IInstitute of Information Engineering, Automation, and Mathematics
SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
FACULTY OF CHEMICAL AND FOOD TECHNOLOGY

Nonlinear Model Predictive Control of Rotary Inverted Pendulum

MASTER THESIS

Bc. Alexey Morozov

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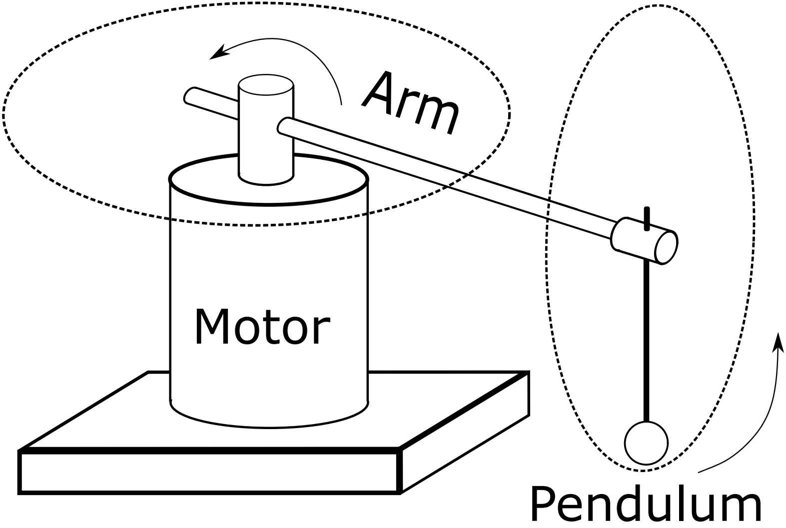
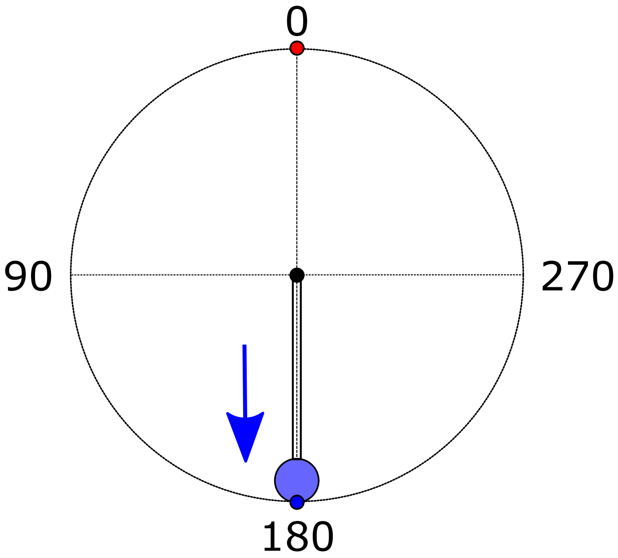
Supervisor: Ing. Martin Klaučo, PhD.
Consultant: Ing. Matúš Furka

Furuta Pendulum Device



Swing-Up Control of the Pendulum



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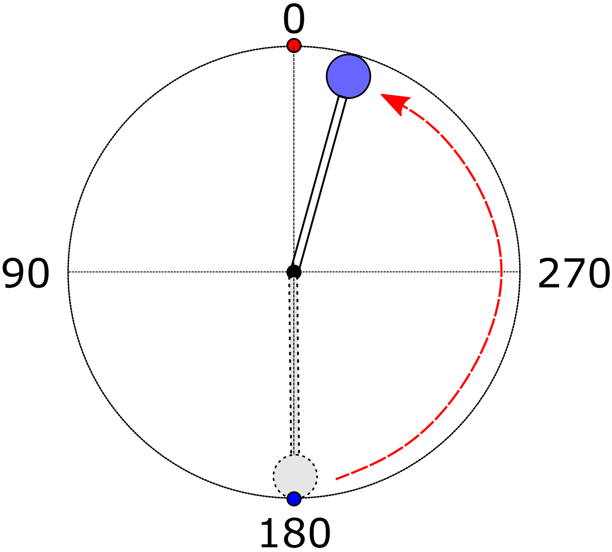

