A low dimensional contractive NMPC scheme for nonlinear systems stabilization

Theoretical Framework & Numerical investigation on relatively fast systems

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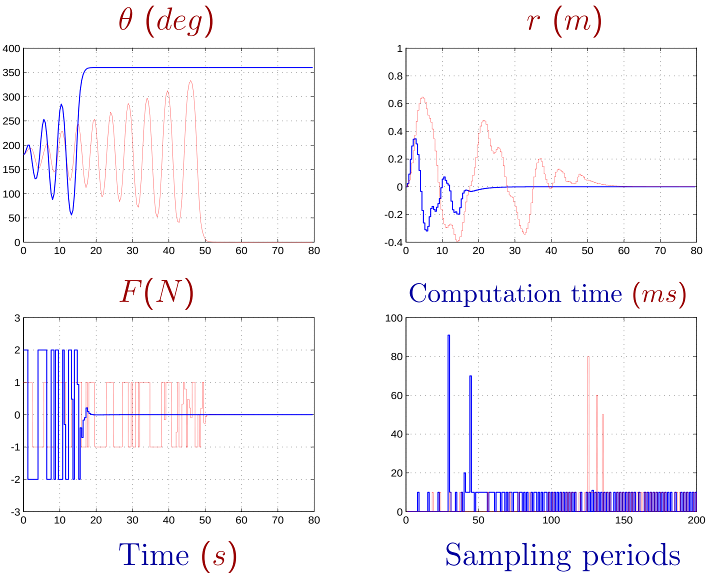
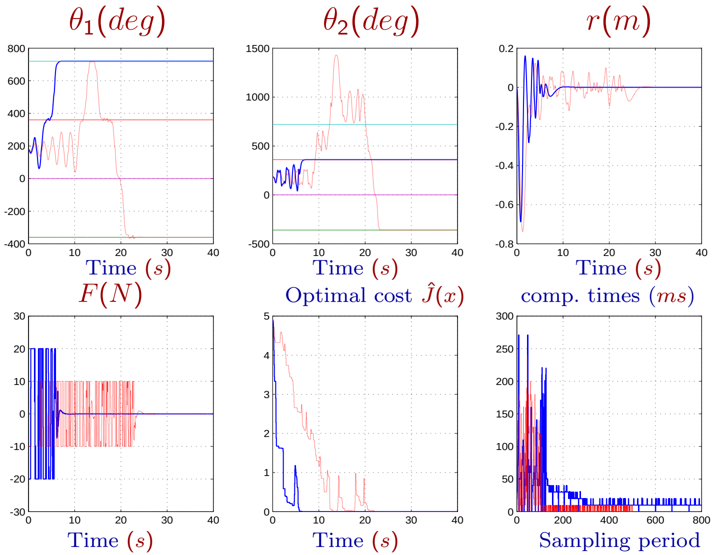
Motivation

- Classical formulations are "**Optimality oriented**"
- Stability is achieved by auxiliary "*tricks*"
  - Final equality constraint
  - Final inequality constraint / terminal region
  - Infinite prediction horizon
- The resulting problem is heavy to tackle and formulate numerically whatever is the implementation "*(complete / real time)*"

What if the stability was the main issue ...?


θ (deg)
r (m)
F(N)
Computation time (ms)
Time (s)
Sampling periods
400
350
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
1
0.8
0.6
0.4
0.2
-0.2
-0.4
3
2
-1
-2
-3
100
150


θ1(deg)
θ2(deg)
r(m)
Time (s)
Time (s)
Time (s)
F(N)
Optimal cost Ĵ(x)
comp. times (ms)
Time (s)
Time (s)
Sampling period

A new contractive formulation

- Finite & **short** prediction horizon
- **Without** any final or terminal requirements
- **provably stable** closed-loop
- **Low dimensional** decision variable (scalar & 2-dimensional)
- Solution uses only **black-box** simulator.

