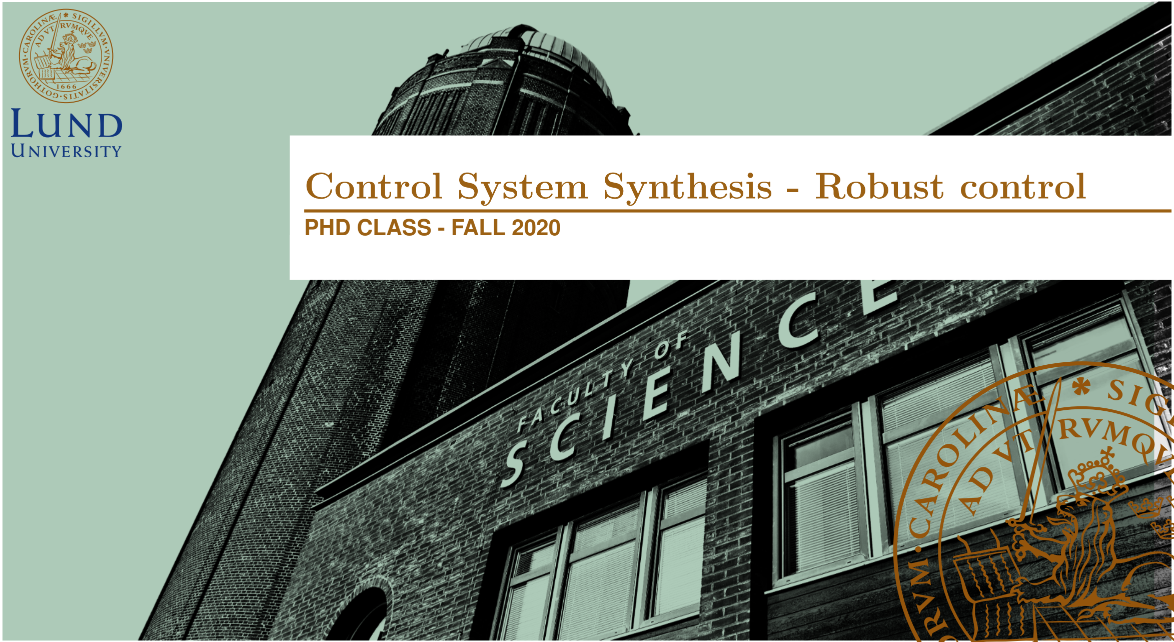
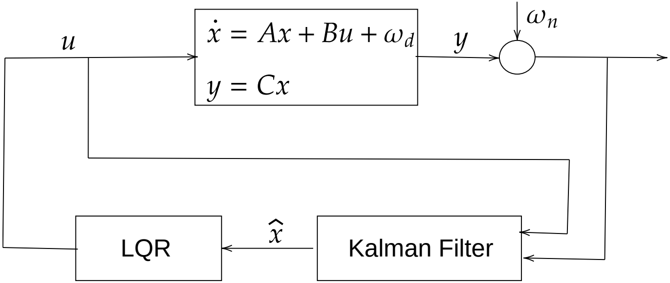
Lund University

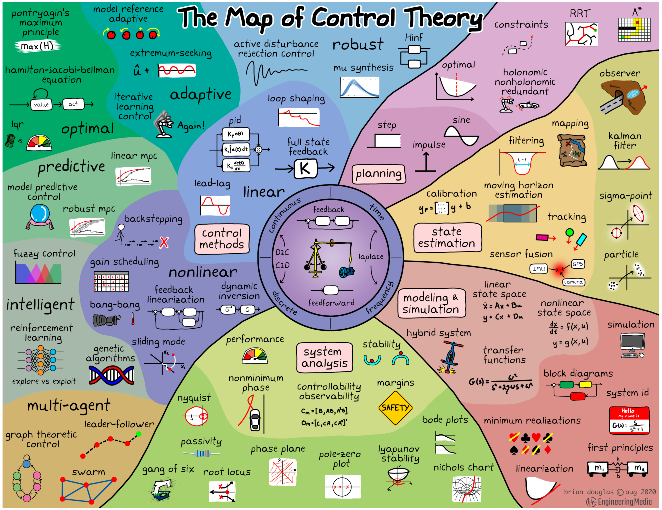
Control System Synthesis - Robust control

