Low-rank approximation problems in system identification

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Aims of the lecture

- review system identification from the perspective of

  linear algebra

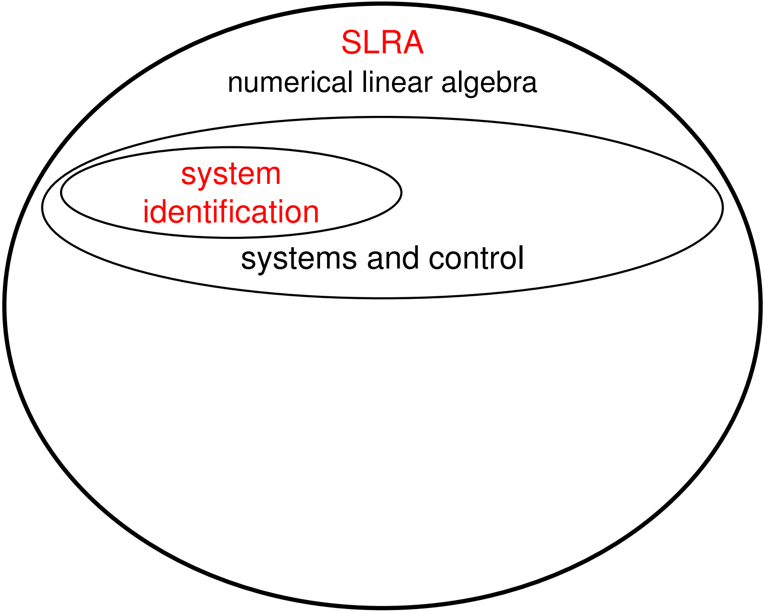
- this leads to a core computational problem:

  (SLRA) *approximate a structured matrix by a low-rank matrix with the same structure*

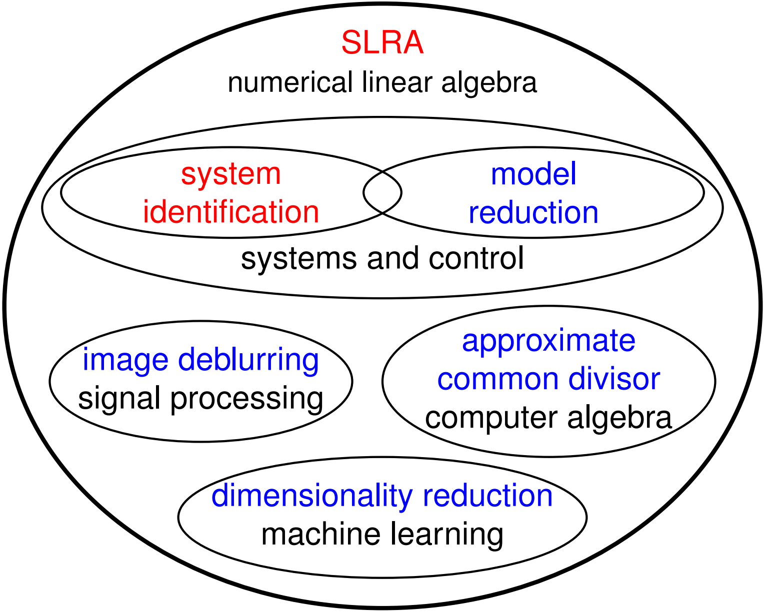
- outline solution approaches and an application to

  model-free control

Scope of structured low-rank approximation



Scope of structured low-rank approximation



Outline

Introduction: data, model class, approximation

Approximation error–model complexity trade-off

System identification $\leftrightarrow$ low-rank approximation

Solution methods: variable projection

Example: model-free control

Conclusions

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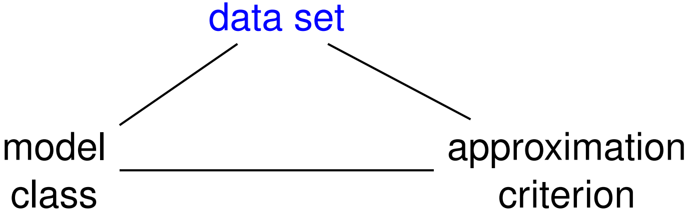
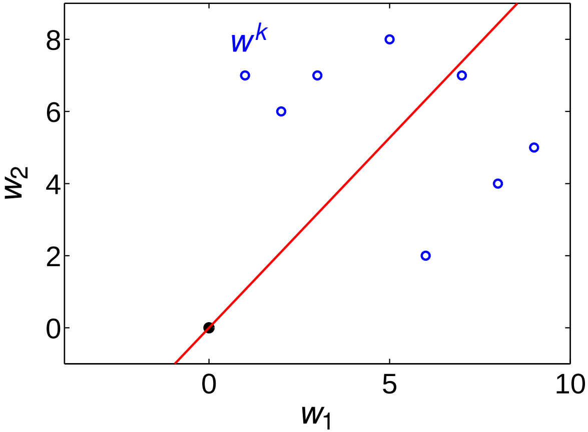
First is the data . . .



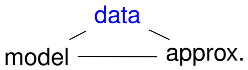
Line fitting (linear static model)

data
model —— approx.

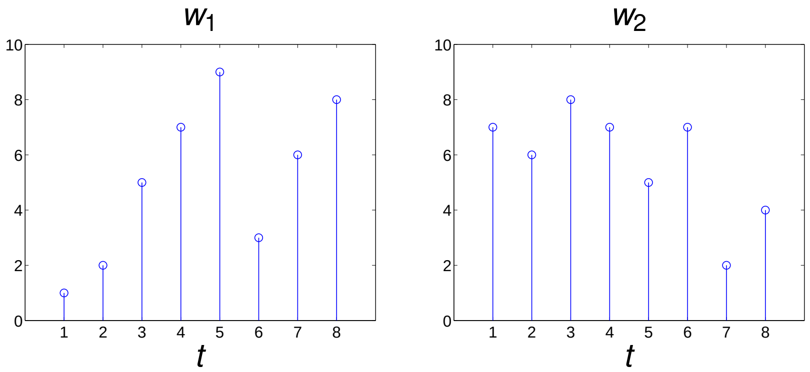
$w^1, \ldots, w^N$ — data points (the order is not important)



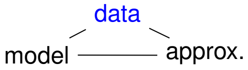
Time series data (dynamic model)



$w(1), \ldots, w(T)$ — samples in time (the order is important)



Summary: data

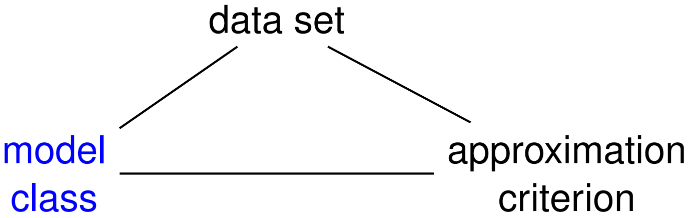


- the data is a set $w = \{w^1, \dots, w^N\}$
- of vector valued $w^k = \begin{bmatrix} w_1^k \\ \vdots \\ w_q^k \end{bmatrix}$
- time series $w_i^k = \big(w_i^k(1), \dots, w_i^k(T_k)\big)$

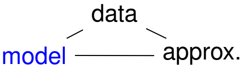
  N — # of repeated experiments
  q — # of variables
  T_k — # of time samples in the kth exp.