Outline

A preliminary example

Consider the nonlinear system

$$\dot{x}_1 = x_2 \quad ; \quad \dot{x}_2 = x_1 u$$

and the "*candidate*" Lyapunov function

$$V(x) = \frac{1}{2}\left[x_1^2 + x_2^2\right]$$

Compute the derivative of V

$$\dot{V}(x) = x_1 x_2 (1 + u)$$

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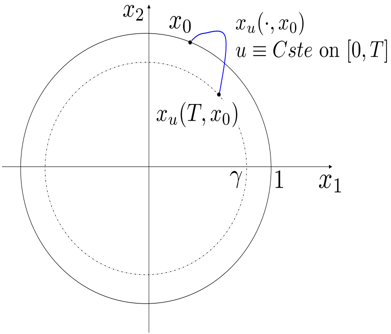
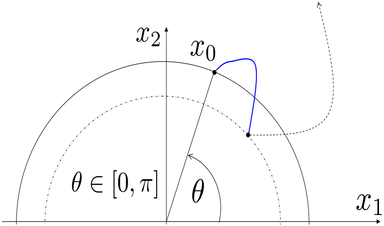
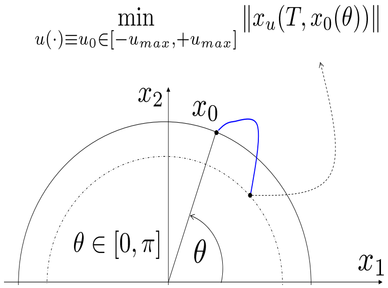
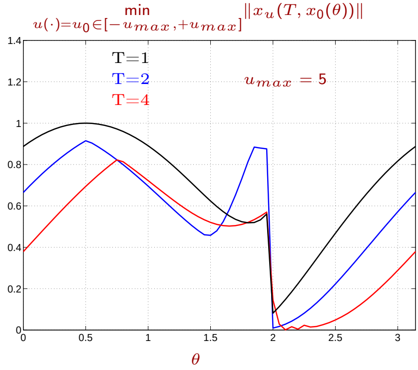
But...



$$\min_{u(\cdot)\equiv u_0\in[-u_{max},+u_{max}]} \|x_u(T,x_0(\theta))\|$$




$\min_{u(\cdot)\equiv u_0 \in [-u_{max}, +u_{max}]} \|x_u(T, x_0(\theta))\|$
x_2
x_0
$\theta \in [0, \pi]$
θ
x_1


$\min_{u(\cdot)=u_0 \in [-u_{max}, +u_{max}]} \|x_u(T, x_0(\theta))\|$
T=1
T=2
T=4
$u_{max} = 5$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
θ

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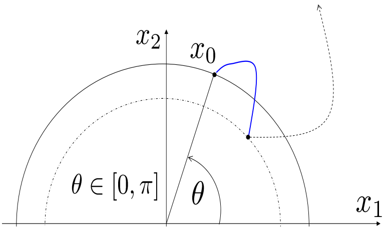

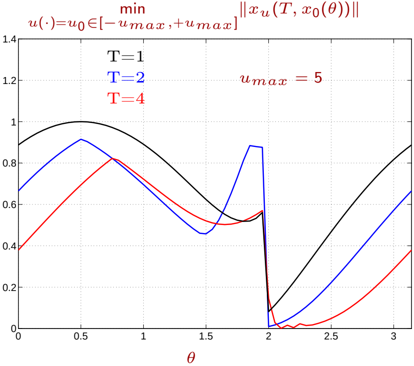

To summarize : A long term contraction property

Whatever is the initial state $x_0 \in B(0,1)$, there exists constant control $u \in [-5,+5]$ such that

$$V\left(x_u(2,x_0)\right)\| \leq 0.9\ V(x_0) \quad \text{or} \quad \left[V\left(x_u(4,x_0)\right)\| \leq 0.82\ V(x_0)\right]$$

A bad formulation

Define a receding horizon feedback based on the following open-loop optimization problem

$$\min_{\mathbf{u}(\cdot),\Delta\in[0,T]} \int_0^{\Delta} L\Big(x_u(\tau,x(t))\Big)d\tau \quad \text{under } V(x_u(t+\Delta,x(t))) \leq \gamma\, V(x(t))$$

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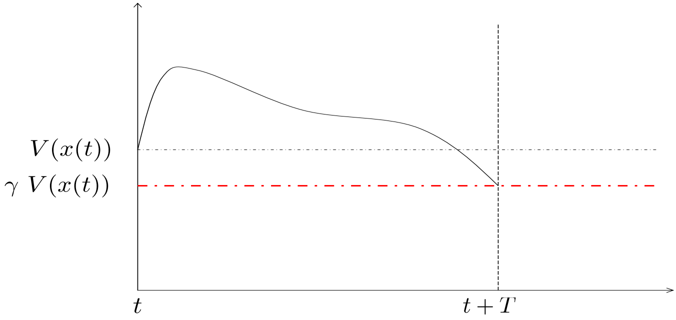