PHD CLASS - FALL 2020



1. Introduction
2. Fundamentals
3. Design techniques
   - PID control
   - Optimal control and LQG




The Map of Control Theory
pontryagin's maximum principle
max (H)
model reference adaptive
extremum-seeking
hamilton-jacobi-bellman equation
value
act
iterative learning control
adaptive
Again!
lqr
vs.
optimal
predictive
linear mpc
model predictive control
robust mpc
fuzzy control
intelligent
reinforcement learning
explore vs exploit
genetic algorithms
multi-agent
graph theoretic control
leader-follower
swarm
active disturbance rejection control
robust
Hinf
mu synthesis
loop shaping
pid
full state feedback
K
lead-lag
linear
control methods
backstepping
gain scheduling
nonlinear
feedback linearization
dynamic inversion
bang-bang
sliding mode
continuous
time
feedback
D2C
C2D
laplace
feedforward
discrete
frequency
constraints
RRT
A*
holonomic
nonholonomic
redundant
optimal
step
sine
impulse
planning
observer
mapping
filtering
kalman filter
calibration
moving horizon estimation
sigma-point
state estimation
tracking
sensor fusion
IMU
GPS
camera
particle
modeling & simulation
linear state space
nonlinear state space
hybrid system
simulation
transfer functions
block diagrams
system id
minimum realizations
first principles
linearization
performance
system analysis
stability
nonminimum phase
controllability observability
margins
SAFETY
nyquist
passivity
phase plane
bode plots
gang of six
root locus
pole-zero plot
lyapunov stability
nichols chart
brian douglas © aug 2020
Engineering Media

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Content overview

Uncertainty and robustness

Where does uncertainty come from?

A model is only an approximation of the reality!

- Complex dynamics

Uncertainty and robustness

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A model is only an approximation of the reality!

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- Uncertain inputs

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- Simplified models

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- Process variations

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- Process variations

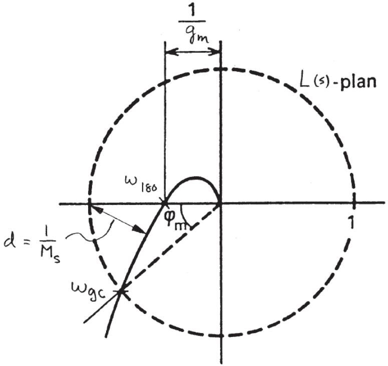
The controller is tailored for the model

- Is your controller good enough for the real system? $\rightarrow$ **analysis**
- Can you take into account the uncertainties during the design? $\rightarrow$ **synthesis**

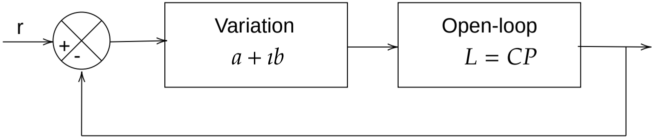
How to handle uncertainty?

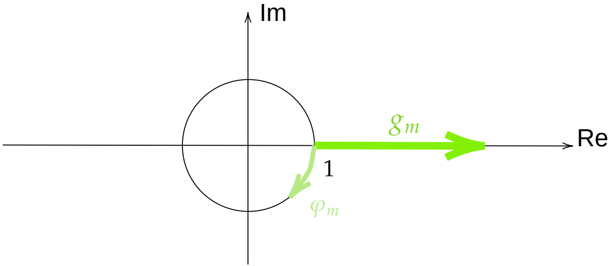
Classical margins requirements

- Gain margin $g_m > 5\text{dB}$
- Phase margin $\varphi_m > 45^\circ$



Limitations of classical margins





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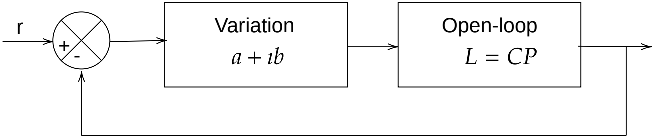

