Data-driven simulation and control

Ivan Markovsky

K.U.Leuven, ESAT-SISTA

Joint work with Paolo Rapisarda

Outline

LTI system representations

- Difference equation

$$R_0 w(t) + R_1 w(t+1) + \cdots + R_\mathtt{l} w(t+\mathtt{l}) = 0$$

- Convolution

$$w = \Pi \operatorname{col}(u,y), \quad y(t) = \textstyle\sum_{\tau=-\infty}^{t} h(\tau) u(t-\tau)$$

- Input/state/output equations

$$w = \Pi \operatorname{col}(u,y), \quad \begin{aligned} x(t+1) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \qquad \text{(I/S/O)}$$

$\mathscr{B}(A,B,C,D)$ — the system defined by (I/S/O)
we will assume that $\Pi = I$

Behavior of a system = solution set of an equation

We identify the system with its behavior $\mathscr{B}$,

$$\mathscr{B} := \{\, w \in (\mathbb{R}^\mathtt{w})^\mathbb{N} \mid \text{representation eqns holds} \,\}, \textit{ e.g.}$$

$$\mathscr{B}(A,B,C,D) = \{\, w \in (\mathbb{R}^\mathtt{w})^\mathbb{N} \mid \exists\, x, \text{ such that (I/S/O) holds} \,\}$$

$\mathtt{w}$ is the number of variables, $\mathbb{N} := \{1,2,\dots\}$ is the time axis

Restriction of the behavior to the interval $\{1,2,\dots t\}$

$$\mathscr{B}_t := \{\, w_\mathrm{p} \in (\mathbb{R}^\mathtt{w})^t \mid \exists\, w_\mathrm{f} \text{ such that } (w_\mathrm{p}, w_\mathrm{f}) \in \mathscr{B} \,\}$$

$\mathtt{lag}(\mathscr{B})$ — lag of $\mathscr{B}$ (observability index of I/S/O repr.)
$\mathtt{order}(\mathscr{B})$ — order of $\mathscr{B}$

Notation for Hankel matrices

Given a signal $w = \big(w(1),\dots,w(T)\big)$ and $t \leq T$, define

$$\mathscr{H}_t(w) := \begin{bmatrix} w(1) & w(2) & w(3) & \cdots & w(T-t+1) \\ w(2) & w(3) & w(4) & \cdots & w(T-t+2) \\ w(3) & w(4) & w(5) & \cdots & w(T-t+3) \\ \vdots & \vdots & \vdots & & \vdots \\ w(t) & w(t+1) & w(t+2) & \cdots & w(T) \end{bmatrix}$$

block-Hankel matrix with t block-rows, composed of w

The simulation problem

Classical simulation problem: Given

- system $\mathscr{B} := \mathscr{B}(A,B,C,D)$,
- input $u \in (\mathbb{R}^{\mathtt{m}})^t$, and
- initial conditions $x_{\text{ini}} \in \mathbb{R}^{\mathtt{n}}$,

find the response y of $\mathscr{B}$ to u and ini. cond. x_{ini}.

Data-driven simulation problem: Given

- trajectory $w_{\text{d}} \in (\mathbb{R}^{\mathtt{w}})^T$ of $\mathscr{B}$,
- input $u \in (\mathbb{R}^{\mathtt{m}})^t$, and
- initial trajectory $w_{\text{ini}} \in (\mathbb{R}^{\mathtt{w}})^{T_{\text{ini}}}$, $w_{\text{ini}} \in \mathscr{B}_{T_{\text{ini}}}$,

find the response y of $\mathscr{B}$ to u, such that $\big(w_{\text{ini}},(u,y)\big) \in \mathscr{B}_{T_{\text{ini}}+t}$.

Notes:

- $\mathscr{B}$ is specified implicitly by w_{d},
- the ini. cond. x_{ini} is specified implicitly by w_{ini}.

Algorithm 1: data-driven simulation, using I/S/O repr.

1. identification $\quad w_{\text{d}} \mapsto (A,B,C,D)$
2. observer $\quad \big(w_{\text{ini}},(A,B,C,D)\big) \mapsto x_{\text{ini}}$
3. classical simulation $\quad \big(u,x_{\text{ini}},(A,B,C,D)\big) \mapsto y$

Can we find y without deriving an explicit representation of $\mathscr{B}$?