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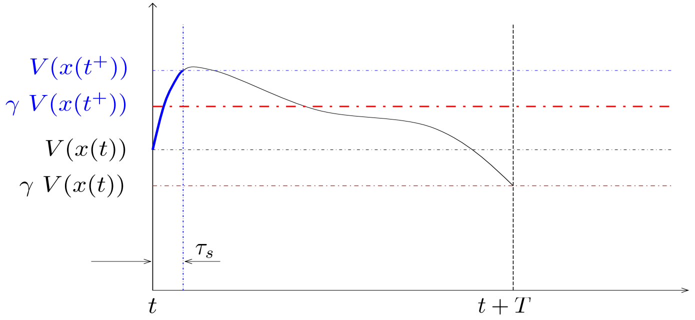

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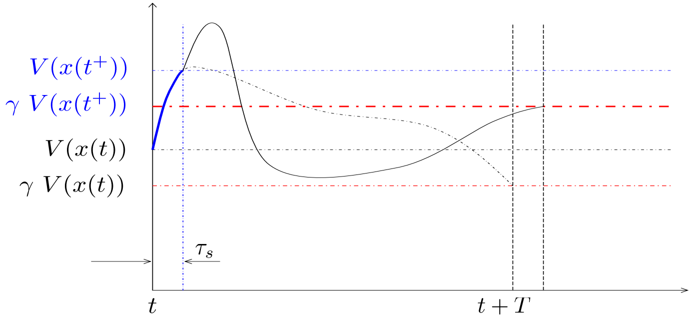

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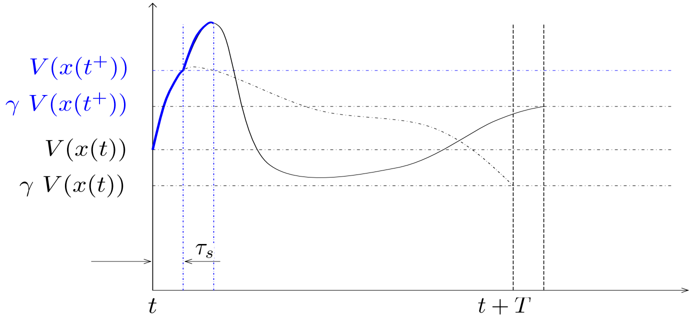

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Updating systematically the contractive constraint

$$V(x_u(\Delta,x(t))) \leq \gamma\, V(x(t))$$

May cause instability in closed-loop

Kothare, S. L. de Oliveira and Morari, M. IEEE-TAC Vol 45 pp 1053-1071 (2000)

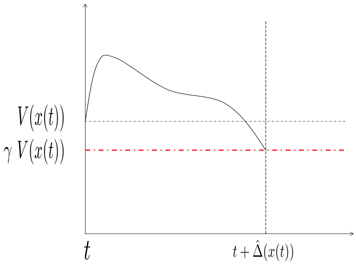
Kothare, S. L. de Oliveira and Morari, M. IEEE-TAC Vol 45 pp 1053-1071 (2000)

Either

Use the open-loop control

$$\hat{u}(\cdot, x(t))$$

on $[t, t + \hat{\Delta}(x(t))]$



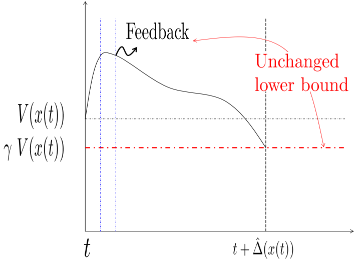
Kothare, S. L. de Oliveira and Morari, M. IEEE-TAC Vol 45 pp 1053-1071 (2000)

Or

Memorize $x(t)$ and use

$$V(x_u(\Delta, x(t+k\tau_s))) \leq \gamma\, V(x(t))$$

in a RH scheme during the time interval $[t, t+\hat{\Delta}(x(t))]$



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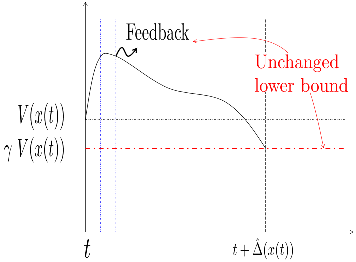

- Non standard RH implementation
- Lack of reactivity
- Potential feasibility problems
  - In presence of disturbances
  - Under truncated optimization