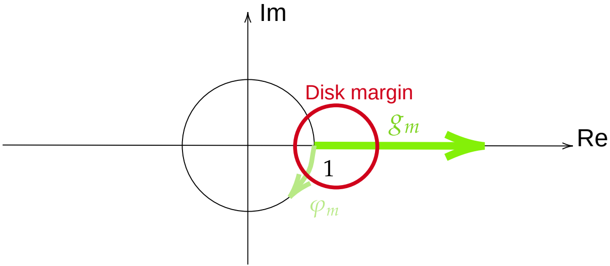

Less structured representations of uncertainty

$\rightarrow$ set of transfer functions around the nominal model

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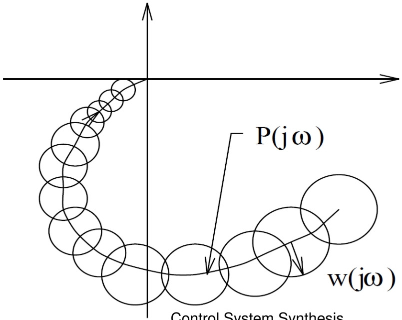
Less structured representations of uncertainty

$\rightarrow$ set of transfer functions around the nominal model

Additive uncertainty

$$P_\Delta(s) = P(s) + W_1(s)\Delta(s)W_2(s),\ \forall\omega > 0\ \overline{\sigma}(\Delta(\jmath\omega)) < 1$$

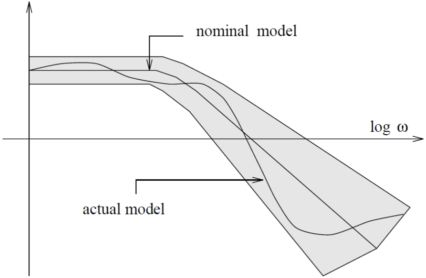
W_1 and W_2: spatial and frequency structure of the uncertainty



Less structured representations of uncertainty
$\rightarrow$ set of transfer functions around the nominal model

Multiplicative uncertainty

$$P_\Delta(s) = (I + W_1(s)\Delta(s)W_2(s))P(s),\ \forall\omega > 0\ \overline{\sigma}(\Delta(j\omega)) < 1$$



Definition of robustness

Ability to meet requirements (stability and performances) under disturbance and model uncertainty

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- Nominal stability: $S = (I + PC)^1$ stable
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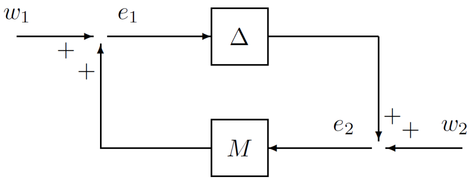
How to analyze/enforce robust stability and performance?

Uncertainty and robustness

Small gain theorem



Small-gain theorem

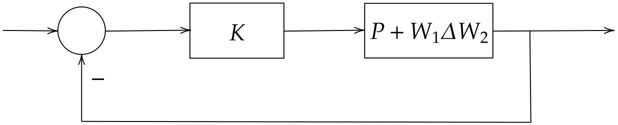
Suppose $M \in \mathcal{RH}_\infty$ and let $\gamma > 0$. Then this interconnected system is well-posed and internally stable for all $\Delta(s) \in \mathcal{RH}_\infty$ with:

- $\|\Delta\|_\infty \leq \frac{1}{\gamma}$ if and only if $\|M\|_\infty < \gamma$
- $\|\Delta\|_\infty < \frac{1}{\gamma}$ if and only if $\|M\|_\infty \leq \gamma$

Uncertainty and robustness

Robust stability

$$P_\Delta(s) = P(s) + W_1(s)\Delta(s)W_2(s),\ \forall\omega > 0\ \overline{\sigma}(\Delta(\jmath\omega)) < 1$$



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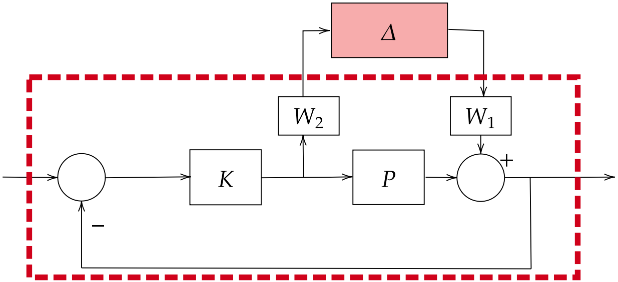

