

Case Studies Nonlinear Optimization

Open Cast Mining

Final Presentation

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Table of Contents

1 Problem Setting

2 Physical Model

3 Parameter Optimization

4 Summary

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2 Physical Model

3 Parameter Optimization

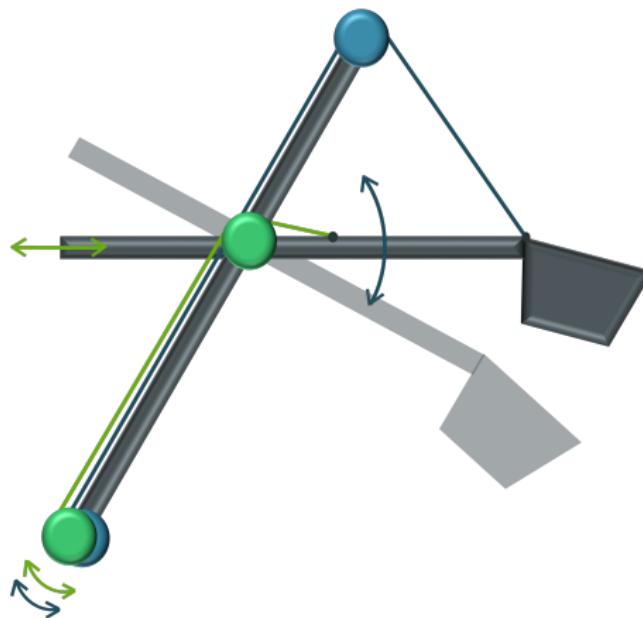
4 Summary



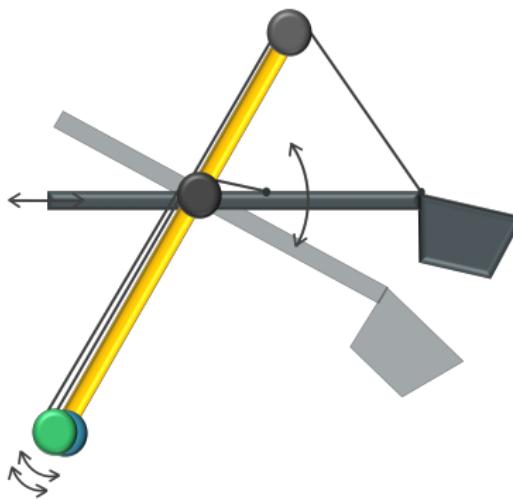
originally posted to Flickr by FAndrey at <http://flickr.com/photos/43301444@N06/4141786255>

- Goal: **optimization of model parameters**
- Models of technical system = physical properties + control properties

Problem Setting

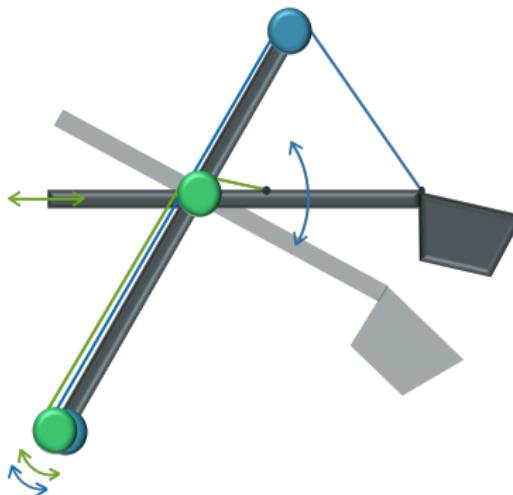


Problem Setting



- arm element fixed to base
- cannot be moved w.r.t. the base

Problem Setting



- green shovel motion **back and forth**
- blue shovel motion **up and down**

Main Problems

1. Physical Modelling

- Modelling rope properties
- Determining information needed for calibration of model

Main Problems

1. Physical Modelling

- Modelling rope properties
- Determining information needed for calibration of model

2. Parameter Optimization

- Optimizing parameters for a complex, unknown model (black box)

Physical Modelling

Why?

Building an accurate model



Good description of the effects of control and motion

Physical Modelling

Why?

Building an accurate model



Good description of the effects of control and motion

To consider:

- Friction in cable reels
- Deformation of ropes
- etc.

Parameter Optimization

What are parameters?

- Friction coefficients
- Mass
- Inertia

Parameter Optimization

What are parameters?

- Friction coefficients
- Mass
- Inertia

Why?