Consider nonlinear systems

$$\dot{x} = f(x,u) \quad ; \quad x \in \mathbb{R}^n \quad ; \quad u \in \mathbb{R}^m \quad ; \quad f \text{ continuous}$$

satisfying the following assumption

Infinitely fast state excursions need infinite control

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Infinitely fast state excursions need infinite control

For all finite horizon $T > 0$,

$$\lim_{\|x_0\| \to \infty} \left[\min_{\mathbf{u} \in \mathbb{W}^{[0,T]}} \quad \min_{t \in [0,T]} \|F(t, x_0, \mathbf{u})\| \right] = \infty$$

for all compact subset $\mathbb{W} \subset \mathbb{R}^m$. ♭

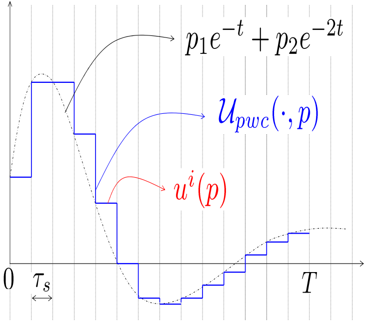
- ✓ Choose a sampling period τ_s
- ✓ Define a τ_s-piece-wise constant control profile

$$\mathcal{U}_{pwc}(\cdot, p) \quad ; \quad p \in \mathbb{P}$$

- ✓ The parametrization is called "*translatable*" if for all $p \in \mathbb{P}$, there is $p^+ \in \mathbb{P}$ s.t.

$$u^i(p^+) = u^{i+1}(p)$$

$$\forall i \in \{1, \dots, N-1\}$$



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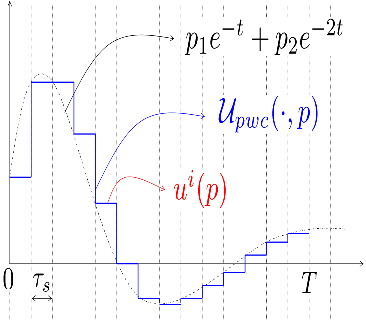

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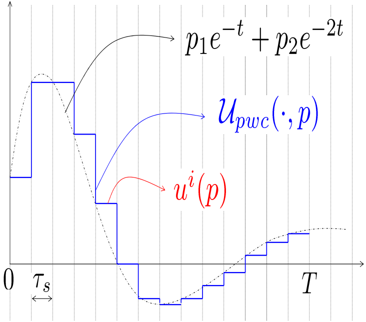

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Notation $F(\cdot, x, p)$, $V(\cdot, x, p)$

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The strong contraction property

1. $\exists \gamma \in]0,1[$ s.t. for all x, there exists $p^c(x) \in \mathbb{P}$ such that

$$\min_{q \in \{1,\dots,N\}} V(q\tau_s, x, p^c(x)) \leq \gamma V(x)$$

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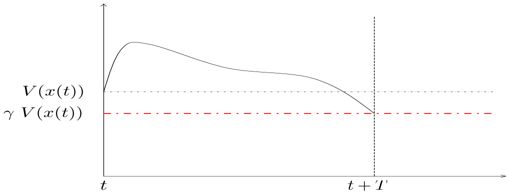
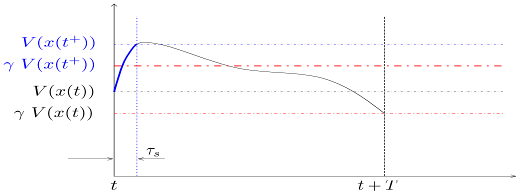
2. $p_c(\cdot)$ is bounded over bounded sets
3. $\exists$ a continuous function $\varphi : \mathbb{R}^n \to \mathbb{R}_+$ s.t. for all x :

$$\|V_{1\to N}(\cdot, x, p^c(x))\|_\infty \leq \varphi(x) \cdot V(x)$$

where

$$\|V_{1\to q}(\cdot, x, p)\|_\infty = \max_{i\in\{1,\dots,q\}} V(i\tau_s, x, p)$$