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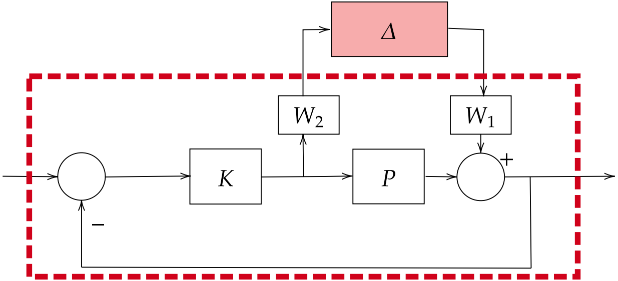
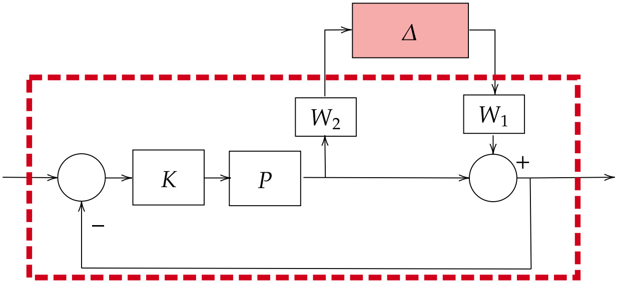


The closed-loop is internally stable for $\Delta \in \mathcal{RH}_\infty$ such that $\|\Delta\|_\infty < 1$ if and only if $\|M\|_\infty \leq 1$

$$M = W_2K(I + KP)^{-1}W_1$$

$$P_\Delta(s) = (I + W_1(s)\Delta(s)W_2(s))P(s),\ \forall\omega > 0\ \overline{\sigma}(\Delta(\jmath\omega)) < 1$$



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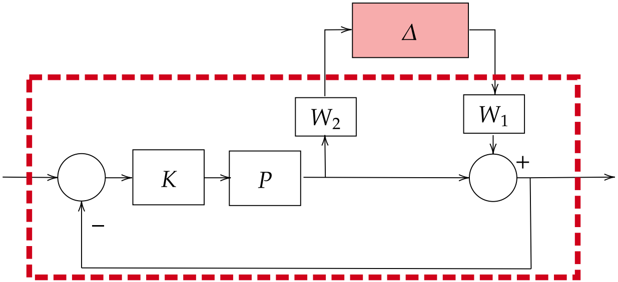

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Uncertainty and robustness

Robust stability

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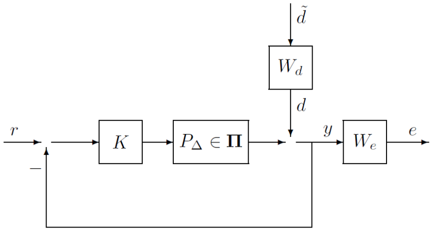
$W_1 \in \mathcal{RH}_\infty \quad W_2 \in \mathcal{RH}_\infty \quad \Delta \in \mathcal{RH}_\infty \quad \|\Delta\|_\infty < 1$		
Perturbed Model Sets Π	Representative Types of Uncertainty Characterized	Robust Stability Tests
$(I + W_1 \Delta W_2)P$	output (sensor) errors neglected HF dynamics uncertain rhp zeros	$\|W_2 T_o W_1\|_\infty \leq 1$
$P(I + W_1 \Delta W_2)$	input (actuators) errors neglected HF dynamics uncertain rhp zeros	$\|W_2 T_i W_1\|_\infty \leq 1$
$(I + W_1 \Delta W_2)^{-1} P$	LF parameter errors uncertain rhp poles	$\|W_2 S_o W_1\|_\infty \leq 1$
$P(I + W_1 \Delta W_2)^{-1}$	LF parameter errors uncertain rhp poles	$\|W_2 S_i W_1\|_\infty \leq 1$
$P + W_1 \Delta W_2$	additive plant errors neglected HF dynamics uncertain rhp zeros	$\|W_2 K S_o W_1\|_\infty \leq 1$
$P(I + W_1 \Delta W_2 P)^{-1}$	LF parameter errors uncertain rhp poles	$\|W_2 S_o P W_1\|_\infty \leq 1$
$(\tilde{M} + \tilde{\Delta}_M)^{-1}(\tilde{N} + \tilde{\Delta}_N)$ $P = \tilde{M}^{-1}\tilde{N}$ $\Delta = \begin{bmatrix} \tilde{\Delta}_N & \tilde{\Delta}_M \end{bmatrix}$	LF parameter errors neglected HF dynamics uncertain rhp poles & zeros	$\left\| \begin{bmatrix} K \\ I \end{bmatrix} S_o \tilde{M}^{-1} \right\|_\infty \leq 1$
$(N + \Delta_N)(M + \Delta_M)^{-1}$ $P = NM^{-1}$ $\Delta = \begin{bmatrix} \Delta_N \\ \Delta_M \end{bmatrix}$	LF parameter errors neglected HF dynamics uncertain rhp poles & zeros	$\|M^{-1} S_i [K \ I]\|_\infty \leq 1$

