FRTN10 Multivariable Control, Lecture 13

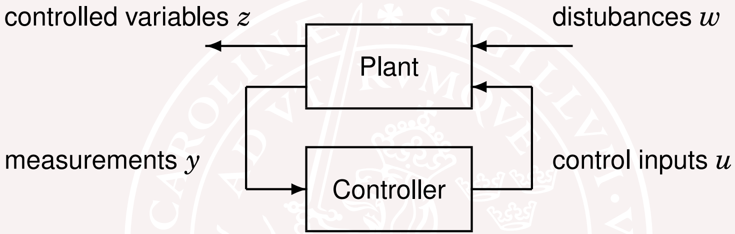
Anders Robertsson

Automatic Control LTH, Lund University

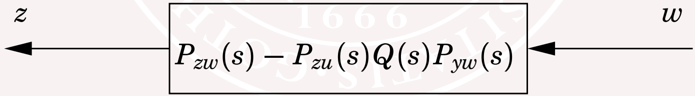
Course outline

- L1-L5 Purpose, models and loop-shaping by hand
- L6-L8 Limitations on achievable performance
- L9-L11 Controller optimization: Analytic approach
- L12-L14 Controller optimization: Numerical approach
  - L12 Youla parameterization, Internal Model Control
  - L13 **Synthesis by convex optimization**
  - L14 Controller simplification
- L15 Summary

The Q-parametrization (Youla)



Idea for lecture 12-14:
The choice of controller generally corresponds to finding $Q(s)$, to get desirable properties of the map from w to z:



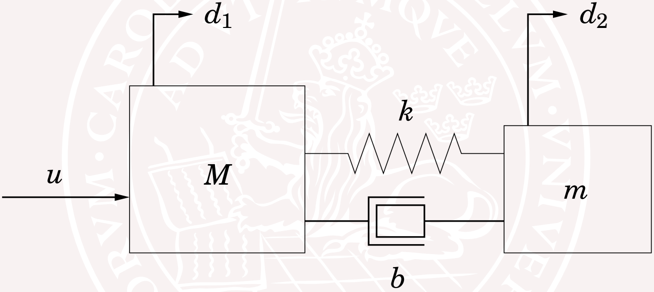
Once $Q(s)$ is determined, a corresponding controller is derived.

Lecture 13: Synthesis by Convex Optimization

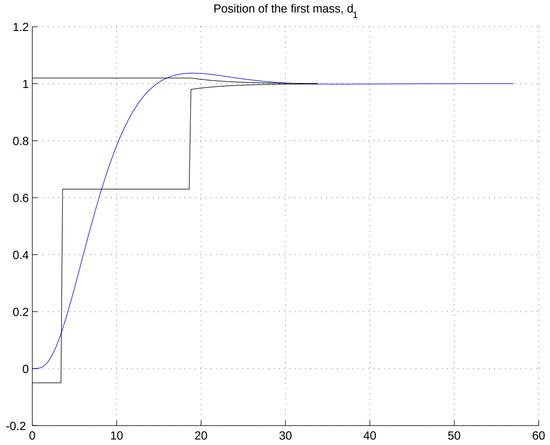
- **Example: Spring-mass system**
- Introduction to convex optimization
- Controller optimization using Youla parametrization
- Examples revisited

Most of this lecture is based on source material from Boyd, Vandenberghe and coauthors. See
http://www.control.lth.se/Education/EngineeringProgram/FRTN10.html