Basic idea

Assuming that w_{d} is a trajectory of $\mathscr{B}$ (exact data),

lin. comb. of the columns of $\mathscr{H}_t(w_{\text{d}})$ are trajectories of $\mathscr{B}$, *i.e.*,
for all g, $\quad \mathscr{H}_t(w_{\text{d}})g \in \mathscr{B}_t$

$\Longrightarrow$ computing the response of $\mathscr{B}$ to given input and initial conditions from data w_{d}, requires choosing a suitable g

Under what conditions is every trajectory generated that way?

The fundamental lemma

u_d is persistently exciting of order L if $\mathscr{H}_L(u_\mathrm{d})$ is of full row rank.

Fundamental Lemma: Assume that

- the LTI system $\mathscr{B}$ is controllable,
- u_d is persistently exciting of order $L + \text{order}(\mathscr{B})$, and
- $w_\mathrm{d} := (u_\mathrm{d}, y_\mathrm{d})$ is a trajectory of $\mathscr{B}$, *i.e.*, $w_\mathrm{d} \in \mathscr{B}_T$.

Then

$$\text{image}\,\big(\mathscr{H}_L(w_\mathrm{d})\big) = \mathscr{B}_L.$$

Construction of responses from data

Problem: Find y, such that $\big(w_\mathrm{ini}, (u, y)\big) \in \mathscr{B}$, where w_ini, u are given, and $\mathscr{B}$ is implicitly defined by w_d.

Under the conditions of the FL, there is g, such that

$$\mathscr{H}_{T_\mathrm{ini}+t}(w_\mathrm{d})g = \big(w_\mathrm{ini}, (u, y)\big).$$

The eqns with RHS y, define y, for given g. The others restrict g.

Generic data-driven simulation algorithm:

1. compute any solution g of the equations with RHS w_ini, u
2. substitute g in the equations for y

Define

$$U := \mathscr{H}_{T_\mathrm{ini}+t}(u_\mathrm{d}), \qquad Y := \mathscr{H}_{T_\mathrm{ini}+t}(y_\mathrm{d})$$

and the partitionings

$$U =: \begin{bmatrix} U_\mathrm{p} \\ U_\mathrm{f} \end{bmatrix}, \qquad Y =: \begin{bmatrix} Y_\mathrm{p} \\ Y_\mathrm{f} \end{bmatrix}.$$

Algorithm 2: data-driven simulation

1. compute the least norm solution of

$$\begin{bmatrix} U_\mathrm{p} \\ Y_\mathrm{p} \\ U_\mathrm{f} \end{bmatrix} g = \begin{bmatrix} u_\mathrm{ini} \\ y_\mathrm{ini} \\ u \end{bmatrix}.$$

2. compute $y := Y_\mathrm{f} g$.

Special case $u = 0$: free response

Allows to compute an observability matrix $\mathscr{O}$ of $\mathscr{B}$ from data, by finding $\mathrm{n} \geq \text{order}(\mathscr{B})$ linearly indep. free responses.

Let $\mathtt{l}_\mathrm{max}$ be an upper bound for the lag of $\mathscr{B}$ and take $T_\mathrm{ini} = \mathtt{l}_\mathrm{max}$.

Algorithm 3: compute an observability matrix $\mathscr{O}$

1. compute the least norm solution of

$$\begin{bmatrix} U_\mathrm{p} \\ Y_\mathrm{p} \\ U_\mathrm{f} \end{bmatrix} G = \begin{bmatrix} U_\mathrm{p} \\ Y_\mathrm{p} \\ 0 \end{bmatrix}$$

2. compute $Y := Y_\mathrm{f} G$
3. compute a rank revealing factorization $Y = \mathscr{O} X_\mathrm{ini}$

Special case $w_{\text{ini}} = 0$: zero initial cond. response

Let h be the impulse response of $\mathscr{B}$, and define

$$\mathscr{T}_t(h) := \begin{bmatrix} h(0) & & & & \\ h(1) & h(0) & & & \\ h(2) & h(1) & h(0) & & \\ \vdots & \ddots & \ddots & \ddots & \\ h(t-1) & \cdots & \cdots & h(1) & h(0) \end{bmatrix}$$

For any $w = \text{col}(u, y) \in \mathscr{B}_t$,

$$y = \mathscr{O}x_{\text{ini}} + \mathscr{T}_t(h)u$$

We can compute a basis for $\mathscr{B}_{0,t} := \text{image}\left(\mathscr{T}_t(h)\right)$ from data, by finding $\mathtt{tm}$ lin. indep. zero initial cond. responses.