Table 8.1: Unstructured robust stability tests (HF: high frequency, LF: low frequency)

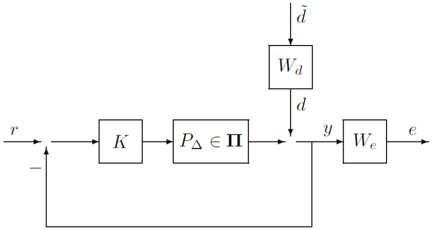
Essentials of robust control
Zhou, K., Doyle, J. C. (1998).



robust stability and $\sup_{\|\tilde{\delta}\|_2 \leq 1} \|e\|_2 \leq 1$

Uncertainty and robustness

Robust performance

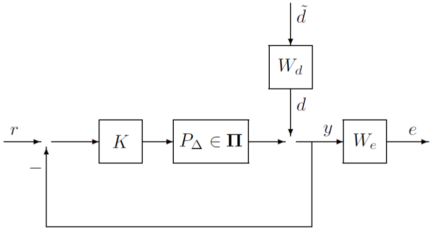


robust stability and $\|T_{\tilde{\delta}e}\|_\infty \leq 1, \; \forall \Delta \in \mathcal{RH}_\infty, \|\Delta\|_\infty < 1$

$$T_{\tilde{\delta}e} = W_e(I + P_\Delta K)^{-1} W_d \text{ with } P_\Delta \in \Pi$$

Uncertainty and robustness

Robust performance



Sufficient condition in the case of multiplicative uncertainty:

$$\forall \omega,\ \overline{\sigma}(W_d)\overline{\sigma}(W_e S) + \overline{\sigma}(W_1)\overline{\sigma}(W_2 T) \leq 1$$

$$S = (I + KP)^{-1},\ T = I - S$$

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  - Margins

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- Small-gain theorem $\rightarrow$ Robust stability test

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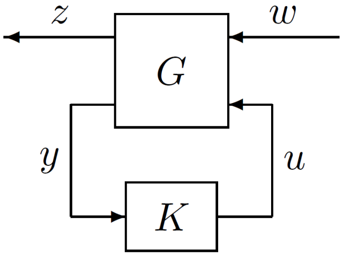
- Requires to represent uncertainty
  - Margins
  - Model set for the system's transfer function
- Small-gain theorem $\rightarrow$ Robust stability test
- Additional sufficient conditions for robust performance

Robust synthesis

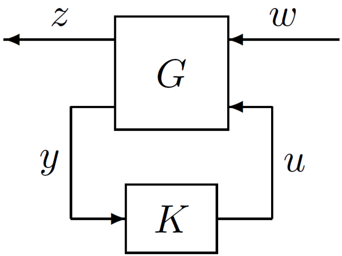
$\mathcal{H}_\infty$-synthesis



- **Optimal $\mathcal{H}_\infty$ Control**: Find all admissible controllers $K(s)$ such that $\|T_{z\omega}\|_\infty$ is minimized.