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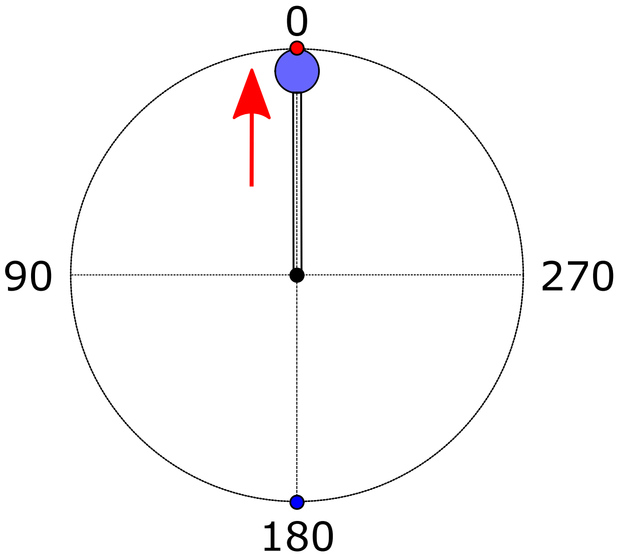
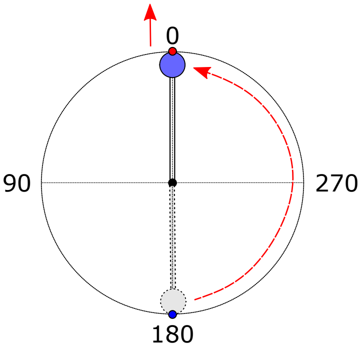


Swing-Up Control of the Pendulum

Main control strategies

1. Heuristic Swing-Up Control strategy
2. Optimal Swing-Up Control strategy



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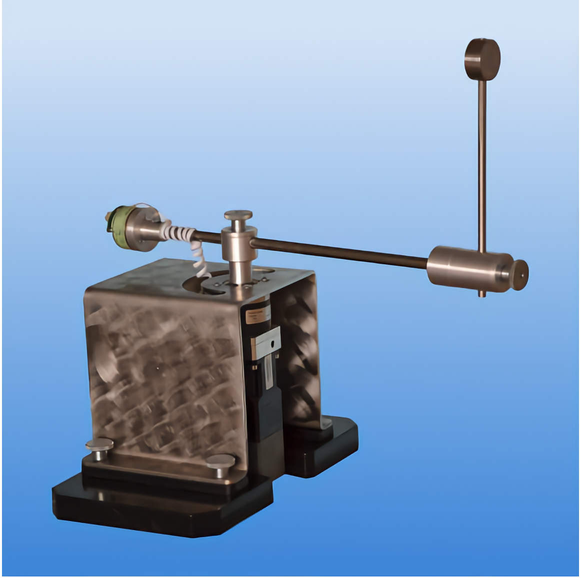


Lagrangian Formulation

Lagrangian

$$L = E_\mathsf{k} - E_\mathsf{p}$$

Euler-Lagrange Equations

$$\frac{\mathrm{d}}{\mathrm{d}\,t}\left(\frac{\partial\, L}{\partial\,\dot{\theta}_0}\right) - \frac{\partial\, L}{\partial\,\dot{\theta}_0} = \tau$$
$$\frac{\mathrm{d}}{\mathrm{d}\,t}\left(\frac{\partial\, L}{\partial\,\dot{\theta}_1}\right) - \frac{\partial\, L}{\partial\,\dot{\theta}_1} = 0$$