- in static problems, $T_1 = \cdots = T_N = 1$

Next is the model class . . .

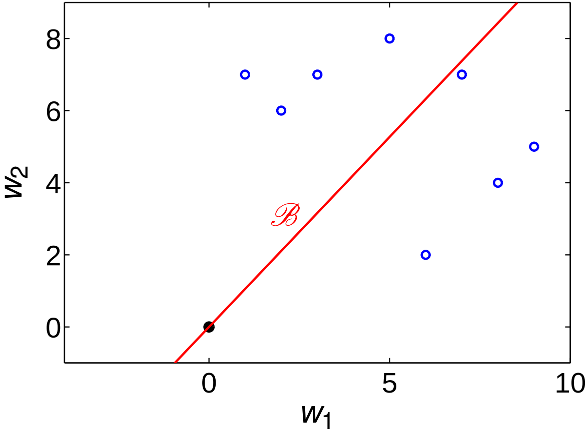


Line fitting (linear static model)

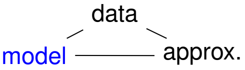


$\mathscr{B}$ — model: line through the origin

$\mathscr{M}$ — model class: all lines through the origin

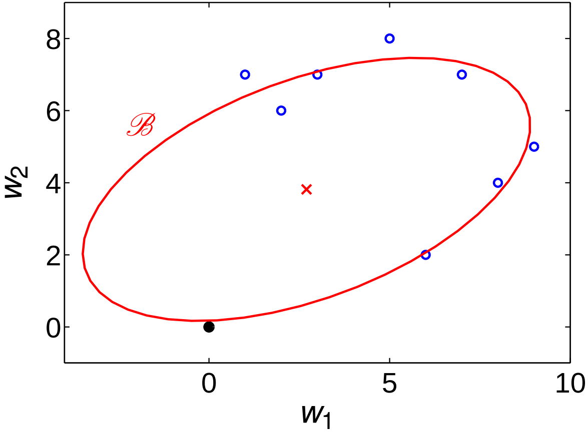


Conic section fitting (quadratic static model)

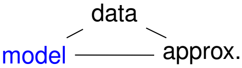


$\mathscr{B}$ — model: conic section

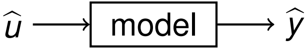
$\mathscr{M}$ — model class: all conic sections

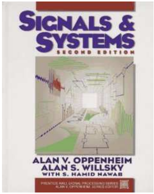


Classical definition of dynamical model



- dynamical model is signal processor

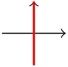
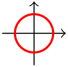




- specified by a map $\widehat{y} = f(\widehat{u})$

- "state space model", "transfer function model", ...

- however, lines and conic sections may not be graphs

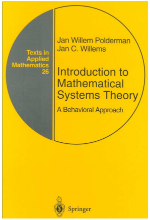
- *e.g.*,  ,  can't be represented by $f : \widehat{u} \mapsto \widehat{y}$

"good definition should formalize sensible intuition"

Jan Willems, Paradigms and puzzles, TAC'91

Behavioral definition of model

data
model —— approx.



- a model is a subset

$$\mathscr{B} = \{\, \widehat{w} \mid g(\widehat{w}) = 0 \text{ holds} \,\}$$

- represented by an implicit function g

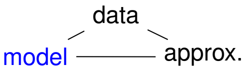
- in the static case, $g(\widehat{w}) = 0$ is algebraic equation

- in the dynamic case, $g(\widehat{w}) = 0$ is difference equation

- $\widehat{w} = \begin{bmatrix} \widehat{u} \\ \widehat{y} \end{bmatrix}$, $\widehat{y} = f(\widehat{u})$ is a special case of $g(\widehat{w}) = 0$

$$(g(\widehat{u}, \widehat{y}) = \widehat{y} - f(\widehat{u}))$$

Summary: model



- three data modeling examples:

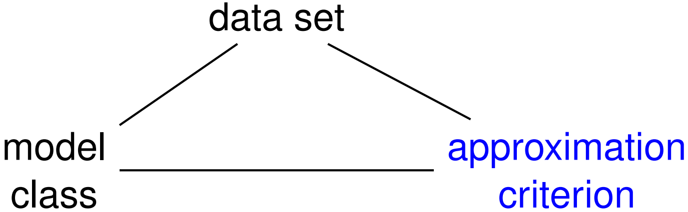
problem	model
line fitting	static linear
conic section fitting	static nonlinear
system identification	dynamic

- two definitions of a model:

classical	behavioral
map $\widehat{y} = f(\widehat{u})$	set $\{\, \widehat{w} \mid g(\widehat{w}) = 0 \,\}$
f — function	g — relation

- the classical one can not deal with all examples

Finally, the approximation criterion . . .