$V(x(t))$
$\gamma\ V(x(t))$
t
$t+T$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τ_s
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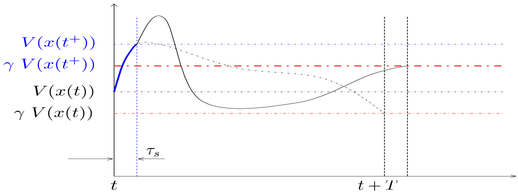
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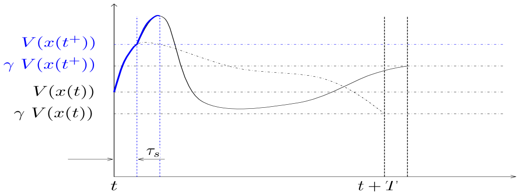
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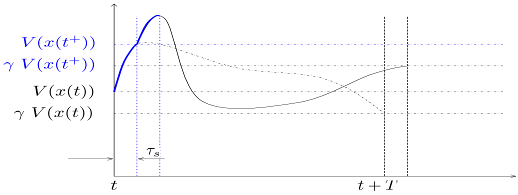
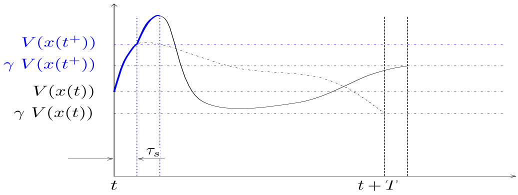


The open-loop optimal control problem

$$\min_{(q,p)\in\{1,\dots,N\}\times\mathbb{P}_{\mathbb{X}}} V(q\tau_s, x, p) + \alpha\frac{q}{N}\cdot\min\left\{\varepsilon^2, \|V_{1\to q}(\cdot, x, p)\|_\infty^2\right\}$$



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The receding-horizon state feedback

$$u(k\tau_s+\tau)=u^1(\hat{p}(x(k\tau_s)))\quad\forall\tau\in[0,\tau_s[$$

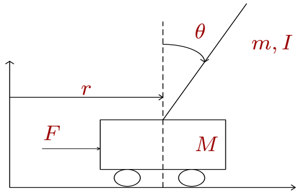
Basic Result

If the following conditions hold

1. Continuity (system/parametrization)
2. Infinitely fast excursions need infinite controls
3. The control parametrization is translatable on

$$\mathbb{P}_{\mathbb{X}} := \mathbb{P} \cap B\Big(0, \sup_{x \in \bar{B}(0,\rho(\mathbb{X}))} \|p^c(x)\| + \varepsilon_0\Big) \subseteq \mathbb{P} \subseteq \mathbb{R}^{n_p}$$

Then, $\exists$ sufficiently small $\varepsilon > 0$ and $\alpha > 0$ such that the RH feedback is well defined and makes the origin $x = 0$ asymptotically stable for the resulting CL dynamics with a region of attraction that contains $\mathbb{X}$.

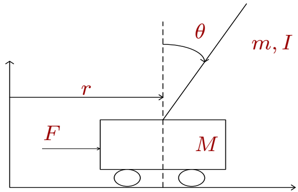


The system equations

$$\begin{pmatrix} mL^2 + I & mL\cos\theta \\ mL\cos\theta & m+M \end{pmatrix} \begin{pmatrix} \ddot{\theta} \\ \ddot{r} \end{pmatrix} = \begin{pmatrix} mLg\sin\theta - k_\theta\dot{\theta} \\ F + mL\dot{\theta}^2\sin\theta - k_x\dot{r} \end{pmatrix}$$

A pre-compensator

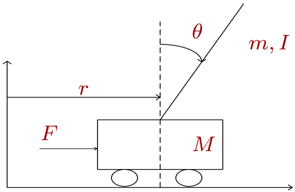
$$F = -K_{pre}\begin{pmatrix} r \\ \dot{r} \end{pmatrix} + u$$



The system equations

$$\dot{x}_1 = x_3 \quad ; \quad \dot{x}_2 = x_4$$

$$\begin{pmatrix} \dot{x}_3 \\ \dot{x}_4 \end{pmatrix} = [M(x)]^{-1} \begin{pmatrix} mLg\sin(x_1) - k_\theta \cdot x_3 \\ -K_{pre_1} x_2 - K_{pre_2} x_4 + mLx_3^2 \sin(x_1) - k_x x_4 + u \end{pmatrix}$$

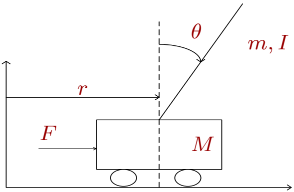


Control parametrization

$$u^i(p) = p \cdot e^{-t_i/t_r} \quad ; \quad t_i = \frac{(i-1)\tau_s}{N}$$

where $p \in \mathbb{P}(x) := [p_{min}(x), p_{max}(x)]$ s.t

$$\begin{aligned} p_{min}(x) &= -F_{max} + K_{pre_1} x_2 + K_{pre_2} x_4 \\ p_{max}(x) &= +F_{max} + K_{pre_1} x_2 + K_{pre_2} x_4 \end{aligned}$$