Example: Spring-mass System

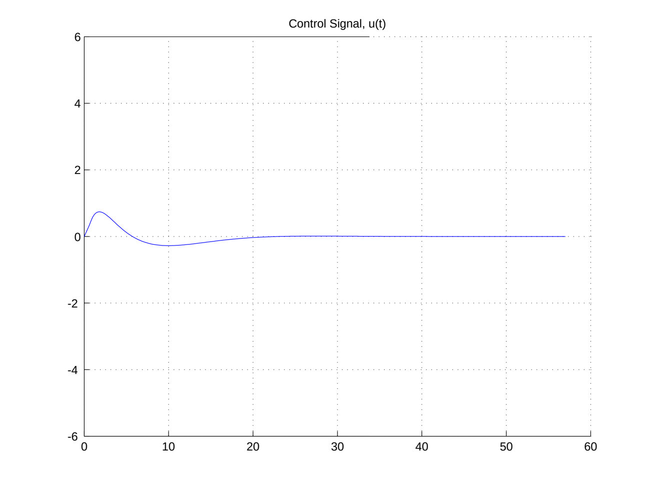


Lecture 13: Synthesis by Convex Optimization



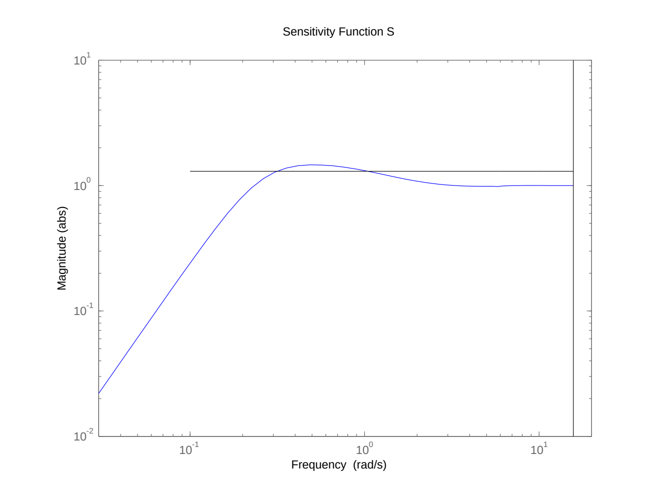
The step response is not within its upper and lower bounds.

Lecture 13: Synthesis by Convex Optimization



The step input stays within its amplitude bound $|u(t)| \leq 6$.

Lecture 13: Synthesis by Convex Optimization



The sensitivity does not satisfy the magnitude bound $|S| \leq 1.3$

Lecture 13: Synthesis by Convex Optimization

- ◦ Example: Spring-mass system
- • **Introduction to convex optimization**
- ◦ Controller optimization using Youla parametrization
- ◦ Examples revisited

Most of this lecture is based on source material from Boyd, Vandenberghe and coauthors. See
http://www.control.lth.se/Education/EngineeringProgram/FRTN10.html

Least-squares

$$\text{minimize} \quad \|Ax - b\|_2^2$$

solving least-squares problems

- analytical solution: $x^\star = (A^T A)^{-1} A^T b$
- reliable and efficient algorithms and software
- computation time proportional to $n^2 k$ ($A \in \mathbf{R}^{k \times n}$); less if structured
- a mature technology

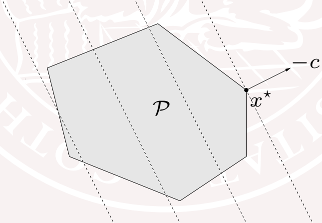
using least-squares

- least-squares problems are easy to recognize
- a few standard techniques increase flexibility ($e.g.$, including weights, adding regularization terms)

Linear program (LP)

$$
\begin{array}{ll}
\text{minimize} & c^T x + d \\
\text{subject to} & Gx \preceq h \\
& Ax = b
\end{array}
$$

- convex problem with affine objective and constraint functions
- feasible set is a polyhedron



Linear programming

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & a_i^T x \leq b_i, \quad i = 1, \ldots, m \end{array}$$

solving linear programs

- no analytical formula for solution
- reliable and efficient algorithms and software
- computation time proportional to $n^2 m$ if $m \geq n$; less with structure
- a mature technology

using linear programming

- not as easy to recognize as least-squares problems
- a few standard tricks used to convert problems into linear programs ($e.g.$, problems involving ℓ_1- or ℓ_∞-norms, piecewise-linear functions)

Convex optimization problem

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq b_i, \quad i = 1, \ldots, m \end{array}$$

- objective and constraint functions are convex:

$$f_i(\alpha x + \beta y) \leq \alpha f_i(x) + \beta f_i(y)$$

if $\alpha + \beta = 1$, $\alpha \geq 0$, $\beta \geq 0$

- includes least-squares problems and linear programs as special cases

solving convex optimization problems

- no analytical solution
- reliable and efficient algorithms
- computation time (roughly) proportional to $\max\{n^3, n^2m, F\}$, where F is cost of evaluating f_i's and their first and second derivatives
- almost a technology

using convex optimization

- often difficult to recognize
- many tricks for transforming problems into convex form
- surprisingly many problems can be solved via convex optimization