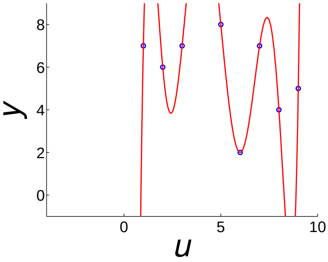


Exact model

$$w \subset \mathscr{B} \quad \Longleftrightarrow \quad w^1, \ldots, w^N \in \mathscr{B}$$
$$\Longleftrightarrow: \quad \text{"}w \text{ is exact data of } \mathscr{B}\text{"}$$

- two well known exact modeling problems
  - realization: LTI model class, impulse resp. data
  - interpolation: static nonlinear model class

polynomial interpolation



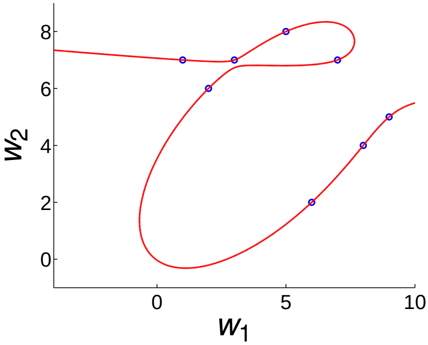
$$\mathscr{B} = \left\{ \begin{bmatrix} \widehat{u} \\ \widehat{y} \end{bmatrix} \mid \widehat{y} = f(\widehat{u}) \right\}$$

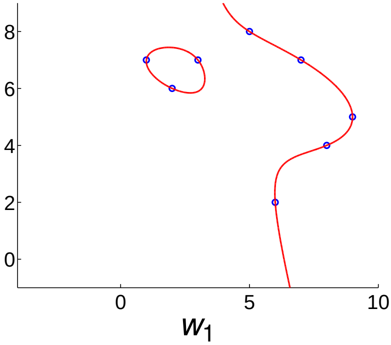
f is 8th order polynomial

Exact 3rd order nonlinear static models

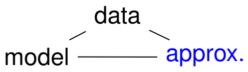
$$\mathscr{B} = \left\{ \begin{bmatrix} \widehat{w}_1 \\ \widehat{w}_2 \end{bmatrix} \;\middle|\; g(\widehat{w}_1, \widehat{w}_2) = 0 \right\}$$

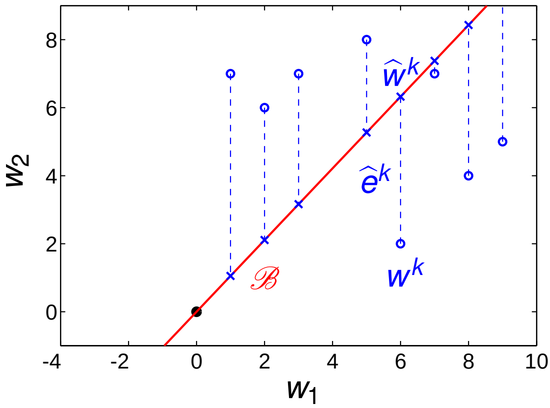
g is 3rd order polynomial in $\widehat{w}_1$, $\widehat{w}_2$





Ordinary least squares

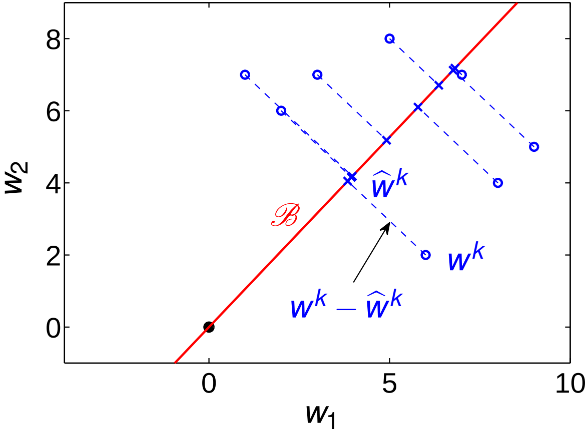


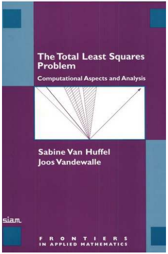


Total least squares

data

model — approx.

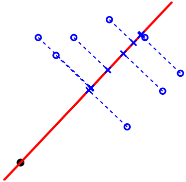




Linear static case

data

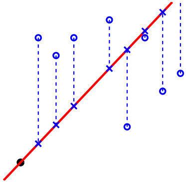
model — approx.



- total least squares

$$\min_{\widehat{u},\widehat{y},\theta} \left\| \begin{bmatrix} u-\widehat{u} & y-\widehat{y} \end{bmatrix} \right\|_{\mathrm{F}} \text{ s.t. } \underbrace{\widehat{u}\theta = \widehat{y}}_{(\widehat{u},\widehat{y})\subset\mathscr{B}(\theta)}$$

$\widehat{w} = (\widehat{u},\widehat{y})$ approximates $w = (u,y)$



- ordinary least squares

$$\min_{\widehat{e},\theta} \|\widehat{e}\|_2 \quad \text{s.t.} \quad \underbrace{u\theta = y+\widehat{e}}_{(\widehat{e},u,y)\subset\mathscr{B}_{\mathrm{ext}}(\theta)}$$

$\widehat{e}$ is unobserved (latent) input

Exact models in the approximation criteria

- Misfit approach:

  modify w as little as possible,
  so that $\widehat{w}$ is exact

  $\|w - \widehat{w}\|$ is the misfit criterion

- Latency approach:

  augment $\mathscr{B}$ by as small as possible e,
  so that (e, w) is exact

  $\|e\|$ is the latency criterion

Deterministic vs stochastic setting

data

model —— approx.

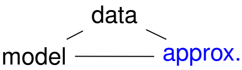
- stochastic estimation $\leftrightarrow$ deterministic approx.

noise model $\xleftrightarrow{\text{maximum likelihood}}$ cost function

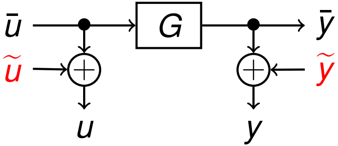
- also in control

LQG control $\leftrightarrow$ H_2 optimal control

Misfit and latency in the stochastic setting



EIV $\leftrightarrow$ misfit

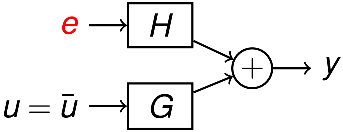


$\widetilde{u}$, $\widetilde{y}$ — measurement errors

$$\min_{\widehat{w} \subset \mathscr{B}} \|w - \widehat{w}\|$$

$$\mathscr{B} := \left\{ \begin{bmatrix} \widehat{u} \\ \widehat{y} \end{bmatrix} \mid \widehat{y} = \widehat{G}\widehat{u} \right\}$$

ARMAX $\leftrightarrow$ latency



e — disturbance

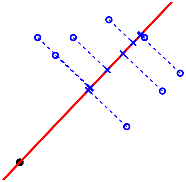
$$\min_{(\widehat{e}, w) \subset \mathscr{B}_{\text{ext}}} \|\widehat{e}\|$$

$$\mathscr{B}_{\text{ext}} := \left\{ \begin{bmatrix} \widehat{e} \\ u \\ y \end{bmatrix} \mid y = [\widehat{H} \ \widehat{G}] \begin{bmatrix} \widehat{e} \\ u \end{bmatrix} \right\}$$

Summary: approximation criterion

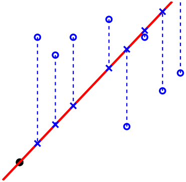
data

model —— approx.



