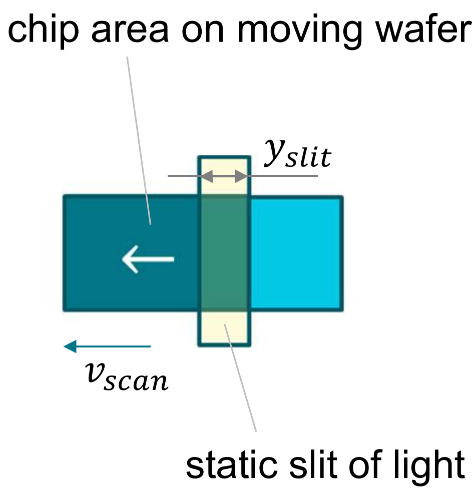


OVL is misalignment between one layer and the next



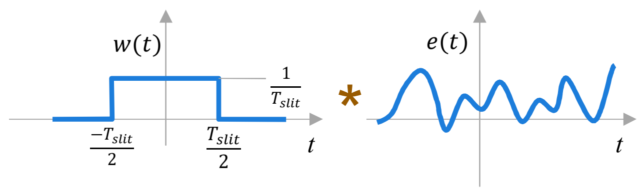
MA/MSD evaluation

time domain:

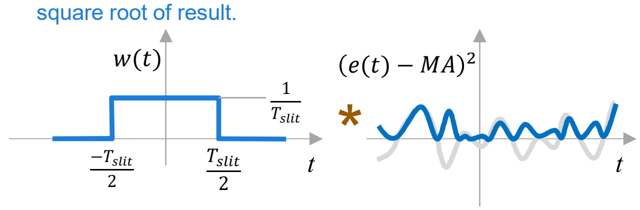


$$T_{slit} = \frac{y_{slit}}{v_{scan}}$$

MA: **convolute** error signal with **window function**:



MSD: convolute square of (error signal – MA) with **window function** and take square root of result.



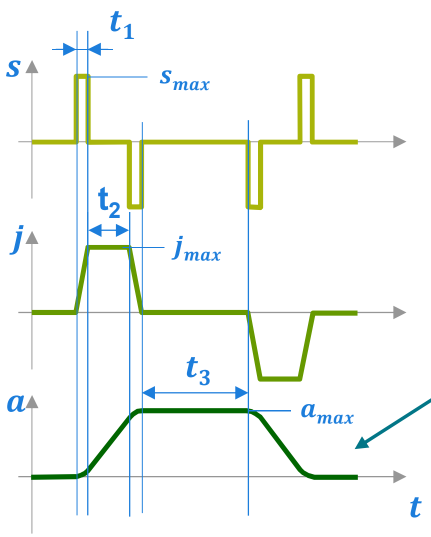
position error $e(t)$

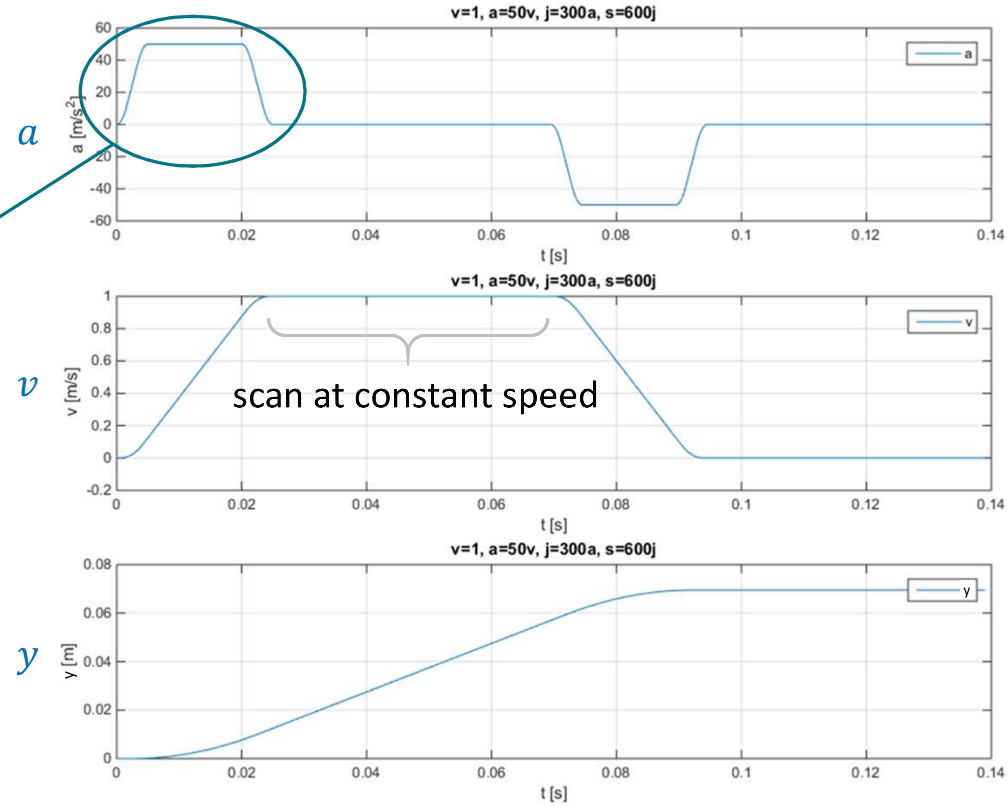
$$MA = \frac{1}{T_{slit}} \int_{\frac{-T_{slit}}{2}}^{\frac{T_{slit}}{2}} e(t) \cdot dt$$