Robust synthesis

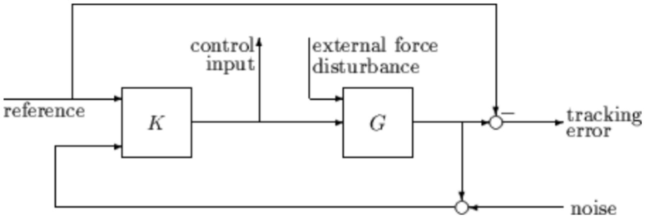
$\mathcal{H}_\infty$-synthesis



- **Optimal $\mathcal{H}_\infty$ Control**: Find all admissible controllers $K(s)$ such that $\|T_{z\omega}\|_\infty$ is minimized.
- **Suboptimal $\mathcal{H}_\infty$ Control**: Given $\gamma > 0$, find all admissible controllers $K(s)$ such that $\|T_{z\omega}\|_\infty < \gamma$.

Robust synthesis

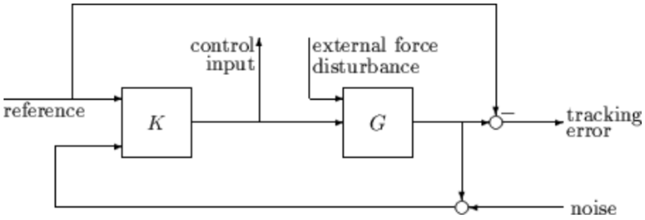
$\mathcal{H}_\infty$-synthesis



- Tracking
- Disturbance rejection
- Measurement noise
- Moderate command signal

Robust synthesis

$\mathcal{H}_\infty$-synthesis



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$\Rightarrow$ regulated variables = T(external signals)

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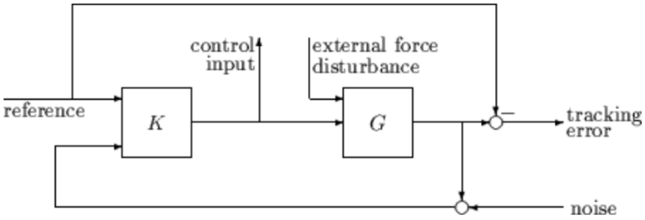

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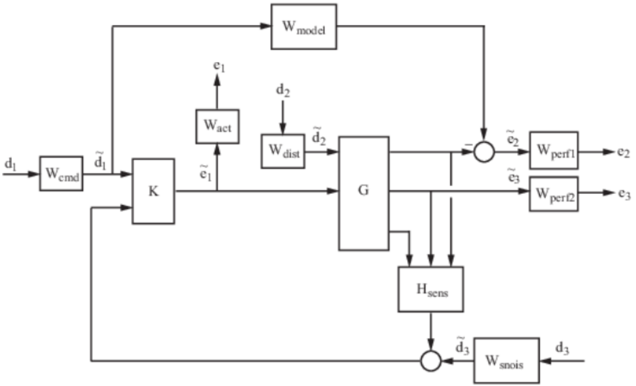
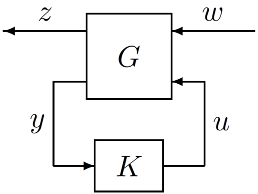
Performance as Generalized Disturbance Rejection

Generalized and Weighted Performance Block Diagram

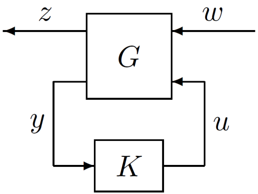


Use of weights to handle magnitudes and frequency dependency



Resolution

- Matlab Robust control toolbox:
  K,CL,gamma= hinfsyn(P,nmeas,ncont,gam)



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  - Riccati

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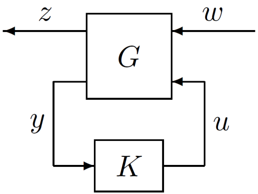

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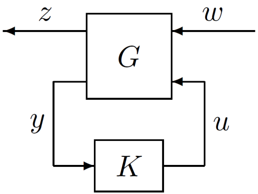
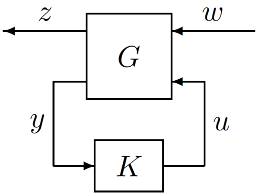
  - LMIs