Algorithm 4: compute a basis of $\mathscr{B}_{0,t}$

1. compute the least norm solution of

$$\begin{bmatrix} U_{\text{p}} \\ Y_{\text{p}} \\ U_{\text{f}} \end{bmatrix} G = \begin{bmatrix} 0 \\ 0 \\ \mathscr{H}_{t,\mathtt{tm}}(u_{\text{d}}) \end{bmatrix}$$

2. compute $Y_0 := Y_{\text{f}}G$

Then $\text{image}(Y_0) = \text{image}\left(\mathscr{T}_t(h)\right) = \mathscr{B}_{0,t}$.

Special case $w_{\text{ini}} = 0$, $u = I\delta$: impulse response

With the same construction we can find the first t Markov parameters of $\mathscr{B}$, which is a system identification method.

Algorithm 5: compute the impulse response

1. compute the least norm solution of

$$\begin{bmatrix} U_{\text{p}} \\ Y_{\text{p}} \\ U_{\text{f}} \end{bmatrix} G = \begin{bmatrix} 0 \\ 0 \\ \text{col}(I_{\mathtt{m}}, 0) \end{bmatrix}$$

2. compute $h := Y_{\text{f}}G$

Simulation example $w_{\text{d}} \mapsto h$

Compared algorithms

- Algorithm 5 (block computation)
- iterative version of Algorithm 5
- `impulse` from the Identification Toolbox of MATLAB

Approximation error $e = \|h - \widehat{h}\|_{\text{F}}$ and execution time

method	error, e	time, sec.
Algorithm 5	10^{-14}	0.293
iterative algorithm	10^{-14}	0.066
`impulse`	0.059	0.584

The output matching problem

"Classical" output matching problem: Given

- system $\mathscr{B} = \mathscr{B}(A, B, C, D)$,
- initial condition $x_{\text{ini}} \in \mathbb{R}^{\mathtt{n}}$, and
- reference response $y_{\text{r}} \in (\mathbb{R}^{\mathtt{p}})^{T_{\text{r}}}$

find an input $u_{\text{f}} \in (\mathbb{R}^{\mathtt{m}})^{T_{\text{r}}}$, such that the response of $\mathscr{B}$ to u_{f} and ini. cond. x_{ini} is y_{r}.

Data-driven output matching problem: Given

- trajectory $w_{\text{d}} \in (\mathbb{R}^{\mathtt{w}})^{T}$ of $\mathscr{B}$,
- initial trajectory $w_{\text{ini}} \in (\mathbb{R}^{\mathtt{w}})^{T_{\text{ini}}}$, $w_{\text{ini}} \in \mathscr{B}_{T_{\text{ini}}}$, and
- reference response $y_{\text{r}} \in (\mathbb{R}^{\mathtt{p}})^{T_{\text{r}}}$

find an input $u_{\text{f}} \in (\mathbb{R}^{\mathtt{m}})^{T_{\text{r}}}$, such that $\big(w_{\text{ini}}, (u_{\text{f}}, y_{\text{r}})\big) \in \mathscr{B}_{T_{\text{ini}}+T_{\text{r}}}$.

Output matching = "inverse simulation"

Note: simulation can be viewed as an "input matching" problem.

Algorithm 6: data-driven output matching

1. compute the least norm solution of

$$\begin{bmatrix} U_{\text{p}} \\ Y_{\text{p}} \\ Y_{\text{f}} \end{bmatrix} g = \begin{bmatrix} u_{\text{ini}} \\ y_{\text{ini}} \\ y_{\text{r}} \end{bmatrix}$$

2. compute $u_{\text{f}} := U_{\text{f}} g$

An arbitrary input is allowed.