- TLS $\leftrightarrow$ misfit $\leftrightarrow$ errors-in-variables

$$\min_{\widehat{w} \subset \mathscr{B}} \; \|w - \widehat{w}\| \qquad \left(\begin{array}{c} \text{projection} \\ \text{of } w \text{ on } \mathscr{B} \end{array} \right)$$



- OLS $\leftrightarrow$ latency $\leftrightarrow$ ARMAX

$$\min_{(\widehat{e}, w) \in \mathscr{B}_{\text{ext}}} \; \|\widehat{e}\|$$

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A general problem

$$\begin{array}{ccc} \text{data} & \xrightarrow{\text{identification}} & \text{model} \\ w & & \mathscr{B} \in \mathscr{M} \end{array}$$

the aim is to obtain "simple" and "accurate" model:

"accurate" $\rightarrow$ min. error$(w, \widehat{\mathscr{B}})$ = misfit/latency

"simple" $\rightarrow$ Occam's razor principle:
among equally accurate models,
choose the simplest

Model complexity

- simple models are small models

$$\mathscr{B}_1 \subset \mathscr{B}_2 \quad \Longrightarrow \quad \mathscr{B}_1 \text{ is simpler than } \mathscr{B}_2$$

- nonlinear model complexity is an open problem

- in the linear time-invariant case, $\mathscr{B}$ is a subspace

$$\text{size of the model} = \text{dimension of } \mathscr{B}$$

- however, models with inputs are infinite dimensional

Linear time-invariant model's complexity

- restriction of $\mathscr{B}$ on an interval $[1, T]$

$$\mathscr{B}|_T = \{\, w = \big(w(1), \dots, w(T)\big) \mid \exists\, w_{\text{p}}, w_{\text{f}}, \\ \text{such that } (w_{\text{p}}, w, w_{\text{f}}) \in \mathscr{B} \,\}$$

- for sufficiently large T

$$\dim(\mathscr{B}|_T) = (\text{\# of inputs}) \cdot T + (\text{order})$$

$$\text{complexity}(\mathscr{B}) = \begin{bmatrix} \mathtt{m} \\ \ell \end{bmatrix} \begin{matrix} \rightarrow & \text{\# of inputs} \\ \rightarrow & \text{order or lag} \end{matrix}$$

- $\mathscr{L}_{\mathtt{m},\ell}$ — set of LTI systems of bounded complexity

Complexity selection

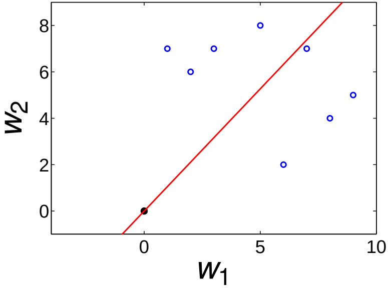
- if m is given and fixed, choosing the complexity is an

  order selection problem

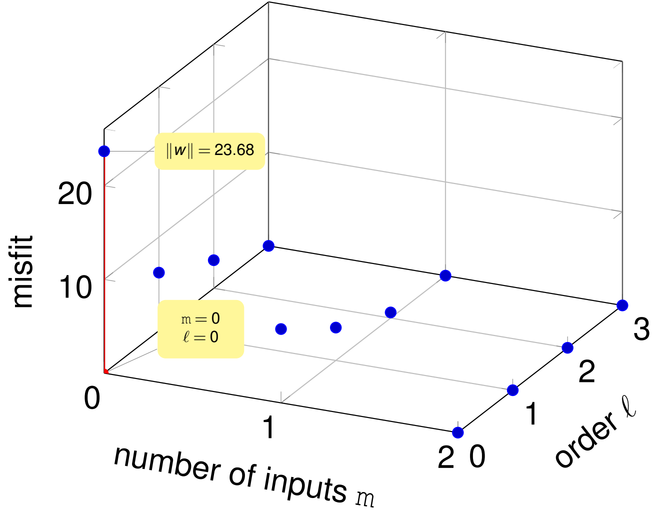
- in general, choosing the complexity involves

  order selection and input selection

  illustrated next on the example from the introduction

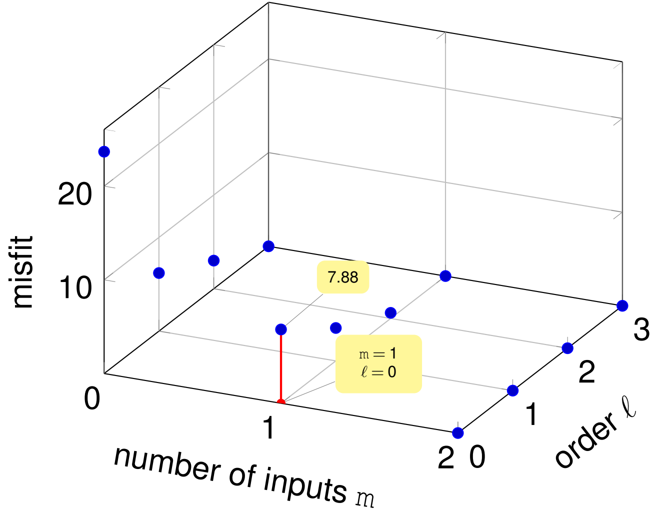


Example: misfit-complexity trade-off



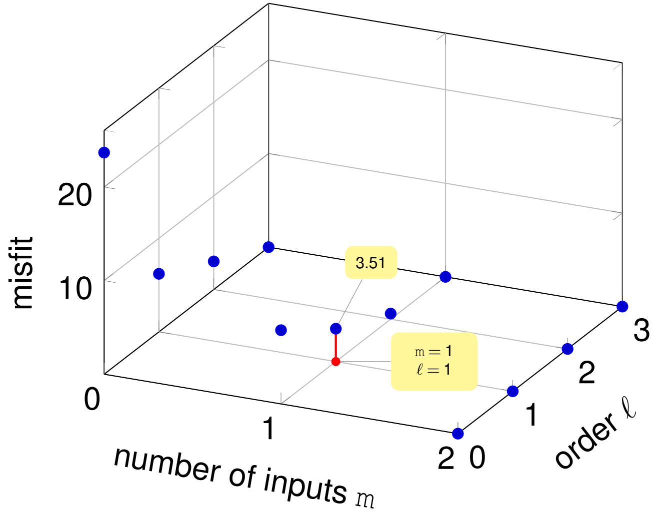
$\mathrm{m} = 0,\ \ell = 0 \implies \mathscr{B} = \{0\}$ is the only model