Resolution

- Matlab Robust control toolbox: K,CL,gamma= hinfsyn(P,nmeas,ncont,gam)
  - Riccati
  - LMIs
- K has the same order than P + centralized structure



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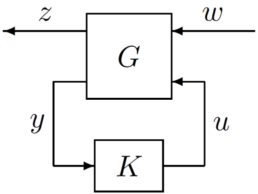
$\rightarrow$ structured version with hinfstruct



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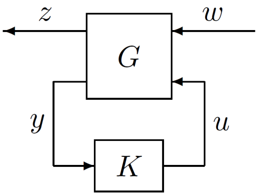
$\rightarrow$ structured version with hinfstruct

$\rightarrow$ Controller reduction



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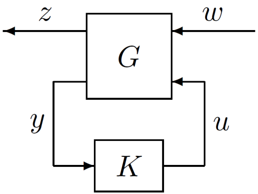
- Difficulty to tune the weights



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$\rightarrow$ structured version with hinfstruct

$\rightarrow$ Controller reduction

- Difficulty to tune the weights

$\rightarrow$ Use systune : Specify only high-level design requirements (reference tracking, overshoot, disturbance rejection, or open-loop stability margins)

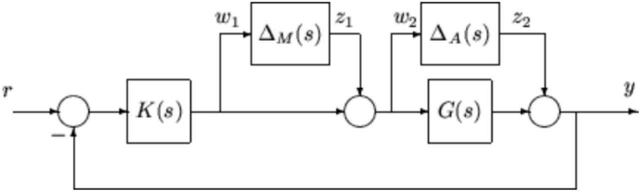
Further reading

1. Riccati approach
   - Doyle, J.C., K. Glover, P. Khargonekar, and B. Francis. *State-space solutions to standard $\mathcal{H}_2$ and $\mathcal{H}_\infty$ control problems.* IEEE Transactions on Automatic Control, 1989.
2. LMI approach
   - Gahinet, P., and P. Apkarian. *A linear matrix inequality approach to $\mathcal{H}_\infty$-control.* International Journal of Robust and Nonlinear Control, 1994.
3. Structured $\mathcal{H}_\infty$-controller design
   - P. Apkarian and D. Noll, *Nonsmooth H-infinity Synthesis*, IEEE Transactions on Automatic Control, 2006.

Robust synthesis

$\mathcal{H}_\infty$-synthesis

Robustness in the $\mathcal{H}_\infty$ framework



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$\mathcal{H}_\infty$-synthesis

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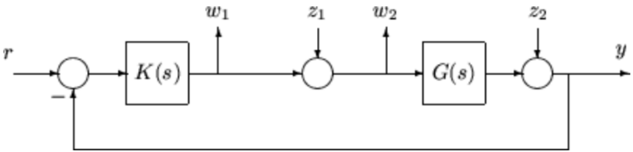

- Keep $T_{z_1\omega_1}$ and $T_{z_2\omega_2}$ small
- Robustness objectives = additional ”disturbance to error” transfer functions to be kept small

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Glover-McFarlane Method
Step 1: Loop-shaping

Considering the nominal plant P, shape the desired open-loop through a precompensator W_1 and a postcompensator W_2

$$P_s = W_2 P W_1$$

Typical good open-loop design

- Large gain in the low frequency region (disturbance rejection)

$$\underline{\sigma}(PK) >> 1$$

- Small gain in the high frequency region:

$$\overline{\sigma}(PK) << 1$$

Glover-McFarlane Method
Step 2: Robust stabilization

- Normalize coprime factorization $P_s = M^{-1}N$

Glover-McFarlane Method
Step 2: Robust stabilization

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- Uncertainty $P_\Delta = (M + \Delta_M)^{-1}(N + \Delta_N)$ with $\Delta_M, \Delta_N \in \mathcal{RH}_\infty$ and $\|[\Delta_M, \Delta_N]\|_\infty < \varepsilon$