Brief history of convex optimization

theory (convex analysis): ca1900–1970

algorithms

- 1947: simplex algorithm for linear programming (Dantzig)
- 1960s: early interior-point methods (Fiacco & McCormick, Dikin, . . .)
- 1970s: ellipsoid method and other subgradient methods
- 1980s: polynomial-time interior-point methods for linear programming (Karmarkar 1984)
- late 1980s–now: polynomial-time interior-point methods for nonlinear convex optimization (Nesterov & Nemirovski 1994)

applications

- before 1990: mostly in operations research; few in engineering
- since 1990: many new applications in engineering (control, signal processing, communications, circuit design, . . .); new problem classes (semidefinite and second-order cone programming, robust optimization)

Examples on R

convex:

- affine: $ax + b$ on **R**, for any $a, b \in$ **R**
- exponential: e^{ax}, for any $a \in$ **R**
- powers: x^α on $\mathbf{R}_{++}$, for $\alpha \geq 1$ or $\alpha \leq 0$
- powers of absolute value: $|x|^p$ on **R**, for $p \geq 1$
- negative entropy: $x \log x$ on $\mathbf{R}_{++}$

concave:

- affine: $ax + b$ on **R**, for any $a, b \in$ **R**
- powers: x^α on $\mathbf{R}_{++}$, for $0 \leq \alpha \leq 1$
- logarithm: $\log x$ on $\mathbf{R}_{++}$

Examples on $\mathbf{R}^n$ and $\mathbf{R}^{m\times n}$

affine functions are convex and concave; all norms are convex

examples on $\mathbf{R}^n$

- affine function $f(x) = a^T x + b$
- norms: $\|x\|_p = (\sum_{i=1}^n |x_i|^p)^{1/p}$ for $p \geq 1$; $\|x\|_\infty = \max_k |x_k|$

examples on $\mathbf{R}^{m\times n}$ ($m \times n$ matrices)

- affine function

$$f(X) = \mathbf{tr}(A^T X) + b = \sum_{i=1}^{m} \sum_{j=1}^{n} A_{ij} X_{ij} + b$$

- spectral (maximum singular value) norm

$$f(X) = \|X\|_2 = \sigma_{\max}(X) = (\lambda_{\max}(X^T X))^{1/2}$$

Convex optimization problem

standard form convex optimization problem

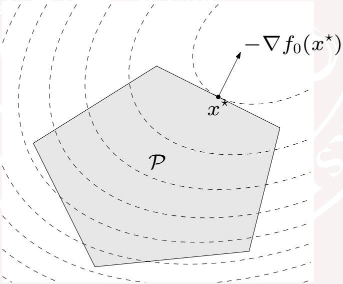
$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & a_i^T x = b_i, \quad i = 1, \ldots, p \end{array}$$

- f_0, f_1, . . . , f_m are convex; equality constraints are affine
- problem is *quasiconvex* if f_0 is quasiconvex (and f_1, . . . , f_m convex)

Quadratic program (QP)

$$\begin{array}{ll} \text{minimize} & (1/2)x^T P x + q^T x + r \\ \text{subject to} & Gx \preceq h \\ & Ax = b \end{array}$$

- $P \in \mathbf{S}^n_+$, so objective is convex quadratic
- minimize a convex quadratic function over a polyhedron



Second-order cone programming

$$\begin{array}{ll} \text{minimize} & f^T x \\ \text{subject to} & \|A_i x + b_i\|_2 \le c_i^T x + d_i, \quad i = 1, \ldots, m \\ & Fx = g \end{array}$$

($A_i \in \mathbf{R}^{n_i \times n}$, $F \in \mathbf{R}^{p \times n}$)

Semidefinite program (SDP)

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & x_1 F_1 + x_2 F_2 + \cdots + x_n F_n + G \preceq 0 \\ & Ax = b \end{array}$$