Example: misfit-complexity trade-off



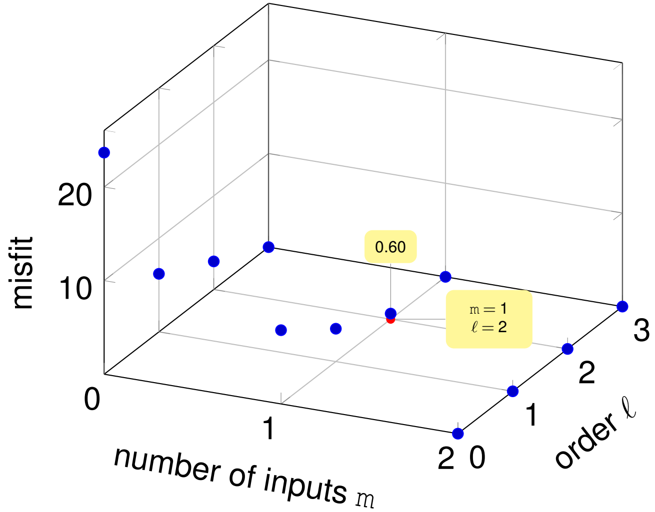
$\mathrm{m} = 1,\ \ell = 0 \implies \mathscr{B}$ is a line through 0

Example: misfit-complexity trade-off



$\mathrm{m} = 1,\ \ell = 1 \implies \mathscr{B}$ is 1st order SISO

Example: misfit-complexity trade-off



$\mathtt{m} = 1$, $\ell = 2 \implies \mathscr{B}$ is 2nd order SISO

Approximation error-complexity trade-off

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}} \in \mathscr{L} \quad \begin{bmatrix} \text{error}(w, \widehat{\mathscr{B}}) \\ \text{complexity}(\widehat{\mathscr{B}}) \end{bmatrix}$$

three ways to "scalarize" the problem:

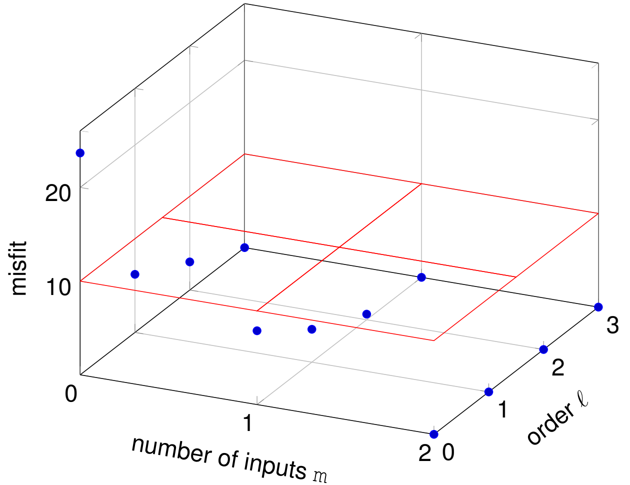
1. minimize over $\widehat{\mathscr{B}} \in \mathscr{L}$ $\text{error}(w, \widehat{\mathscr{B}}) + \lambda\, \text{complexity}(\widehat{\mathscr{B}})$

2. $$\begin{array}{ll} \text{minimize} & \text{over } \widehat{\mathscr{B}} \in \mathscr{L} \quad \text{complexity}(\widehat{\mathscr{B}}) \\ \text{subject to} & \text{error}(w, \widehat{\mathscr{B}}) \leq \mu \end{array}$$

3. $$\begin{array}{ll} \text{minimize} & \text{over } \widehat{\mathscr{B}} \quad \text{error}(w, \widehat{\mathscr{B}}) \\ \text{subject to} & \widehat{\mathscr{B}} \in \mathscr{L}_{\text{m},\ell} \end{array}$$

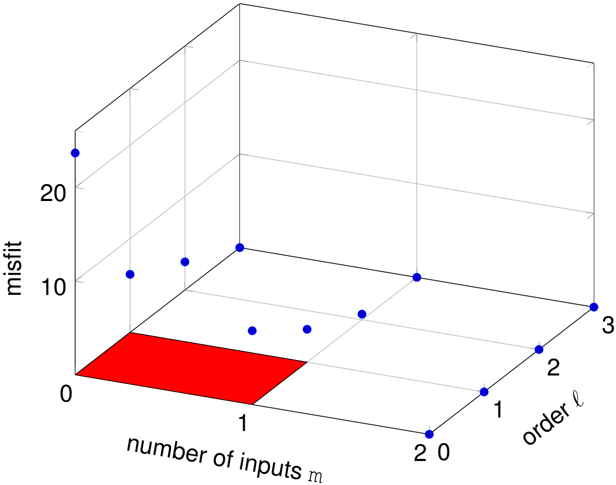
Complexity minimization with error bound

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}} \in \mathscr{L} \quad \text{complexity}(\widehat{\mathscr{B}})$$
$$\text{subject to} \quad \text{error}(w, \widehat{\mathscr{B}}) \leq \mu$$



Error minimization with complexity bound

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}} \quad \text{error}(w, \widehat{\mathscr{B}})$$
$$\text{subject to} \quad \widehat{\mathscr{B}} \in \mathscr{L}_{\mathtt{m},\ell}$$



Summary: error-complexity trade-off

- LTI model complexity

$$\text{complexity}(\mathscr{B}) = \begin{bmatrix} \mathtt{m} \\ \ell \end{bmatrix} \begin{array}{ll} \to & \text{\# of inputs} \\ \to & \text{order or lag} \end{array}$$

- error-complexity trade-off

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}} \in \mathscr{L} \quad \begin{bmatrix} \text{error}(w, \widehat{\mathscr{B}}) \\ \text{complexity}(\widehat{\mathscr{B}}) \end{bmatrix}$$

- tracing all optimal solutions requires hyper parameter
  1. λ — no physical meaning
  2. μ — bound on the error
  3. $(\mathtt{m}, \ell)$ — bound on the complexity

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Approximate identification problem