Lagrangian Formulation

Equations of motion

$$\ddot{\theta}_0 = \frac{\gamma(\epsilon\dot{\theta}_0^2 + \rho) - \delta(\tau + \beta\dot{\theta}_1^2 - \sigma\dot{\theta}_0\dot{\theta}_1)}{\gamma^2 - \alpha\delta}$$

$$\ddot{\theta}_1 = \frac{\gamma(\tau + \beta\dot{\theta}_1^2 - \sigma\dot{\theta}_0\dot{\theta}_1) - \alpha(\epsilon\dot{\theta}_0^2 + \rho)}{\gamma^2 - \alpha\delta}$$

Parametres

$$\alpha = I_0 + L_0^2 m_1 + l_1^2 m_1 \sin^2\theta_1$$

$$\beta = L_0 m_1 l_1 \sin\theta_1$$

$$\gamma = L_0 m_1 l_1 \cos\theta_1$$

$$\delta = I_1 + l_1^2 m_1$$

$$\epsilon = l_1^2 m_1 \sin\theta_1 \cos\theta_1$$

$$\rho = m_1 g l_1 \sin\theta_1$$

$$\sigma = 2 l_1^2 m_1 \sin\theta_1 \cos\theta_1$$

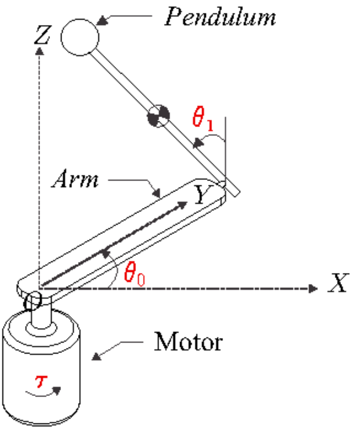
State-Space Formulation

State variables

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{bmatrix} = \begin{bmatrix} \theta_0(t) \\ \dot{\theta}_0(t) \\ \theta_1(t) \\ \dot{\theta}_1(t) \end{bmatrix}$$

Control input

$$u(t) = \tau(t)$$



State-Space Formulation

Non-linear model

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \\ \dot{x}_4(t) \end{bmatrix} = \begin{bmatrix} \dot{\theta}_0 \\ \frac{\gamma(\epsilon\dot{\theta}_0^2+\rho)-\delta(\tau+\beta\dot{\theta}_1^2-\sigma\dot{\theta}_0\dot{\theta}_1)}{\gamma^2-\alpha\delta} \\ \dot{\theta}_1 \\ \frac{\gamma(\tau+\beta\dot{\theta}_1^2-\sigma\dot{\theta}_0\dot{\theta}_1)-\alpha(\epsilon\dot{\theta}_0^2+\rho)}{\gamma^2-\alpha\delta} \end{bmatrix}$$

State-Space Formulation

Linear model

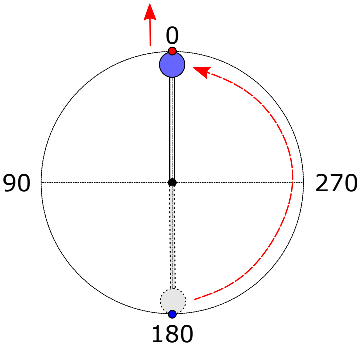
$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{-gL_0 l_1^2 m_1^2}{(m_1 L_0^2 + I_0)(m_1 l_1^2 + I_1) - L_0^2 l_1^2 m_1^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{g l_1 m_1 (m_1 L_0^2 + I_0)}{(m_1 L_0^2 + I_0)(m_1 l_1^2 + I_1) - L_0^2 l_1^2 m_1^2} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ \frac{m_1 L_1^2 + I_1}{(m_1 L_0^2 + I_0)(m_1 l_1^2 + I_1) - L_0^2 l_1^2 m_1^2} \\ 0 \\ \frac{-L_0 l_1 m_1}{(m_1 L_0^2 + I_0)(m_1 l_1^2 + I_1) - L_0^2 l_1^2 m_1^2} \end{bmatrix}$$