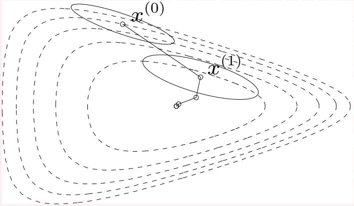
with F_i, $G \in \mathbf{S}^k$

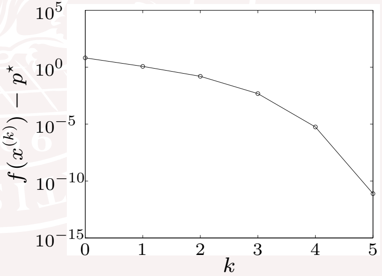
- inequality constraint is called linear matrix inequality (LMI)

Newton's method

given a starting point $x \in \textbf{dom}\, f$, tolerance $\epsilon > 0$.
repeat

1. *Compute the Newton step and decrement.*
   $$\Delta x_{\text{nt}} := -\nabla^2 f(x)^{-1} \nabla f(x); \quad \lambda^2 := \nabla f(x)^T \nabla^2 f(x)^{-1} \nabla f(x).$$
2. *Stopping criterion.* **quit** if $\lambda^2/2 \leq \epsilon$.
3. *Line search.* Choose step size t by backtracking line search.
4. *Update.* $x := x + t\Delta x_{\text{nt}}$.





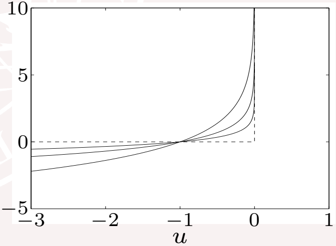
Barrier method for constrained minimization

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0 \quad 1 = 1, \ldots, m \\ & Ax = b \end{array}$$

approximation via logarithmic barrier

$$\begin{array}{ll} \text{minimize} & f_0(x) - (1/t) \sum_{i=1}^{m} \log(-f_i(x)) \\ \text{subject to} & Ax = b \end{array}$$

- an equality constrained problem
- for $t > 0$, $-(1/t)\log(-u)$ is a smooth approximation of I_-
- approximation improves as $t \to \infty$



Outline

- ∘ Example: Spring-mass system
- ∘ Introduction to convex optimization
- • **Controller optimization using Youla parametrization**
- ∘ Examples revisited

Scheme for numerical optimization of Q

Given some fixed set of basis function $\phi_0(s), \dots, \phi_N(s)$, we will search numerically for matrices $Q_0, \dots, Q_N$ such that the closed loop transfer matrix $G_{zw}(s)$ satisfies given specifications when

$$G_{zw}(s) = P_{zw}(s) - P_{zu}(s)Q(s)P_{yw}(s) \qquad \text{and } Q(s) = \sum_{k=0}^{N} Q_k \phi_k(s)$$

Once $Q(s)$ has been determined, we will recover the desired controller from the formula

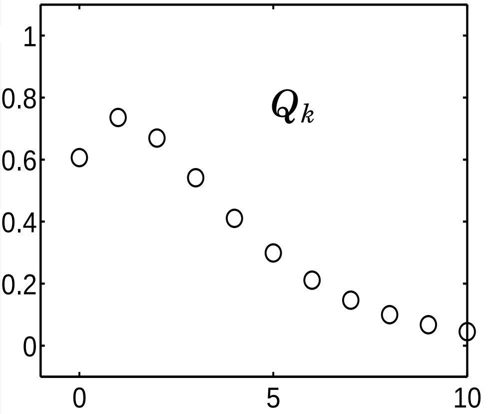
$$C(s) = \left[I - Q(s)P_{yu}(s)\right]^{-1} Q(s)$$

It is possible to choose the sequence $\phi_0(s), \phi_1(s), \phi_2(s), \dots$ such that every stable Q can be approximated arbitrarily well. Hence, in principle, every convex control design problem can be solved this way.

But, what specifications give a convex design problem?

Pulse response parameterization

We will use an intuitively simple parametrization of $Q(s)$ where each parameter Q_k represents a point on the corresponding impulse response in time domain.