Simulation example

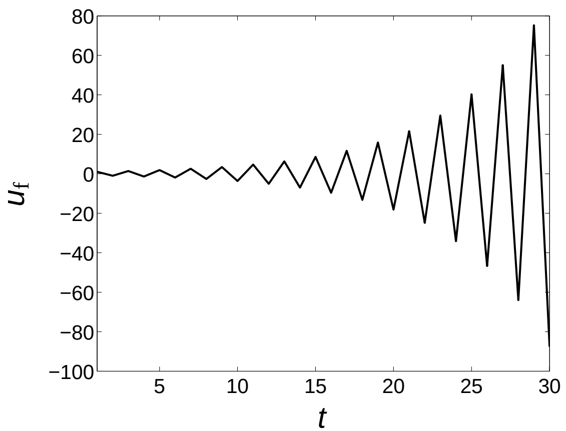
$\mathscr{B}$ — 2nd order, $\mathtt{m} = 1$ input, $\mathtt{p} = 1$ output

w_{d} — random trajectory of $\mathscr{B}$ with $T = 200$ samples

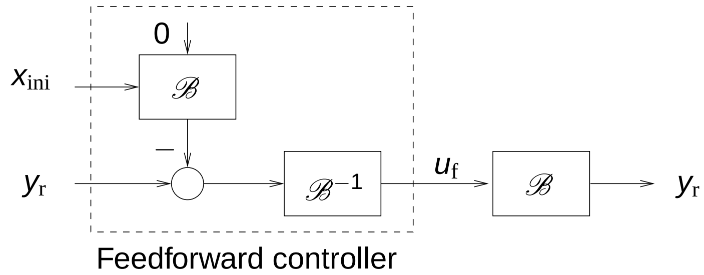
$y_{\text{r}} = 0$

$T_{\text{r}} = 30$

$w_{\text{ini}} = (1, 1)$



Structure of the output matching controller



In the example, $\mathscr{B}$ is non-minimum phase $\implies$ $\mathscr{B}^{-1}$ unstable.

More general tracking problem:

follow a reference traj. w_{r} by trading-off errors in both u and y

Linear quadratic tracking problem

Given

- a trajectory $w_{\mathrm{d}} \in (\mathbb{R}^{\mathtt{w}})^T$ of $\mathscr{B}$,
- an initial trajectory $w_{\mathrm{ini}} \in (\mathbb{R}^{\mathtt{w}})^{T_{\mathrm{ini}}}$, $w_{\mathrm{ini}} \in \mathscr{B}_{T_{\mathrm{ini}}}$,
- a reference trajectory $w_{\mathrm{r}} \in (\mathbb{R}^{\mathtt{w}})^{T_{\mathrm{r}}}$, and
- a positive definite matrix $\Phi \in \mathbb{R}^{\mathtt{w}\times\mathtt{w}}$,

find a trajectory of $\mathscr{B}$ that is optimal with respect to the criterion

$$J(w_{\mathrm{r}}, w) := (w_{\mathrm{r}} - w)^\top \Phi (w_{\mathrm{r}} - w)$$

and has as a prefix the initial trajectory w_{ini}, *i.e.*, find

$$w_{\mathrm{f}}^* := \arg\min_{w_{\mathrm{f}}} J(w_{\mathrm{r}}, w_{\mathrm{f}}) \quad \text{subject to} \quad (w_{\mathrm{ini}}, w_{\mathrm{f}}) \in \mathscr{B}_{T_{\mathrm{ini}}+T_{\mathrm{f}}}.$$

Solution using an I/S/O representation

The classical but indirect solution is:

Algorithm 7: data-driven LQ tracking, using I/S/O repr.

1. $w_{\mathrm{d}} \xrightarrow{\text{Identification}} (A,B,C,D)$
2. $\big(w_{\mathrm{ini}}, (A,B,C,D)\big) \xrightarrow{\text{Observer (1,2)}} x_{\mathrm{ini}}$
3. $\big(\Phi, w_{\mathrm{r}}, x_{\mathrm{ini}}, (A,B,C,D)\big) \xrightarrow{\text{Synthesis (3,4,5)}} w_{\mathrm{f}}^*$

We aim to find algorithms that do not derive a repr. of $\mathscr{B}$.

Observer design

Let h be the impulse response of $\mathscr{B}$. We have,

$$y_{\mathrm{ini}} = \mathscr{O}(A,C)x(1) + \mathscr{T}_{T_{\mathrm{ini}}}(h)u_{\mathrm{ini}}, \tag{1}$$

where

$$\mathscr{O}(A,C) := \operatorname{col}(C, CA, \dots, CA^{T_{\mathrm{ini}}-1})$$

defines a system of equations for the initial state $x(1)$.