Use the contractive RH formulation given by :

$$V(x) = \frac{1}{2}\left[\dot{\theta}^2 + \beta r^2 + \dot{r}^2\right] + [1-\cos(\theta)]^2$$

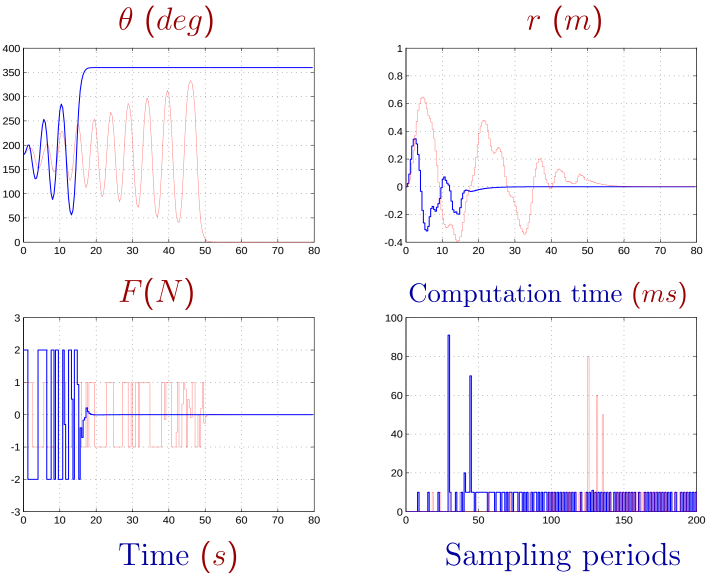
$$\min_{(q,p)\in\{1,\dots,N\}\times\mathbb{P}(x)} \quad V(q\tau_s, x, p) + \frac{\alpha}{N}\cdot\min\{\varepsilon, \|V_{1\to q}(\cdot, x, p)\|_\infty\}$$

$$u(k\tau_s + \tau) = u^1(\hat{p}(x(k\tau_s))) \quad \forall \tau \in [0, \tau_s[$$

The parameters of the controller

parameter	value	signification
τ_s	$0.4\ s$	sampling period
N	8	horizon length
t_r	0.2	Constant for the control param.
$\alpha = \varepsilon$	0.01	cost function parameters
K_{pre}	$\begin{pmatrix} 2.5 & 10.0 \end{pmatrix}$	Pre-compensation gain
F_{max}	$\in \{1.0, 2.0\}$	saturation level on F
β	$\in 10$	weighting coefficient on r

Runs on a $1.3\ GHz$ Pentium-III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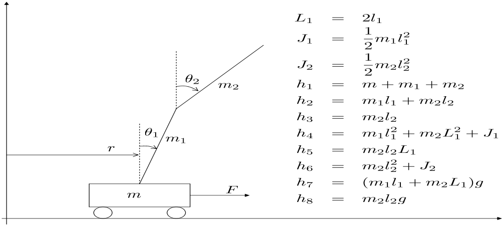
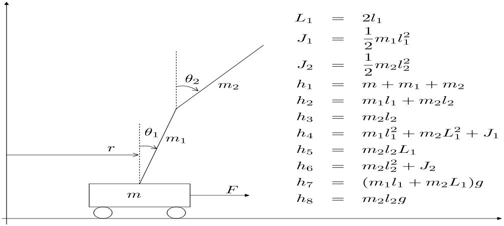


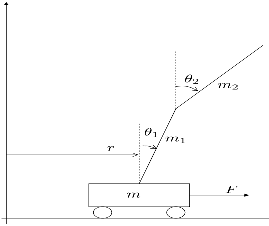
$$
\begin{aligned}
L_1 &= 2l_1 \\
J_1 &= \frac{1}{2}m_1 l_1^2 \\
J_2 &= \frac{1}{2}m_2 l_2^2 \\
h_1 &= m + m_1 + m_2 \\
h_2 &= m_1 l_1 + m_2 l_2 \\
h_3 &= m_2 l_2 \\
h_4 &= m_1 l_1^2 + m_2 L_1^2 + J_1 \\
h_5 &= m_2 l_2 L_1 \\
h_6 &= m_2 l_2^2 + J_2 \\
h_7 &= (m_1 l_1 + m_2 L_1) g \\
h_8 &= m_2 l_2 g
\end{aligned}
$$