Swing-Up Control of the Pendulum

Main control strategies

1. Heuristic Swing-Up Control strategy
2. Optimal Swing-Up Control strategy



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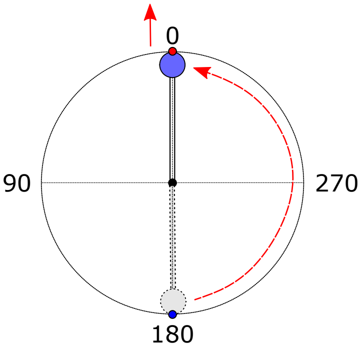


Heuristic Swing-Up Control

Two phases of control:

1. Initial excitation of the system (by Energy-Shaping controller)
2. Stabilisation of the pendulum (by Predictive controller)

Heuristic Swing-Up Control

Development of control strategy:

1. Design of Energy-Shaping controller
2. Design of Model Predictive controller
3. Full-range control of the pendulum

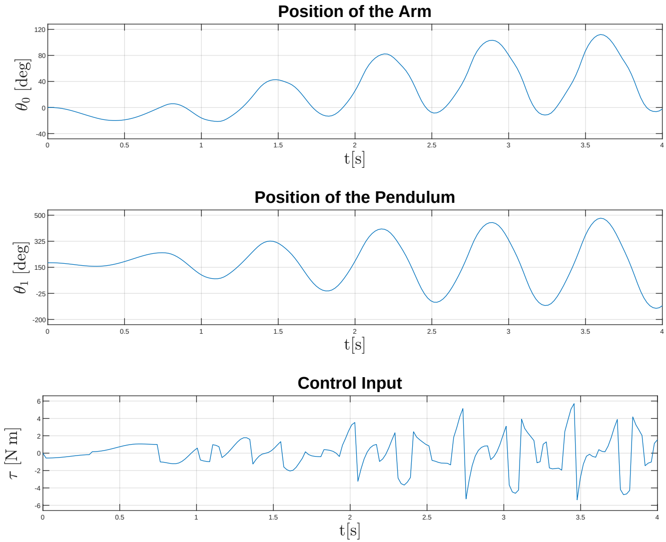
Initial Excitation of the System

Energy-Shaping controller

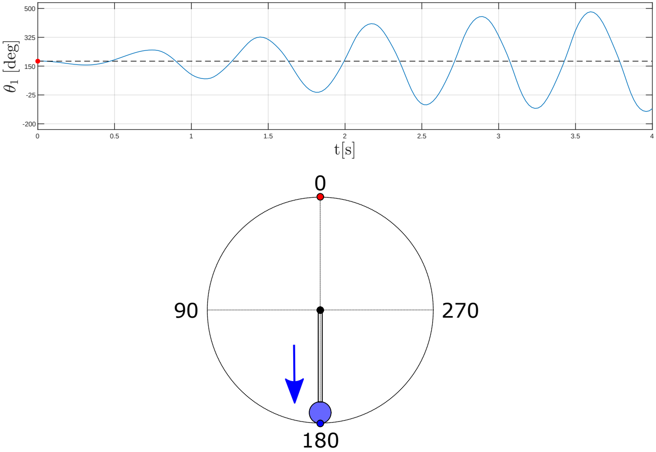
$$E = \frac{m_1 g l_1}{2}\left(\left(\frac{\dot{\theta}_1}{\omega_0}\right)^2 + \cos(\theta_1) - 1\right)$$