$$\begin{array}{lcl} w_{\mathrm{ini}} \in \mathscr{B}_{T_{\mathrm{ini}}} & \Longrightarrow & \text{existence of solution} \\ (A,B,C,D) \text{ minimal} & \Longrightarrow & \text{uniqueness} \end{array}$$

$$x_{\mathrm{ini}} = x(T_{\mathrm{ini}}+1) = CA^{T_{\mathrm{ini}}}x(1) + \begin{bmatrix} h(T_{\mathrm{ini}}-1) & h(T_{\mathrm{ini}}-2) & \cdots & h(0) \end{bmatrix} u_{\mathrm{ini}}. \tag{2}$$

Regulator synthesis

LQ tracking problem:

$$\min_{x,u,y} \; (w_{\mathrm{r}} - \operatorname{col}(u,y))^\top \Phi (w_{\mathrm{r}} - \operatorname{col}(u,y))$$

$$\text{subject to} \quad \begin{array}{l} x(t+1) = Ax(t) + Bu(t), \quad x(1) = x_{\mathrm{ini}} \\ y(t) = Cx(t) + Du(t), \quad \text{for } t = 1,\dots,T_{\mathrm{r}}. \end{array}$$

The solution for the $w_{\mathrm{r}} = 0$ case (regulation problem) is

$$\begin{aligned} x^*(t+1) &= (A - BL_t)x^*(t), \quad x(1) = x_{\mathrm{ini}} \\ w_{\mathrm{f}}^*(t) &= \begin{bmatrix} -L_t \\ C - DL_t \end{bmatrix} x^*(t) \end{aligned} \tag{3}$$

a state feedback.

Define

$$\Phi =: \begin{bmatrix} \Phi_u & \Phi_{uy} \\ \Phi_{yu} & \Phi_y \end{bmatrix}.$$

The optimal input is a state feedback with time-varying gain

$$L_t := \left(B^\top S_{t+1} B + \Phi_u + \Phi_{uy} D + D^\top \Phi_{uy}^\top + D^\top \Phi_y D\right)^{-1} \times \left(B^\top S_{t+1} A + \Phi_{uy} C + D^\top \Phi_y C\right) \quad (4)$$

where S is given by the Riccati difference equation

$$S_t = A^\top S_{t+1} A + C^\top \Phi_y C - \left(B^\top S_{t+1} A + \Phi_{uy} C + D^\top \Phi_y C\right)^\top \times \left(B^\top S_{t+1} B + \Phi_u + \Phi_{uy} D + D^\top \Phi_{uy}^\top + D^\top \Phi_y D\right)^{-1} \times \left(B^\top S_{t+1} A + \Phi_{uy} C + D^\top \Phi_y C\right), \qquad S_{T_\mathrm{r}} = 0. \quad (5)$$

Solution using the impulse response representation

LQ tracking problem:

$$\min_{w_\mathrm{f}} (w_\mathrm{r} - w_\mathrm{f})^\top \Phi (w_\mathrm{r} - w_\mathrm{f}) \quad \text{subject to} \quad (w_\mathrm{ini}, w_\mathrm{f}) \in \mathscr{B}_{T_\mathrm{ini}+T_\mathrm{f}}$$

Let $y_{\mathrm{f},0}$ be the free response of $\mathscr{B}$ initiated by w_ini.

$$y_\mathrm{f} = y_{\mathrm{f},0} + \mathscr{T}_{T_\mathrm{r}}(h) u_\mathrm{f}$$

so that the tracking problem becomes

$$\min_{u_\mathrm{f}} (w_\mathrm{r} - w_\mathrm{f})^\top \Phi (w_\mathrm{r} - w_\mathrm{f}) \quad \text{subject to} \quad y_\mathrm{f} = \mathscr{T}_{T_\mathrm{r}}(h) u_\mathrm{f} + y_{\mathrm{f},0}$$

a weighted least squares problem.

With $\widetilde{h} := \operatorname{col}(I\delta, h)$,

$$w_\mathrm{f} := \Big(\operatorname{col}\big(u_\mathrm{f}(1), y_\mathrm{f}(1)\big), \dots, \operatorname{col}\big(u_\mathrm{f}(T_\mathrm{r}), y_\mathrm{f}(T_\mathrm{r})\big)\Big) = \mathscr{T}_{T_\mathrm{r}}(\widetilde{h}) u_\mathrm{f}$$

Then

$$w_\mathrm{f} = \mathscr{T}_{T_\mathrm{r}}(\widetilde{h}) u_\mathrm{f} + w_{\mathrm{f},0}, \quad \text{where} \quad w_{\mathrm{f},0} := \operatorname{col}(0, y_{\mathrm{f},0})$$