$$
\begin{aligned}
L_1 &= 2l_1\\
J_1 &= \frac{1}{2}m_1 l_1^2\\
J_2 &= \frac{1}{2}m_2 l_2^2\\
h_1 &= m + m_1 + m_2\\
h_2 &= m_1 l_1 + m_2 l_2\\
h_3 &= m_2 l_2\\
h_4 &= m_1 l_1^2 + m_2 L_1^2 + J_1\\
h_5 &= m_2 l_2 L_1\\
h_6 &= m_2 l_2^2 + J_2\\
h_7 &= (m_1 l_1 + m_2 L_1)g\\
h_8 &= m_2 l_2 g
\end{aligned}
$$

System equations

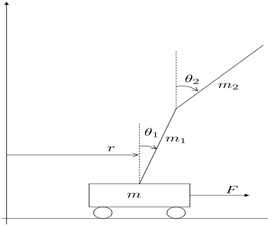
$$
\begin{aligned}
h_1\ddot{r} + h_2\ddot{\theta}_1\cos\theta_1 + h_3\ddot{\theta}_2\cos\theta_2 &= h_2\dot{\theta}_1^2\sin\theta_1 + h_3\dot{\theta}_2^2\sin\theta_2 + F\\
h_2\ddot{r}\cos\theta_1 + h_4\ddot{\theta}_1 + h_5\ddot{\theta}_2\cos(\theta_1-\theta_2) &= h_7\sin\theta_1 - h_5\dot{\theta}_2^2\sin(\theta_1-\theta_2)\\
h_3\ddot{r}\cos\theta_2 + h_5\ddot{\theta}_1\cos(\theta_1-\theta_2) + h_6\ddot{\theta}_2 &= h_5\dot{\theta}_1^2\sin(\theta_1-\theta_2) + h_8\sin\theta_2
\end{aligned}
$$



$$
\begin{aligned}
L_1 &= 2l_1\\
J_1 &= \frac{1}{2}m_1 l_1^2\\
J_2 &= \frac{1}{2}m_2 l_2^2\\
h_1 &= m + m_1 + m_2\\
h_2 &= m_1 l_1 + m_2 l_2\\
h_3 &= m_2 l_2\\
h_4 &= m_1 l_1^2 + m_2 L_1^2 + J_1\\
h_5 &= m_2 l_2 L_1\\
h_6 &= m_2 l_2^2 + J_2\\
h_7 &= (m_1 l_1 + m_2 L_1)g\\
h_8 &= m_2 l_2 g
\end{aligned}
$$

Pre-compensation

$$F = -K_{pre} \cdot \begin{pmatrix} r \\ \dot{r} \end{pmatrix} + u$$



$$
\begin{aligned}
L_1 &= 2l_1 \\
J_1 &= \frac{1}{2}m_1 l_1^2 \\
J_2 &= \frac{1}{2}m_2 l_2^2 \\
h_1 &= m + m_1 + m_2 \\
h_2 &= m_1 l_1 + m_2 l_2 \\
h_3 &= m_2 l_2 \\
h_4 &= m_1 l_1^2 + m_2 L_1^2 + J_1 \\
h_5 &= m_2 l_2 L_1 \\
h_6 &= m_2 l_2^2 + J_2 \\
h_7 &= (m_1 l_1 + m_2 L_1) g \\
h_8 &= m_2 l_2 g
\end{aligned}
$$

Control parametrization

$$u^i(p) = p_1 \cdot e^{\lambda_1 t_i} + p_2 e^{-\lambda_2 t_i} \quad ; \quad t_i = \frac{(i-1)\tau_s}{N}$$

$$p_{min}(x) := \frac{1}{2}\left[-F_{max} + K_{pre}\begin{pmatrix} r \\ \dot{r} \end{pmatrix}\right] \quad ; \quad p_{max}(x) := \frac{1}{2}\left[+F_{max} + K_{pre}\begin{pmatrix} r \\ \dot{r} \end{pmatrix}\right]$$