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}} \quad \text{error}(w, \widehat{\mathscr{B}})$$
$$\text{subject to} \quad \widehat{\mathscr{B}} \in \mathscr{L}_{\mathrm{m},\ell}$$

- in the case error $=$ misfit

$$\text{error}(w, \widehat{\mathscr{B}}) = \min_{\widehat{w} \in \widehat{\mathscr{B}}} \|w - \widehat{w}\|$$

- the problem is

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}}, \, \widehat{w} \quad \|w - \widehat{w}\|$$
$$\text{subject to} \quad \widehat{w} \in \widehat{\mathscr{B}} \in \mathscr{L}_{\mathrm{m},\ell}$$

Exact, noisy, and missing data

- $v_i^k(t)$ — variance of the measurement noise on $w_i^k(t)$

$$\|w - \widehat{w}\|_\alpha^2 = \sum_{k=1}^{N} \sum_{i=1}^{q} \sum_{t=1}^{T} \alpha_i^k(t) \big(w_i^k(t) - \widehat{w}_i^k(t) \big)^2$$

noisy data

$$\alpha_i^k(t) := \frac{1}{v_i^k(t)}$$

exact data

$$v_i^k(t) = 0,\ \alpha_i^k(t) = \infty$$

missing data

$$v_i^k(t) = \infty,\ \alpha_i^k(t) = 0$$

- $v_i^k(t) = \infty$ imposes equality constraint $\widehat{w}_i^k(t) = w_i^k(t)$
- $v_i^k(t) = 0$ makes $\|w - \widehat{w}\|_\alpha^2$ independent of $w_i^k(t)$

Summary: identification problem

- approximate identification in the misfit setting

$$\text{minimize} \quad \text{over } \widehat{\mathscr{B}},\ \widehat{w} \quad \|w - \widehat{w}\|_\alpha \qquad \text{subject to} \quad \widehat{w} \in \widehat{\mathscr{B}} \in \mathscr{L}_{\mathtt{m},\ell} \qquad \text{(SYSID)}$$

- element-wise weighted error criterion $\|\cdot\|_\alpha$

$$\begin{array}{lccc} \text{exact} & w_i^k(t) & \leftrightarrow & \alpha_i^k(t) = \infty \\ \text{missing} & w_i^k(t) & \leftrightarrow & \alpha_i^k(t) = 0 \end{array}$$

Next: SYSID $\leftrightarrow$ Hankel structured LRA

exact trajectory $w \in \mathscr{B} \in \mathscr{L}_{\mathrm{m},\ell}$

$$\Updownarrow$$

$$R_0 w(t) + R_1 w(t+1) + \cdots + R_\ell w(t+\ell) = 0$$

$$\Updownarrow$$

rank deficient

$$\mathscr{H}_{\ell+1}(w) := \begin{bmatrix} w(1) & w(2) & \cdots & w(T-\ell) \\ w(2) & w(3) & \cdots & w(T-\ell+1) \\ w(3) & w(4) & \cdots & w(T-\ell+2) \\ \vdots & \vdots & & \vdots \\ w(\ell+1) & w(\ell+2) & \cdots & w(T) \end{bmatrix}$$

$w \in \mathscr{B} \iff \mathscr{H}_{\ell+1}(w)$ rank deficient

- relation at time $t = 1$

$$R_0 w(1) + R_1 w(2) + \cdots + R_\ell w(\ell+1) = 0$$

- in matrix form:

$$\begin{bmatrix} R_0 & R_1 & \cdots & R_\ell \end{bmatrix} \begin{bmatrix} w(1) \\ w(2) \\ \vdots \\ w(\ell+1) \end{bmatrix} = 0$$

$w \in \mathscr{B} \iff \mathscr{H}_{\ell+1}(w)$ rank deficient

- relation at time $t = 2$

$$R_0 w(2) + R_1 w(3) + \cdots + R_\ell w(\ell+2) = 0$$

- in matrix form:

$$\begin{bmatrix} R_0 & R_1 & \cdots & R_\ell \end{bmatrix} \begin{bmatrix} w(2) \\ w(3) \\ \vdots \\ w(\ell+2) \end{bmatrix} = 0$$

$w \in \mathscr{B} \iff \mathscr{H}_{\ell+1}(w)$ rank deficient

- relation at time $t = T - \ell$

$$R_0 w(T-\ell) + R_1 w(T-\ell+1) + \cdots + R_\ell w(T) = 0$$

- in matrix form:

$$\begin{bmatrix} R_0 & R_1 & \cdots & R_\ell \end{bmatrix} \begin{bmatrix} w(T-\ell) \\ w(T-\ell+1) \\ w(T-\ell+2) \\ \vdots \\ w(T) \end{bmatrix} = 0$$

Putting it all together

- relation for $t = 1, \ldots, T - \ell$

$$R_0 w(t) + R_1 w(t+1) + \cdots + R_\ell w(t+\ell) = 0$$

- in matrix form:

$$\underbrace{\begin{bmatrix} R_0 & R_1 & \cdots & R_\ell \end{bmatrix}}_{R} \underbrace{\begin{bmatrix} w(1) & w(2) & \cdots & w(T-\ell) \\ w(2) & w(3) & \cdots & w(T-\ell+1) \\ w(3) & w(4) & \cdots & w(T-\ell+2) \\ \vdots & \vdots & & \vdots \\ w(\ell+1) & w(\ell+2) & \cdots & w(T) \end{bmatrix}}_{\mathscr{H}_{\ell+1}(w)} = 0$$

$w \in \mathscr{B} \iff \mathscr{H}_{\ell+1}(w)$ rank deficient

- with $R \in \mathbb{R}^{(q-\mathtt{m})\times q(\ell+1)}$ full row rank,

$$\operatorname{rank}\left(\mathscr{H}_{\ell+1}(w) = 0\right) \leq q\ell + \mathtt{m} \qquad (q \text{ — \# of variables})$$

$$w \in \mathscr{B} \in \mathscr{L}_{\mathtt{m},\ell} \iff \operatorname{rank}\left(\mathscr{H}_{\ell+1}(w)\right) \leq q\ell + \mathtt{m}$$

- multiple time-series $\quad \leftrightarrow \quad$ mosaic-Hankel matrix

$$\{w^1, \dots, w^N\} \subset \mathscr{B} \in \mathscr{L}_{\mathtt{m},\ell}$$

$$\iff \operatorname{rank}\Big(\underbrace{\begin{bmatrix} \mathscr{H}_{\ell+1}(w^1) & \cdots & \mathscr{H}_{\ell+1}(w^N) \end{bmatrix}}_{\mathscr{H}_{\ell+1}(w)}\Big) \leq q\ell + \mathtt{m}$$