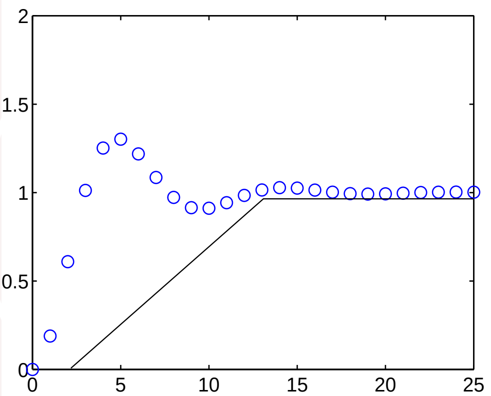


Mini-problem

Which specifications are convex constraints on Q_k?

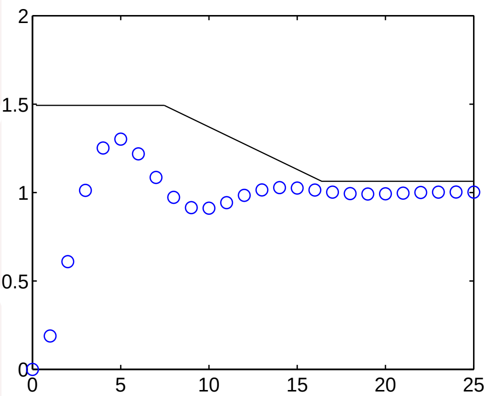
1. Stability of the closed loop system
2. Lower bound on step response from w_i to z_j at time t_i
3. Upper bound on step response from w_i to z_j at time t_i
4. Lower bound on Bode amplitude from w_i to z_j at frequency ω_i
5. Upper bound on Bode amplitude from w_i to z_j at frequency ω_i
6. Interval bound on Bode phase from w_i to z_j at frequency ω_i

Lower bound on step response



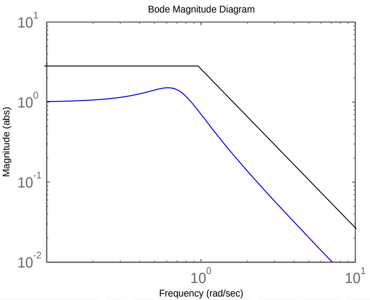
The step response depends linearly on Q_k, so every time t_k with a lower bound gives a linear constraint.

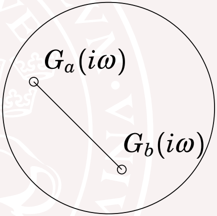
Upper bound on step response



Every time t_k with an upper bound also gives a linear constraint.

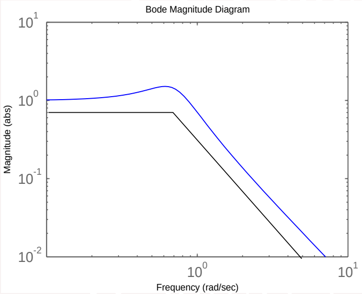
Upper bound on Bode amplitude

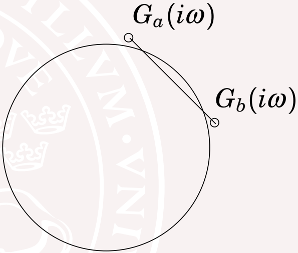




An amplitude bound $|G(i\omega_i)| < c$ is a quadratic constraint.

Lower bound on Bode amplitude





An lower bound $|G(i\omega_i)|$ is a *non-convex* quadratic constraint. This should be avoided in optimization.

Synthesis by convex optimization

A general control synthesis problem can be stated as a convex optimization problem in the variables $Q_0, \dots, Q_m$. The problem has a quadratic objective, with linear and quadratic constraints:

$$\text{Minimize} \quad \int_{-\infty}^{\infty} |P_{zw}(i\omega) + P_{zu}(i\omega) \overbrace{\sum_k Q_k \phi_k(i\omega)}^{Q(i\omega)} P_{yw}(i\omega)|^2 d\omega \quad \Big\} \text{ quadratc objective}$$

subject to

- step response $w_i \rightarrow z_j$ is smaller than f_{ijk} at time t_k
- step response $w_i \rightarrow z_j$ is bigger than g_{ijk} at time t_k