The contractive RH controller

$$
\begin{aligned}
V(x) &= \frac{h_4}{2}\dot{\theta}_1^2 + \frac{h_6}{2}\dot{\theta}_2^2 + h_5\dot{\theta}_1\dot{\theta}_2\cos(\theta_1-\theta_2) + h_7\left[1-\cos(\theta_1)\right] + \\
&+ h_8\left[1-\cos(\theta_2)\right] + h_1\left[r^2+\dot{r}^2\right] \\
u(k\tau_s+t) &= K_{RH}(x(k\tau_s)) := u^1(\hat{p}(x(k\tau_s))) \quad ; \quad t\in[0,\tau_s[
\end{aligned}
$$

The contractive RH controller

$$\begin{aligned} V(x) &= \frac{h_4}{2}\dot{\theta}_1^2 + \frac{h_6}{2}\dot{\theta}_2^2 + h_5\dot{\theta}_1\dot{\theta}_2\cos(\theta_1-\theta_2) + h_7\left[1-\cos(\theta_1)\right] + \\ &+ h_8\left[1-\cos(\theta_2)\right] + h_1\left[r^2+\dot{r}^2\right] \\ u(k\tau_s+t) &= K_{RH}(x(k\tau_s)) := u^1(\hat{p}(x(k\tau_s))) \quad ; \quad t\in[0,\tau_s[\end{aligned}$$

A local LQR controller

$$K_L(x) = -L\cdot\begin{pmatrix} x_1^m \\ x_2^m \\ x_3 \\ \vdots \\ x_6 \end{pmatrix}$$

solving the discrete time Riccati equation

$$A_d^TSA_d - S - (A_d^TSB_d)(R+B_d^TSB_d^T)(B_d^TSA_d) + Q = 0$$

Hybrid controller for swing-up and stabilization of the double inverted pendulum

To summarize, the hybrid controller is given by

$$u(k\tau_s+\tau)=\begin{cases} K_{RH}(x(k\tau_s)) & \text{if} \quad \|x(k\tau_s)\|_S^2>\eta \\ K_L(x(k\tau_s)) & \text{otherwise} \end{cases}$$

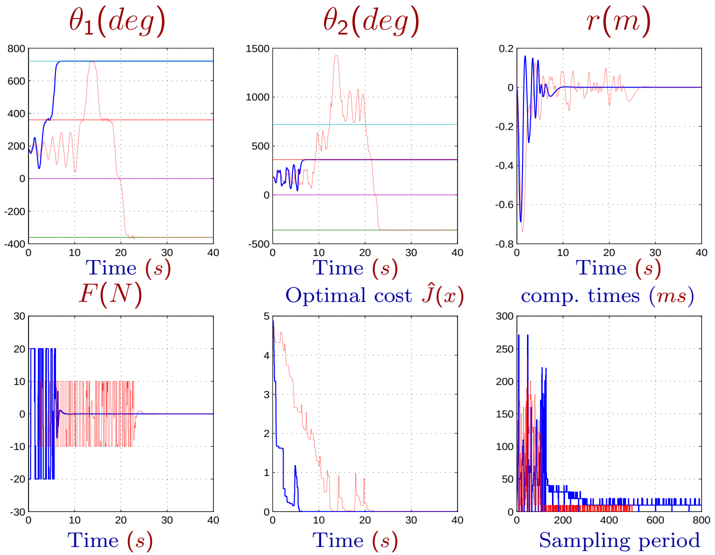
Hybrid controller for swing-up and stabilization of the double inverted pendulum

To summarize, the hybrid controller is given by

$$u(k\tau_s + \tau) = \begin{cases} K_{RH}(x(k\tau_s)) & \text{if} \quad \|x(k\tau_s)\|_S^2 > \eta \\ K_L(x(k\tau_s)) & \text{otherwise} \end{cases}$$

The parameters of the controller

parameter	**value**	**signification**
τ_s	$0.3\ s$	sampling period
N	10	horizon length
L	$(360, 29)$	(linear controller gain)
(λ_1, λ_2)	$(100, 20)$	Control parametrization
η	1.0	switching threshold
i_{max}	20	Max number of function evaluation


$\theta_1(deg)$
$\theta_2(deg)$
$r(m)$
Time (s)
Time (s)
Time (s)
$F(N)$
Optimal cost $\hat{J}(x)$
comp. times (ms)
Time (s)
Time (s)
Sampling period

Conclusion

Whatever are the numerical tools in your hand ...
Don't forget that the added-value of a control-designer is
THE PROVABLY SAFE, SIMPLE & DEDICATED FORMULATION

Don't rely on a black-box tool to overcome a bad formulation,
...you would pay it by "*lines of code*" and even dollars in the final product

The gains in efficiency are multiplicative