The tracking problem becomes

$$\min_{u_\mathrm{f}} \big(w_\mathrm{r} - w_{\mathrm{f},0} - \mathscr{T}_{T_\mathrm{r}}(\widetilde{h})\big)^\top \Phi \big(w_\mathrm{r} - w_{\mathrm{f},0} - \mathscr{T}_{T_\mathrm{r}}(\widetilde{h})\big)$$

and the solution is

$$\begin{aligned} u_\mathrm{f}^* &= \big(\mathscr{T}_{T_\mathrm{r}}^\top(\widetilde{h}) \Phi \mathscr{T}_{T_\mathrm{r}}(\widetilde{h})\big)^{-1} \mathscr{T}_{T_\mathrm{r}}^\top(\widetilde{h}) \Phi (w_\mathrm{r} - w_{\mathrm{f},1}) \\ y_\mathrm{f}^* &= \mathscr{T}_{T_\mathrm{r}}(h) u_\mathrm{f}^* + y_{\mathrm{f},1} \end{aligned} \quad (6)$$

Ingredients of the solution:

- the free response $y_{\mathrm{f},0}$ and
- the impulse response h.

We can compute them directly from w_d.

Algorithm 8: data-driven LQ tracking, using impulse resp. repr.

1. $(w_\mathrm{ini}, w_\mathrm{d}, T_\mathrm{r}) \xrightarrow{\text{Algorithm 2}} y_{\mathrm{f},0}$
2. $(w_\mathrm{d}, T_\mathrm{r}) \xrightarrow{\text{Algorithm 6}} h$
3. $(\Phi, w_\mathrm{r}, w_{\mathrm{f},0}, h) \xrightarrow{(6)} w_\mathrm{f}^*$

Data-driven solution

Define the zero initial conditions subbehavior of $\mathscr{B}$

$$\mathscr{B}_{0,T_\mathrm{r}} := \{ w \in (\mathbb{R}^\mathtt{w})^{T_\mathrm{r}} \mid (\underbrace{0,\dots,0}_{\mathrm{lag}(\mathscr{B})}, w) \in \mathscr{B}_{\mathrm{lag}(\mathscr{B})+T_\mathrm{r}} \}$$

Theorem: Let $W_0 \in \mathbb{R}^{T_\mathrm{r}\mathtt{w}\times\bullet}$ be a matrix, such that

$$\mathrm{image}\,(W_0) = \mathscr{B}_{0,T_\mathrm{r}}$$

Then the LQ optimal trajectory is

$$w_\mathrm{f}^* = W_0 (W_0^\top \Phi W_0)^+ W_0^\top \Phi (w_\mathrm{r} - w_{\mathrm{f},0}) + w_{\mathrm{f},0} \tag{7}$$

where $w_{\mathrm{f},0}$ is the free response of $\mathscr{B}$, caused by w_ini.

Proof

Any zero initial conditions trajectory $w = \mathrm{col}(u,y) \in (\mathbb{R}^\mathtt{w})^{T_\mathrm{r}}$ is of the form $w = \mathscr{T}_{T_\mathrm{r}}(\tilde{h})u$. Therefore,

$$\mathscr{B}_{0,T_\mathrm{r}} = \mathrm{image}\,(\mathscr{T}_{T_\mathrm{r}}(\tilde{h})) = \mathrm{image}\,(W_0)$$

Consider the space $\mathscr{W} = (\mathbb{R}^\mathtt{w})^{T_\mathrm{r}}$ with inner product defined by $\langle w_1, w_2 \rangle = w_1^\top \Phi w_2$. The projector on $\mathscr{B}_{0,T_\mathrm{r}}$ in $\mathscr{W}$ is

$$\mathscr{T}_{T_\mathrm{r}}(\tilde{h}) \big(\mathscr{T}_{T_\mathrm{r}}^\top(\tilde{h}) \Phi \mathscr{T}_{T_\mathrm{r}}(\tilde{h}) \big)^{-1} \mathscr{T}_{T_\mathrm{r}}^\top(\tilde{h}) \Phi = W_0 (W_0^\top \Phi W_0)^+ W_0^\top \Phi$$

Then the data-driven solution (7) follows from the solution (6), using the impulse response representation.