$$u = -4E\,\mathrm{sign}\left(\dot{\theta}_1 \cos(\theta_1)\right)$$

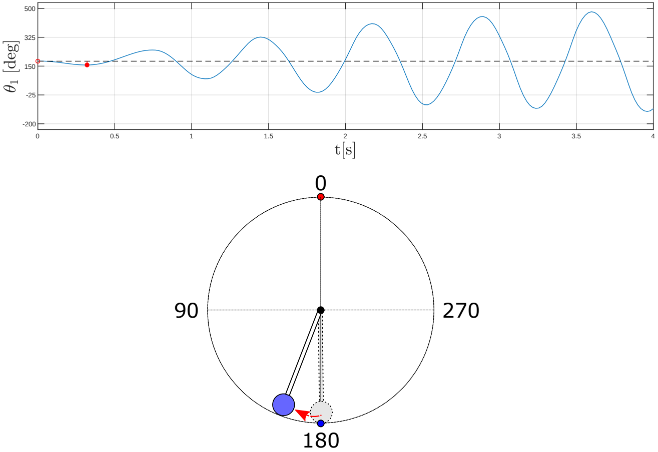
Initial Excitation of the System



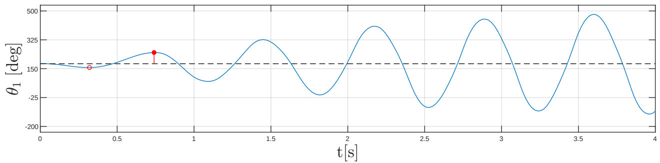
Initial Excitation of the System

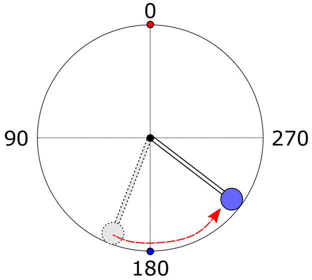


Initial Excitation of the System

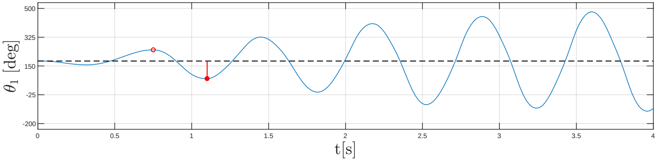


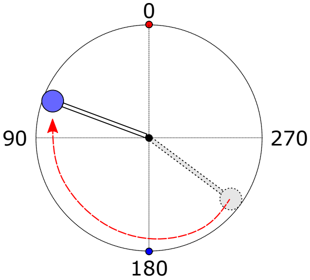
Initial Excitation of the System





Initial Excitation of the System





Stabilisation at the Upright Position

Model Predictive Control strategy

$$\begin{aligned}
\min_{u_0,\ldots,u_{N-1}} \quad & \sum_{k=0}^{N-1} \left(x_k^\mathsf{T} Q_\mathrm{x} x_k + u_k^\mathsf{T} Q_\mathrm{u} u_k\right) \\
\text{s.t.} \quad & x_{k+1} = Ax_k + Bu_k && k \in \mathbb{N}_0^{N-1} \\
& u_{\min} \leq u_k \leq u_{\max} && k \in \mathbb{N}_0^{N-1} \\
& x_0 = x(0)
\end{aligned}$$

Parameter	Symbol	Value
Prediction horizon	N	20
Initial condition	x_0	$\begin{bmatrix} 0 & 0 & 28.5 & -40 \end{bmatrix}^\mathsf{T}$
Constraint on control input-upper bound	$u_{\max}$	10
Constraint on control input-lower bound	$u_{\min}$	-10

Stabilisation at the Upright Position

Model Predictive Control strategy

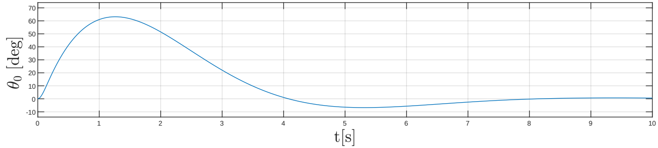
$$\begin{aligned} \min_{u_0,\ldots,u_{N-1}} \quad & \sum_{k=0}^{N-1} \left(x_k^\mathsf{T} Q_\mathrm{x} x_k + u_k^\mathsf{T} Q_\mathrm{u} u_k \right) \\ \text{s.t.} \quad & x_{k+1} = A x_k + B u_k & k \in \mathbb{N}_0^{N-1} \\ & u_\mathrm{min} \le u_k \le u_\mathrm{max} & k \in \mathbb{N}_0^{N-1} \\ & x_0 = x(0) \end{aligned}$$