$$MSD = \sqrt{\frac{1}{T_{slit}} \int_{\frac{-T_{slit}}{2}}^{\frac{T_{slit}}{2}} [e(t) - MA]^2 \cdot dt}$$

$$T_{slit} = \frac{y_{slit}}{v_{scan}}$$

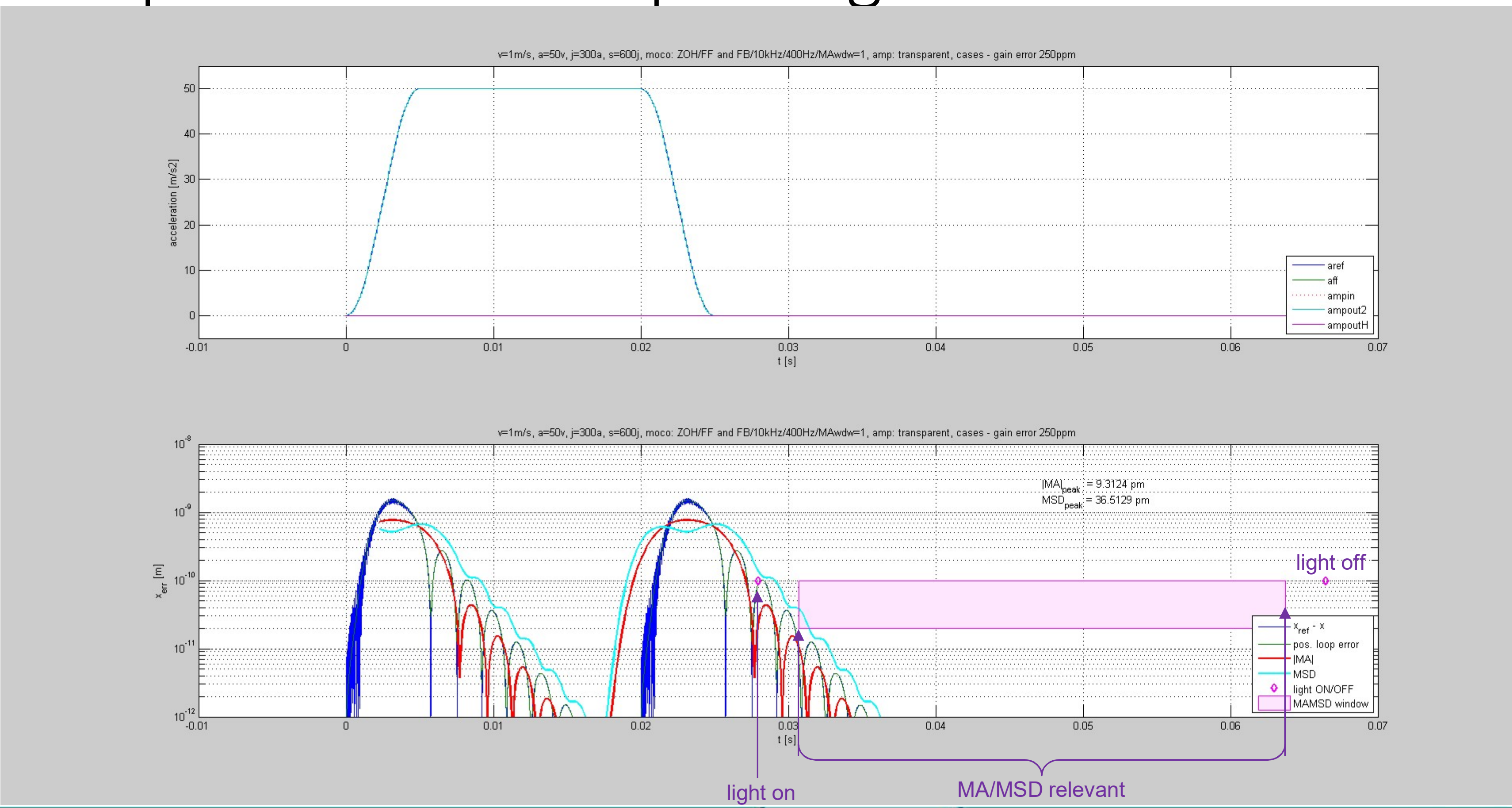
Position set point generator



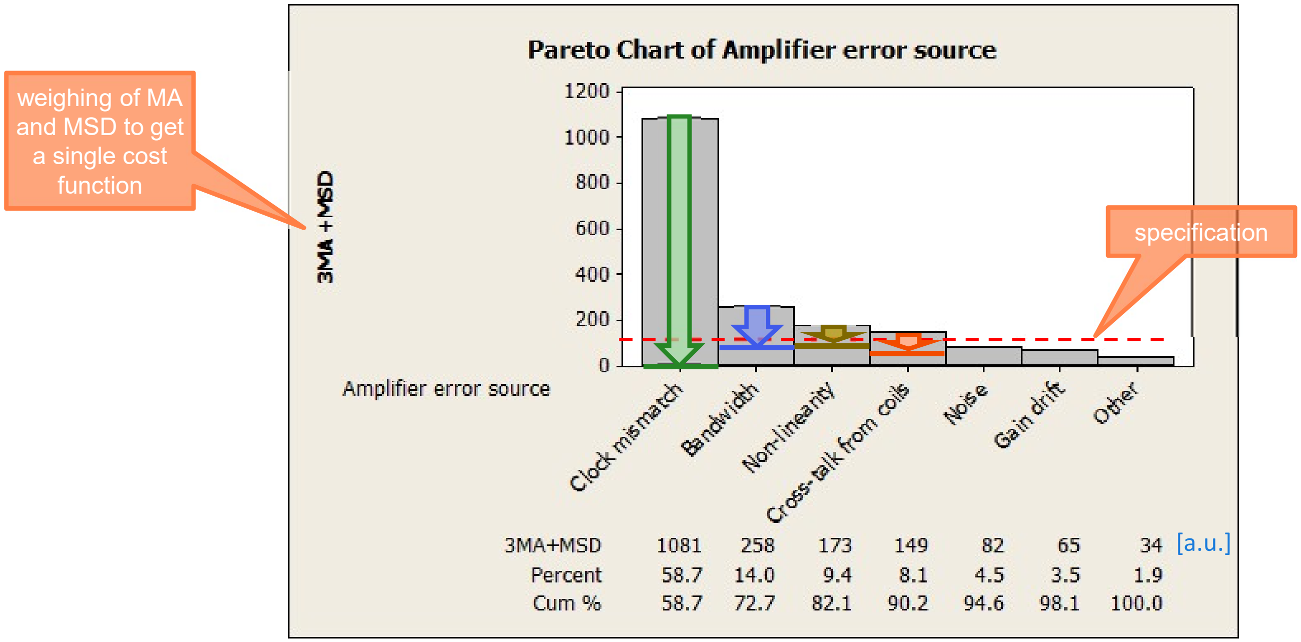


Why not use a simple rectangular acceleration shape?

Example: effect of amplifier gain error