} linear constraints

- Bode magnitude $w_i \rightarrow z_j$ is smaller than h_{ijk} at ω_k

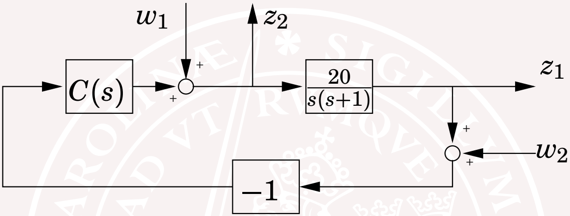
} quadratic constraints

Once the variables $Q_0, \dots, Q_m$ have been optimized, the controller is obtained as $C(s) = \left[I - Q(s)P_{yu}(s)\right]^{-1} Q(s)$

Outline

- ◦ Example: Spring-mass system
- ◦ Introduction to convex optimization
- ◦ Controller optimization using Youla parametrization
- • **Examples revisited**

Example — DC-motor



The transfer matrix from (w_1, w_2) to (z_1, z_2) is

$$G_{zw}(s) = \begin{bmatrix} \frac{P}{1+PC} & \frac{-PC}{1+PC} \\ \frac{1}{1+PC} & \frac{-C}{1+PC} \end{bmatrix}$$

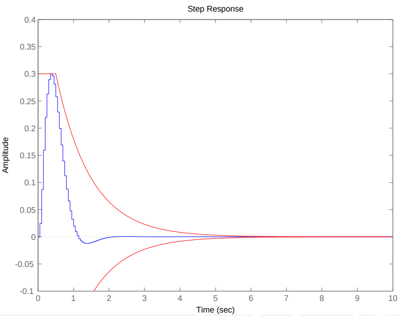
with $P(s) = \frac{20}{s(s+1)}$. We will choose $C(s)$ to minimize

$$\text{trace} \int_{-\infty}^{\infty} G_{zw}(i\omega) G_{zw}(i\omega)^* d\omega$$

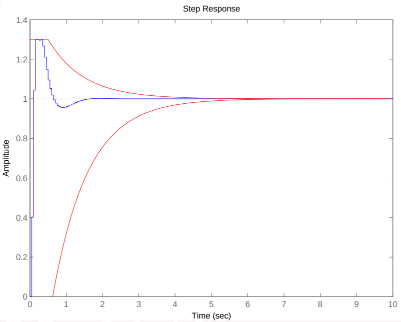
subject time-domain bounds.

DC-servo with time domain bounds

Input step disturbance



Reference step

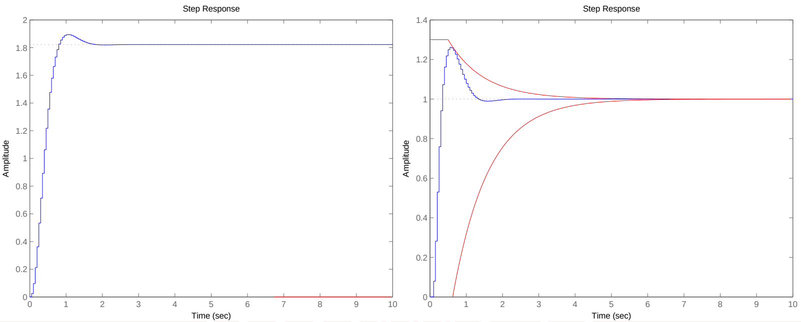


What if we remove the upper bound on the response to input disturbances ?

DC-servo with time domain bounds

Input step disturbance

Reference step



The integral action in the controller is lost, just as in lecture 11!

Summary

- There are efficient algorithms for convex optimization, e.g.
  - Linear programming (LP)
  - Quadratic programming (QP)
  - Second order cone programming (SOCP)
  - Semi-definite programming (SDP)
- The Youla parametrization allows us to use these algorithms for control synthesis
- Resulting controllers have high order. Order reduction will be studied in the next lecture.

Course outline

- L1-L5 Purpose, models and loop-shaping by hand
- L6-L8 Limitations on achievable performance
- L9-L11 Controller optimization: Analytic approach
- L12-L14 Controller optimization: Numerical approach
  - L12 Youla parameterization, Internal Model Control
  - L13 Synthesis by convex optimization
  - L14 Controller simplification