Weight matrices

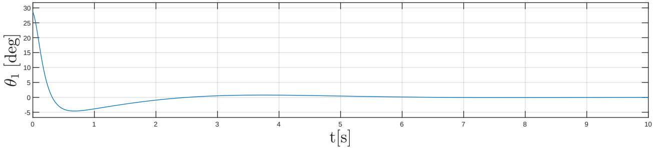
$$Q_\mathrm{x} = \begin{bmatrix} 5 & 0 & 0 & 0 \\ 0 & 0.08 & 0 & 0 \\ 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0.2 \end{bmatrix} \qquad Q_\mathrm{u} = 1 \times 10^{-3} \tag{8}$$

Stabilisation at the Upright Position

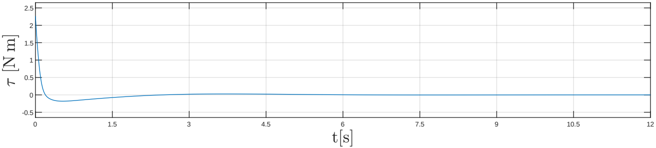
Position of the Arm



Position of the Pendulum



Control Input

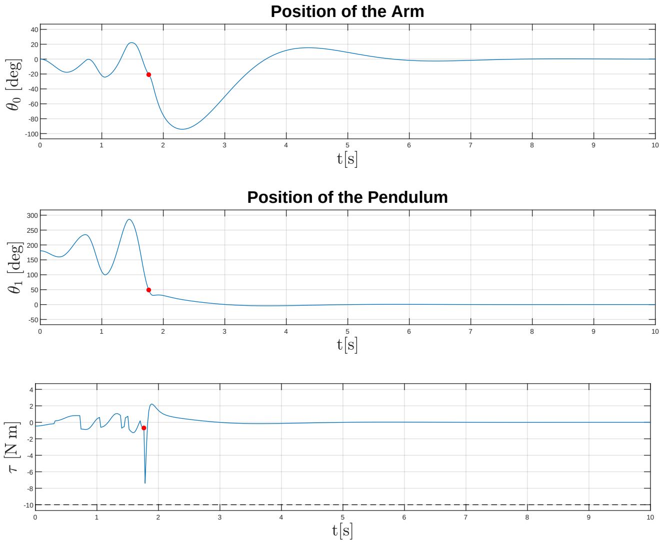


Full-Range Control

Algorithm 1 Heuristic Swing-Up Control strategy

```
procedure HEURISTIC SWING-UP CONTROL
    θ1 ← 180 deg
    Pendulum is controlled by Energy-Shaping controller
    if θ1 ∈ [−50, 50] deg then
        Pendulum is controlled by Predictive controller
    end if
end procedure
```

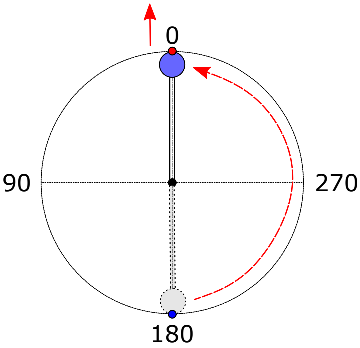
Full-Range Control



Swing-Up Control of the Pendulum

Main control strategies

1. Heuristic Swing-Up Control strategy
2. Optimal Swing-Up Control strategy



Optimal Control Strategy

Two phases of control:

1. Initial excitation of the system
(by Non-linear Predictive controller)
2. Stabilisation of the pendulum
(by Non-linear Predictive controller)