Structured weighted low-rank approximation

$$\begin{array}{lll} \text{minimize} & \text{over } \widehat{\mathscr{B}} \text{ and } \widehat{w} & \|w - \widehat{w}\|_\alpha \\ \text{subject to} & \widehat{w} \subset \widehat{\mathscr{B}} \in \mathscr{L}_{\mathrm{m},\ell} & \end{array} \qquad \text{(SYSID)}$$

$$\Updownarrow$$

$$\begin{array}{lll} \text{minimize} & \text{over } \widehat{w} & \|w - \widehat{w}\|_\alpha \\ \text{subject to} & \operatorname{rank}\big(\mathscr{H}_{\ell+1}(\widehat{w})\big) \leq q\ell + \mathrm{m} & \end{array} \qquad \text{(SLRA)}$$

Summary: structured low-rank approximation

- (SYSID) $\iff$ (SLRA)
- LTI model class $\iff$ Hankel structure
- repeated experiments $\iff$ mosaic-Hankel structure

$$\begin{bmatrix} \mathscr{H}_{\ell+1}(w^1) & \cdots & \mathscr{H}_{\ell+1}(w^N) \end{bmatrix}$$

- bounded complexity $\iff$ rank constraint

$$(\mathtt{m}, \ell) \quad \leftrightarrow \quad r = q\ell + \mathtt{m}$$

Outline

Solution methods

- given: data w and complexity bound $(\mathtt{m}, \ell)$
- find: $\widehat{\mathscr{B}}$ that solves (SYSID) or, equivalently, (SLRA)

1. choice of model representation
   - transfer function
   - input/state/output
   - ...
2. choice of optimization method
   - local optimization
   - global optimization
   - convex relaxations

Model vs model representation

- 1st order SISO model $\mathscr{B} \in \mathscr{L}_{1,1}$

$$\mathscr{B}_{\text{de}}(\theta) = \left\{ \widehat{w} \;\middle|\; \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 & \theta_4 \end{bmatrix} \begin{bmatrix} \widehat{w}_1(t) \\ \widehat{w}_2(t) \\ \widehat{w}_1(t+1) \\ \widehat{w}_2(t+1) \end{bmatrix} = 0, \ \forall t \right\}$$

- transfer functions

$$G_{w_1 \mapsto w_2}(z) = -\frac{\theta_1 + \theta_3 z}{\theta_2 + \theta_4 z} \quad , \quad G_{w_2 \mapsto w_1}(z) = -\frac{\theta_2 + \theta_4 z}{\theta_1 + \theta_3 z}$$

- state space, convolution, ..., representations

Problem formulation vs solution method

- in the classical setting, model $=$ representation
- $\implies$ problems are mixed with solution methods
- *e.g.*, "total least-squares" is both problem and method
- the behavioral setting distinguishes

	used for	involves
abstract	problem formulation	$\mathscr{B}$, $\mathscr{L}_{\mathrm{m},\ell}$
concrete	solution methods	$\mathscr{B}(\theta)$, $\theta \in \Theta$

- low-rank approx. is abstract problem formulation

Parameter optimization problem

- model representation

$$\mathscr{B}(\theta) = \{\, \widehat{w} \mid g_\theta(\widehat{w}) = 0 \,\}$$

- parameterized model class

$$\mathscr{M} = \{\, \mathscr{B}(\theta) \mid \theta \in \Theta \,\}$$

- optimization problem

$$\begin{array}{lll} \text{minimize} & \text{over } \theta \in \Theta,\ \widehat{w} & \|w - \widehat{w}\|_\alpha \\ \text{subject to} & g_\theta(\widehat{w}) = 0 & \end{array} \qquad (\text{SYSID}_\theta)$$

Bilinear structure of the problem

- (SYSID_θ) — constrained nonlinear least-squares
- $\mathscr{B}$ linear

  $\implies \quad g_\theta(\widehat{w})$ bilinear (in θ and $\widehat{w}$)

  $\implies \quad (\text{SYSID}_\theta)$ can be solved globally for given θ
- variable projection (VARPRO)
  for separable nonlinear least-squares problems
- if $T \gg \ell$, elimination of $\widehat{w}$ leads to big reduction

System theoretic view of VARPRO

solving (SYSID_θ) for given θ

$\Updownarrow$

misfit evaluation: $\text{error}\big(w, \mathscr{B}(\theta)\big)$

$\Updownarrow$

likelihood evaluation

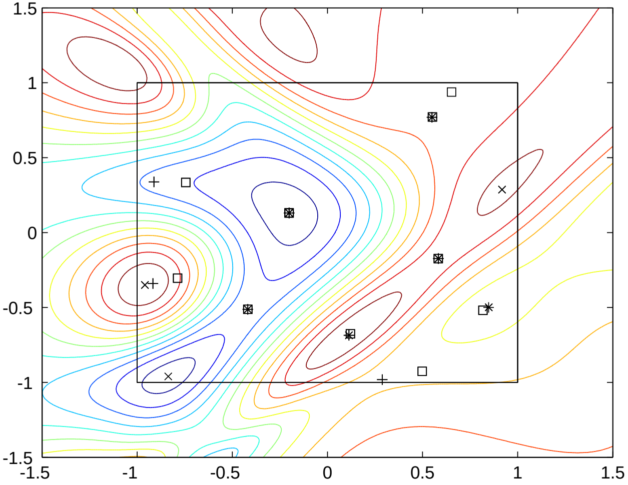
$\Updownarrow$

least-squares smoothing of w by $\mathscr{B}(\theta)$

$\Updownarrow$

fast algorithms:
Kalman smoothing
Cholesky factorization
...

Non-convexity of error$(w, \mathscr{B}(\theta))$



Computational details

- $O(T)$ evaluation of $\text{error}\big(w, \mathscr{B}(\theta)\big)$ and its derivatives
  - using the Kalman smoother
  - Cholesky factorization of banded Toeplitz matrix
  - ...
- $\mathscr{B}(\theta) = \mathscr{B}(\alpha\theta)$, for all $\alpha \neq 0$
- $\Theta = \{\, \theta \mid \|\theta\|_2 = 1 \,\} \implies$ optimization on a manifold
  - generic methods (optimization theory)
  - custom methods (system identification)
    - data driven local coordinates (McKelvey)
    - ...