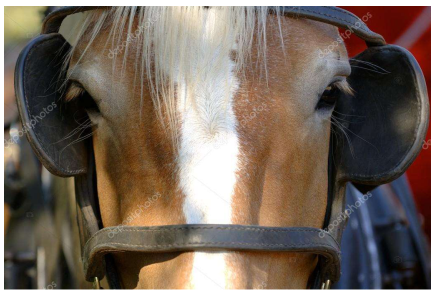


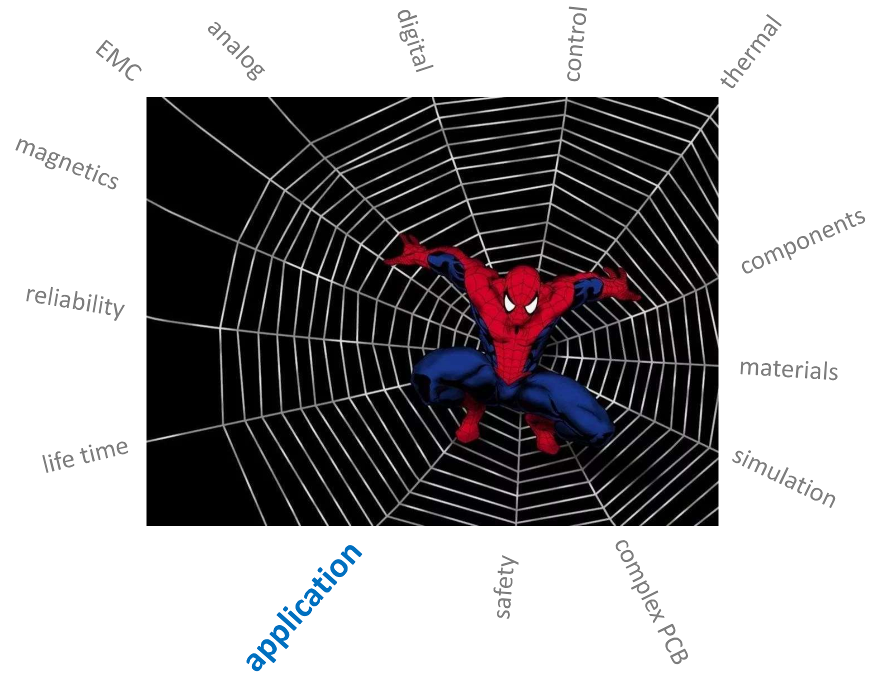
Pareto analysis



➔ identify the lowest number of improvements to get the maximum effect
("bang for buck", "low hanging fruit", "cherry picking")

Summary




EMC
analog
digital
control
thermal
magnetics
components
reliability
materials
life time
simulation
application
safety
complex PCB


thank
you!