Non-Linerar Model Predictive Control

$$
\begin{aligned}
\min_{u_0,\ldots,u_{N-1}} \quad & \sum_{k=0}^{N-1} \left(x_k^\mathsf{T} Q_\mathrm{x} x_k + u_k^\mathsf{T} Q_\mathrm{u} u_k\right) & \\
\text{s.t.} \quad & x_{k+1} = f(x_k, u_k) & k \in \mathbb{N}_0^{N-1} \\
& u_{\min} \leq u_k \leq u_{\max} & k \in \mathbb{N}_0^{N-1} \\
& x_0 = x(0) &
\end{aligned}
$$

Parameter	Symbol	Value
Prediction horizon	N	20
Initial condition	x_0	$\begin{bmatrix} 0 & 0 & 180 & 0 \end{bmatrix}^\mathsf{T}$
Constraint on control input-upper bound	$u_{\max}$	10
Constraint on control input-lower bound	$u_{\min}$	-10

Non-Linerar Model Predictive Control

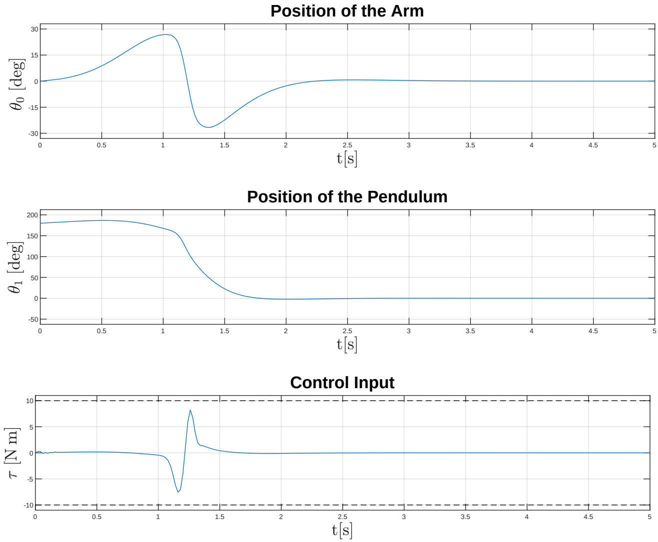
$$
\begin{aligned}
\min_{u_0,\dots,u_{N-1}} \quad & \sum_{k=0}^{N-1} \left(x_k^\intercal Q_\mathrm{x} x_k + u_k^\intercal Q_\mathrm{u} u_k\right) \\
\text{s.t.} \quad & x_{k+1} = f(x_k, u_k) && k \in \mathbb{N}_0^{N-1} \\
& u_\mathrm{min} \le u_k \le u_\mathrm{max} && k \in \mathbb{N}_0^{N-1} \\
& x_0 = x(0)
\end{aligned}
$$

Weight matrices

$$
Q_\mathrm{x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix} \qquad Q_\mathrm{u} = 0.1
$$

Full-Range Control

Control of the arm

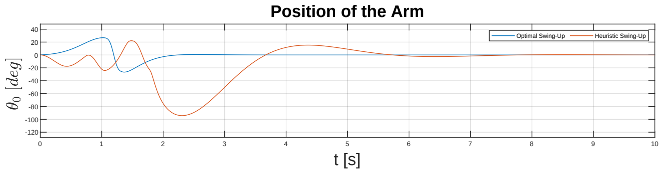


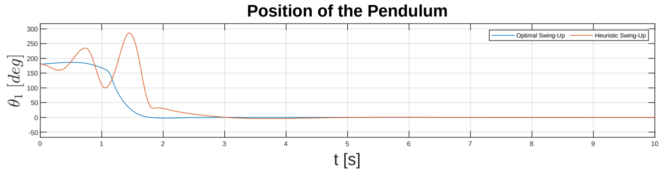
Discussion About Results

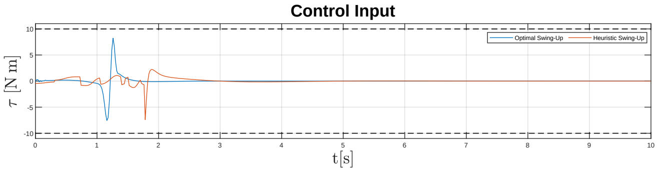
Quality criteria:

- Settling time
- Sum of abslolute error (SAE)
- Sum of squared control differences (SSCD)
- Solver solving time

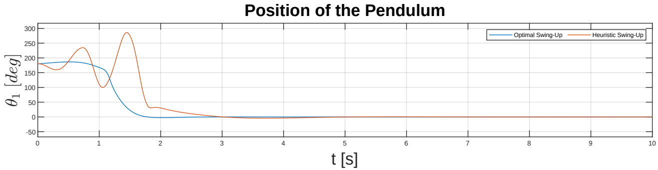
Discussion About Results

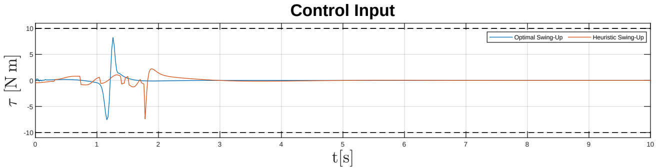






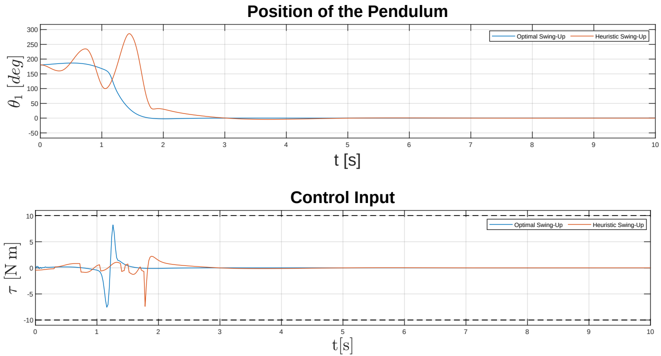
Discussion About Results





Strategy	Settling Time	SAE	SSCD	Solving Time		
				t_{min}	t_{avg}	t_{max}
Heuristic Swing-Up	7.51	305.15	86.77	0.0156	0.0234	0.0313
Optimal Swing-Up	3.20	205.56	88.94	0.0313	0.0469	0.0625

Discussion About Results



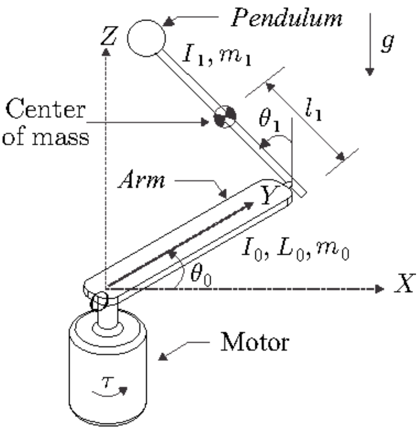
Strategy	Settling Time	SAE	SSCD	Solving Time t_{min}	Solving Time t_{avg}	Solving Time t_{max}
Heuristic Swing-Up	100%	100%	100%	100%	100%	100%
Optimal Swing-Up	42.6%	67.4%	103%	201%	200%	200%

Summary

Main achievements of the thesis

- Design of Optimal Swing-Up control strategy
- Its comparisson against the heuristic method
- Evaluation of control quality and execution time of individual approaches

Parametres of the Pendulum



g-gravitational acceleration [ms^{-2}]
m_0-mass of arm [kg]
m_1-mass of pendulum [kg]
L_0-length of arm [m]
L_1-length of pendulum [m]
l_0-arms center of mass [m]
l_1-pendulums center of mass [m]
I_0-arms moment of inertia [kg m^{-2}]
I_1-pendulums moment of inertia [kg m^{-2}]
θ_0-arm angle[rad]
θ_1-pendulum angle [rad]
τ-motor torque [N m]