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Glover-McFarlane Method
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$$\left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + P_s K)^{-1} M^{-1} \right\|_\infty \leq \frac{1}{\varepsilon}$$

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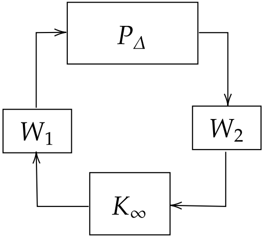
$\rightarrow$ you want to have ε as big as possible. If ε_{max} is not big enough, redesign W_1 and W_2

Glover-McFarlane Method
Step 3: Combine loop-shaping and robust stabilization



- Synthesize a controller K_∞ satisfying

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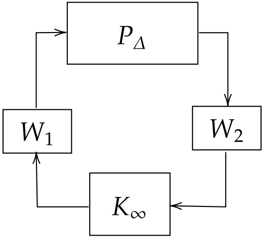

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- The final controller is given by

$$K = W_1 K_\infty W_2$$

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Glover-McFarlane Method

- McFarlane, D.C., and K. Glover, *A Loop Shaping Design Procedure using Synthesis*, IEEE Transactions on Automatic Control, 1992
- Zhou, K., Doyle, J. C., *Essentials of robust control*, 1998

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Motivations:

- Loopshaping is done without handling closed-loop stability requirements.
- Robust stabilization is done without frequency weighting.

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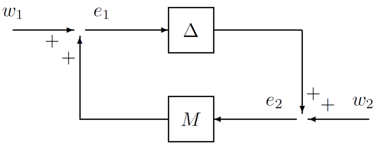
Motivations:

- Loopshaping is done without handling closed-loop stability requirements.
- Robust stabilization is done without frequency weighting.
- ε is a measure of both closed-loop robust stability and the success of the design in meeting the loop-shaping specifications.

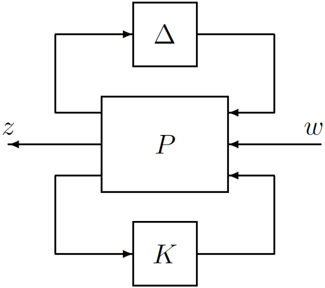
Uncertainty may be modeled in two ways:

- as external inputs

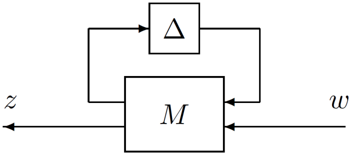


Uncertainty may be modeled in two ways:

- as external inputs
- as perturbations to the nominal model

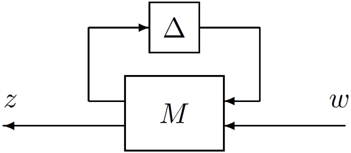


Analysis framework



Δ is a structured block

Analysis framework



Δ is a structured block

μ-analysis

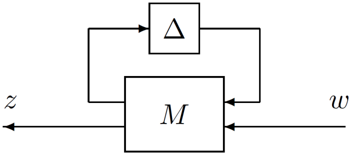
Let $\beta > 0$. Then this interconnected system is well-posed and internally stable for all $\Delta(s) \in \mathcal{M}(\Delta)$ with $\|\Delta\|_\infty \leq 1/\beta$, and $\|\mathcal{F}(N, \Delta)\|_\infty \leq \beta$, if and only if

$$\sup_{\omega \in \mathbb{R}} \mu_\Delta(M(j\omega)) \leq \beta$$

Robust synthesis

μ-analysis and synthesis

Analysis framework



Δ is a structured block

- $\mathcal{F}(N, \Delta)$ is the transfer from ω to z
- μ_Δ is defined as

$$\mu_\Delta(M) = \frac{1}{\min\{\overline{\sigma}(\Delta) : \Delta \in \mathcal{M}(\Delta), \det(I - M\Delta) = 0\}}$$

unless no Δ makes $I - M\Delta$ singular, in which case $\mu_\Delta(M) = 0$.

μ-synthesis

$\rightarrow$ Iterative process called D-K iteration

1. Uses $\mathcal{H}_\infty$-synthesis to find a controller that minimizes the closed-loop gain of the nominal system.

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Robust synthesis

μ-analysis and synthesis

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Extremely computationally demanding!

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