Accurate and realistic
parameters



Better prediction and
planning of motion

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Lagrange Formalism

Method to describe dynamics of an accelerated system

T kinetic energy

V potentials

F non-conservative external forces

r points of actions of forces F

q free variables

Q generalized forces

Lagrange Formalism

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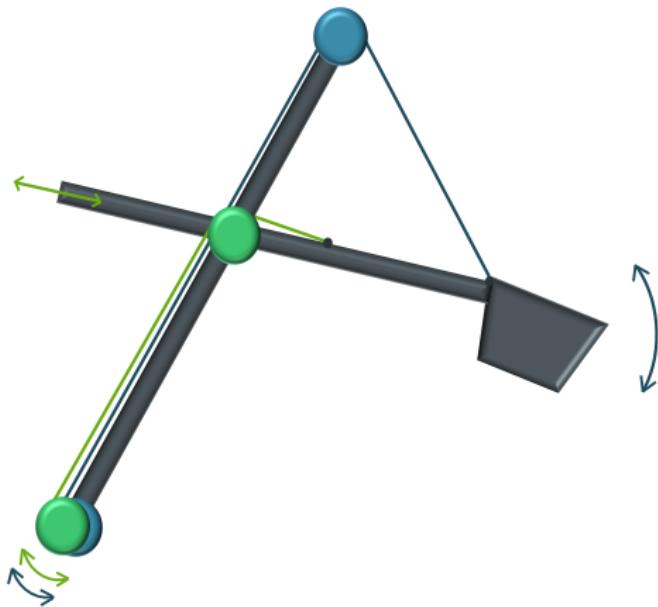
q free variables

Q generalized forces

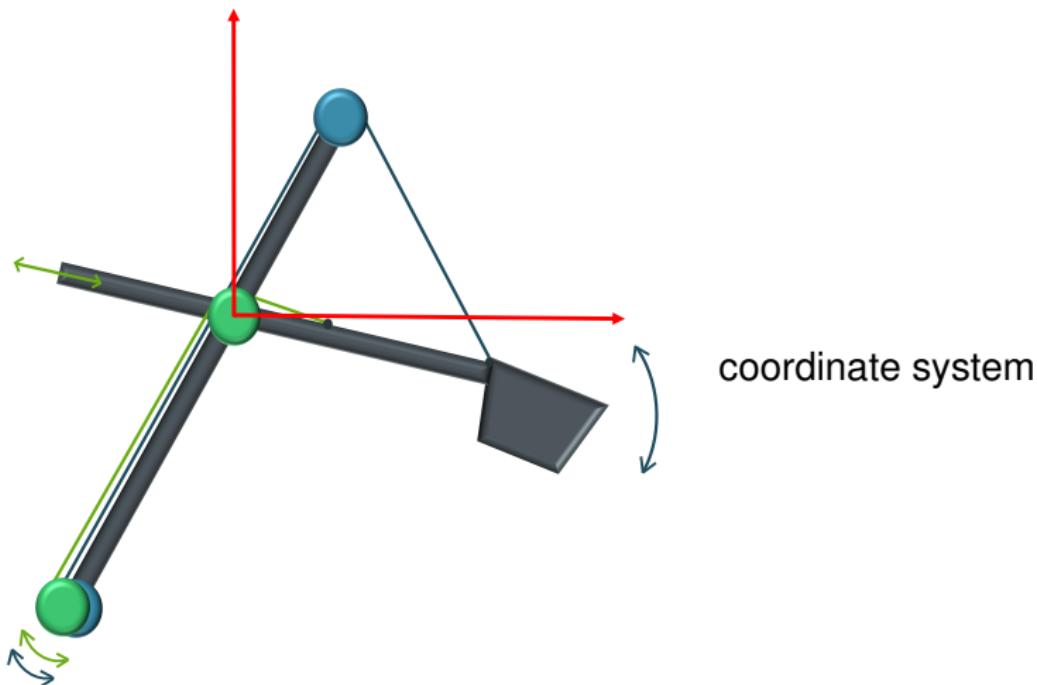
$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i$$