Algorithm 9: data-driven LQ tracking

1. $(w_\mathrm{ini}, w_\mathrm{d}, T_\mathrm{r}) \xrightarrow{\text{Algorithm 2}} y_{\mathrm{f},0}$
2. $(w_\mathrm{d}, T_\mathrm{r}) \xrightarrow{\text{Algorithm 4}} W_0$
3. $(\Phi, w_\mathrm{r}, y_{\mathrm{f},0}, W_0) \xrightarrow{(7)} w_\mathrm{f}^*$

Simulation example

Aim: illustrate numerically the equivalence of the three methods.

$\mathscr{B}$	—	2nd order, $\mathtt{m}=1$ input, $\mathtt{p}=1$ output (the same system as in the output matching example)
w_d	—	random trajectory of $\mathscr{B}$ with $T=200$ samples
Φ	—	identity (assign equal weights to the variables)

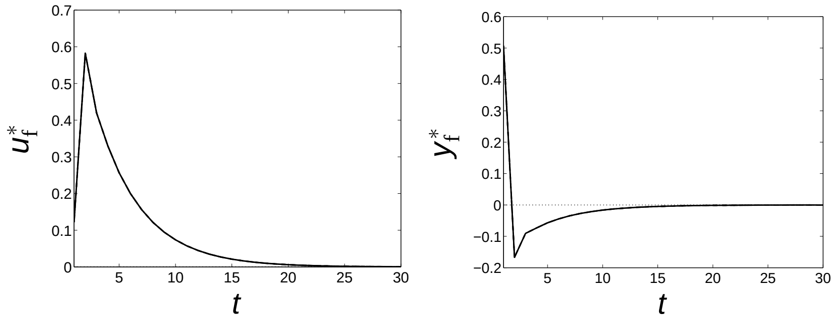
- Experiment 1: data-driven regulation

$$w_\mathrm{r} = 0, \quad T_\mathrm{r} = 30, \quad \text{and} \quad w_\mathrm{ini} = (1,1)$$

- Experiment 2: data-driven step tracking

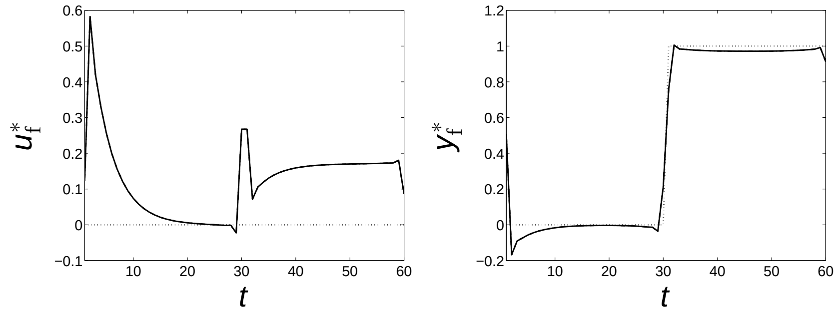
$$u_\mathrm{r} = 0, \quad y_\mathrm{r}(t) = \begin{cases} 0, & \text{for } t = 1,2\dots,30 \\ 1, & \text{for } t = 31,52,\dots,60 \end{cases}, \quad w_\mathrm{ini} = (1,1)$$

Result for Experiment 1



w_{r} — dotted line, w_f^* — solid line, $J(0, w_{\mathrm{f}}^*) = 1.1139$

Result for Experiment 2



w_{r} — dotted line, w_f^* — solid line, $J(w_{\mathrm{r}}, w_{\mathrm{f}}^*) = 2.1034$

Conclusions

- Given $w_{\mathrm{d}} \in \mathscr{B}_T$, we can compute feedforward LQ tracking control without deriving a repr. of $\mathscr{B}$. (data-driven control)
- For doing this we need
  - $\mathscr{B}$ to be controllable,
  - u_{d} to be persistently exciting of sufficient order.
- The construction of the optimal control is based on
  - free response $y_{\mathrm{f},0}$ of $\mathscr{B}$ under w_{ini}, and
  - zero ini. cond. trajectories W_0 (a basis for $\mathscr{B}_{0,T_{\mathrm{r}}}$).

Perspectives for future work

- Find data-driven solutions to other control problems
- Derivation of a feedback controller directly from data
- Recursive algorithms
- Dealing with perturbed data

Final goal:

approximate recursive algorithms for data-driven control.