Summary: solution methods

- solution methods involve two choices:
  1. model representation
  2. optimization method
- in the linear case, bilinear structure $\rightsquigarrow$ VARPRO
- constraint nonlinear least-squares problem

$$\min_{\theta \in \Theta} \; \text{error}\big(w, \mathscr{B}(\theta)\big)$$

- Θ is a manifold $\rightsquigarrow$ optimization on a manifold

Outline

Introduction: data, model class, approximation

Approximation error–model complexity trade-off

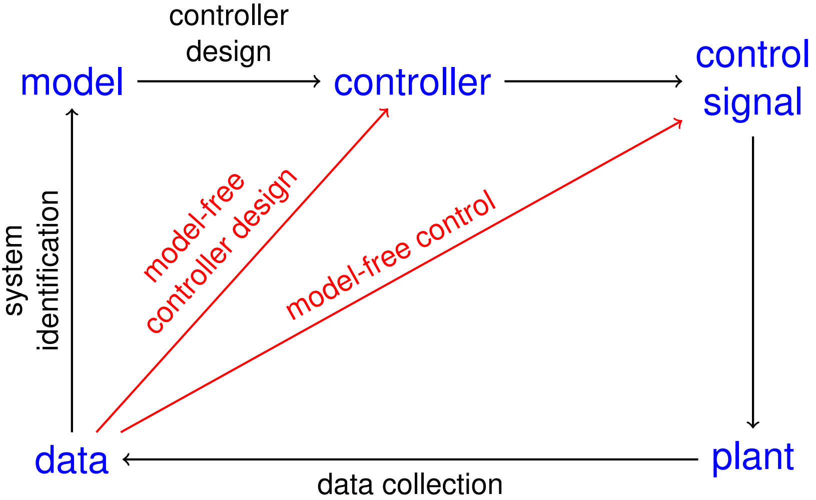
System identification $\leftrightarrow$ low-rank approximation

Solution methods: variable projection

Example: model-free control

Conclusions

Model-free control

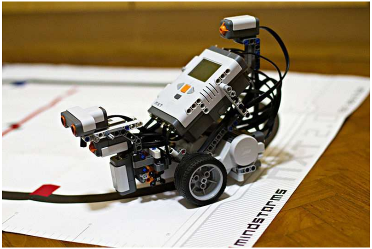


Classical LTI optimal tracking control

- given:
  - system $\mathscr{B} \in \mathscr{L}$
  - desired output y_r

- find: input u, such that

$$\min_{(u,y)\in\mathscr{B}} \|y_r - y\|$$



- there are different algorithms to solve the problem (Riccati equation, spectral factorization, ...)

- they depend on the representation of the model $\mathscr{B}$ (state-space, transfer function, ...)

Model-free LTI optimal tracking control

- given:
  - trajectory w^1 (of a system $\bar{\mathscr{B}} \in \mathscr{L}_{\mathrm{m},\ell}$)
  - desired output $y_{\mathrm{r}} = y^2$

- find: input $\widehat{u}^2$, such that

$$\text{minimize} \quad \underbrace{\|w^1 - \widehat{w}^1\|^2}_{\substack{\text{misfit}\\ \text{error}}} + \underbrace{\|y_{\mathrm{r}} - \widehat{y}^2\|^2}_{\substack{\text{tracking}\\ \text{error}}} \qquad \text{(MFT)}$$

$$\text{subject to} \quad \widehat{w}^1, \widehat{w}^2 \in \widehat{\mathscr{B}} \in \mathscr{L}_{\mathrm{m},\ell}$$

- $\widehat{\mathscr{B}}$ in (MFT) is needed to define the problem

- in a model-free method, $\widehat{\mathscr{B}}$ is not identified explicitly

Solution by SLRA with missing data

- (MFT) is equivalent to

$$\begin{array}{ll} \text{minimize} & \text{over } \widehat{w} \text{ and } \widehat{\mathscr{B}} \quad \|w - \widehat{w}\|_\alpha \\ \text{subject to} & \widehat{w} \subset \widehat{\mathscr{B}} \in \mathscr{L}_{\mathrm{m},\ell} \end{array}$$

the control input u^2 is missing data

- this leads to mosaic-Hankel SLRA with missing data

$$\begin{array}{ll} \text{minimize} & \text{over } \widehat{w} \quad \|w - \widehat{w}\|_\alpha \\ \text{subject to} & \operatorname{rank}\big(\mathscr{H}_{\ell+1}(\widehat{w})\big) \leq q\ell + \mathrm{m} \end{array}$$

- the only truly model free solution methods I know of are based on the nuclear norm heuristic

Outline

Introduction: data, model class, approximation

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Solution methods: variable projection

Example: model-free control

Conclusions

Conclusions

- representation free problem formulation:

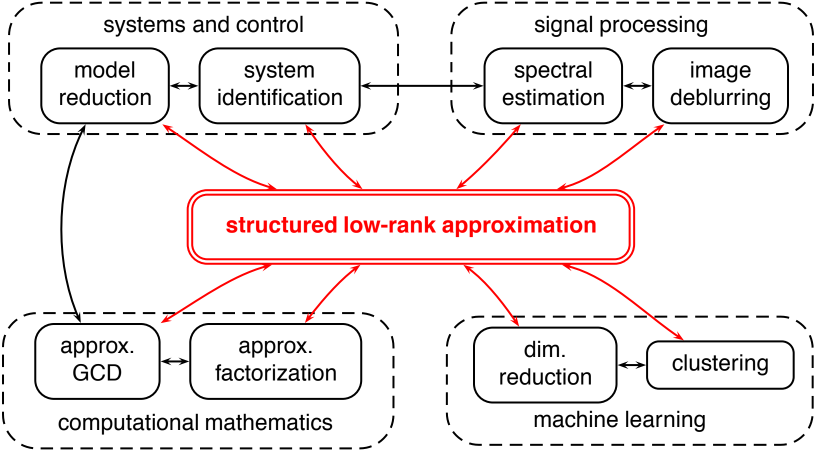
LTI	system identification	complexity bound
$\updownarrow$	$\Updownarrow$	$\updownarrow$
Hankel	matrix approximation	rank constraint

- solution methods based on model representations:

Kalman smoothing	likelihood evaluation
$\updownarrow$	$\updownarrow$
Cholesky factorization	variable projection

- SLRA with other types of structure $\leadsto$ other applications

One problem, one method, many applications



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- project webpage:

  `http://slra.github.io/`