$$Q = \left(\frac{\partial r}{\partial q} \right)^T F$$

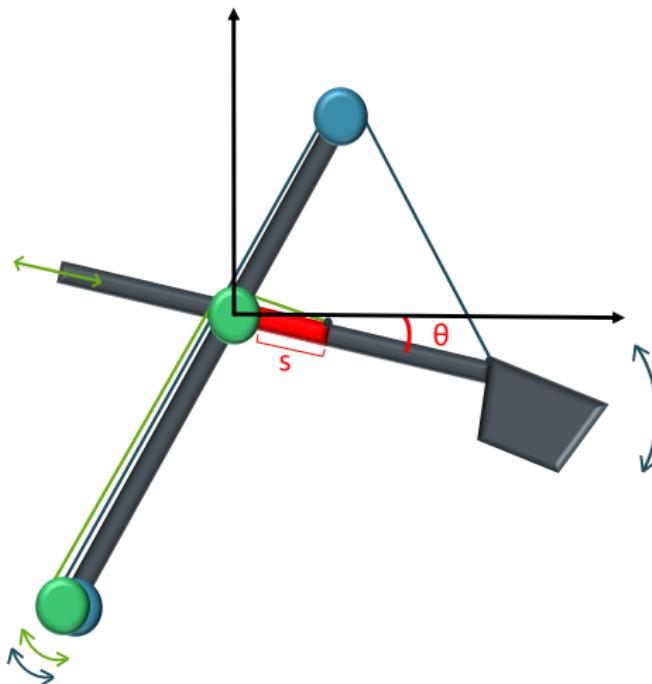
Physical Model of Excavator



Physical Model of Excavator



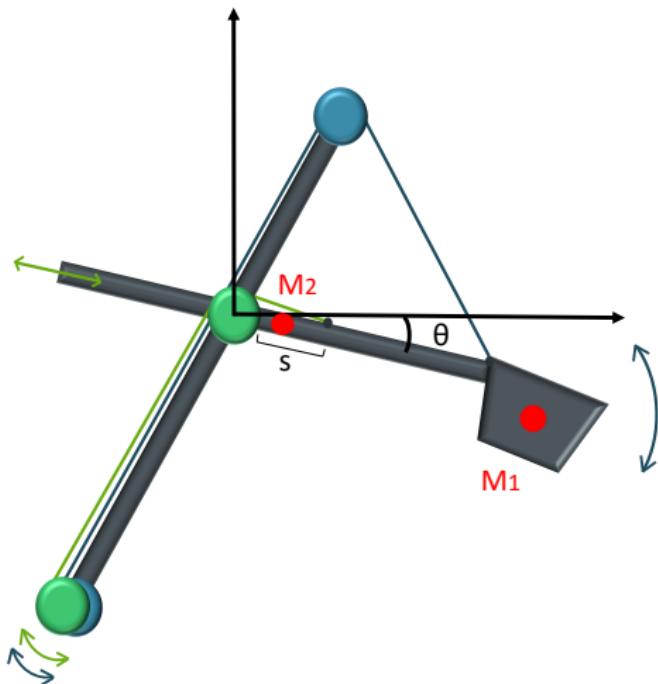
Physical Model of Excavator



degrees of freedom

- length s
- tilt angle θ

Physical Model of Excavator



movable centers of gravity of

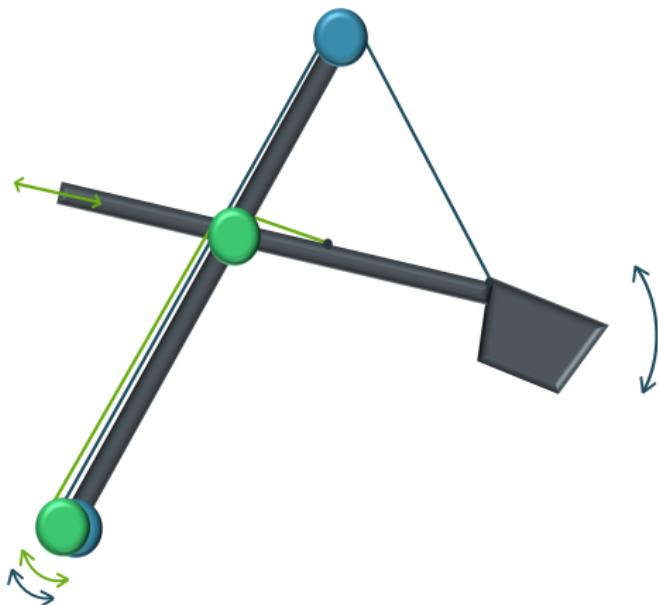
- shovel M_1
- arm M_2

Physical Model of Excavator

Assumptions to the model:

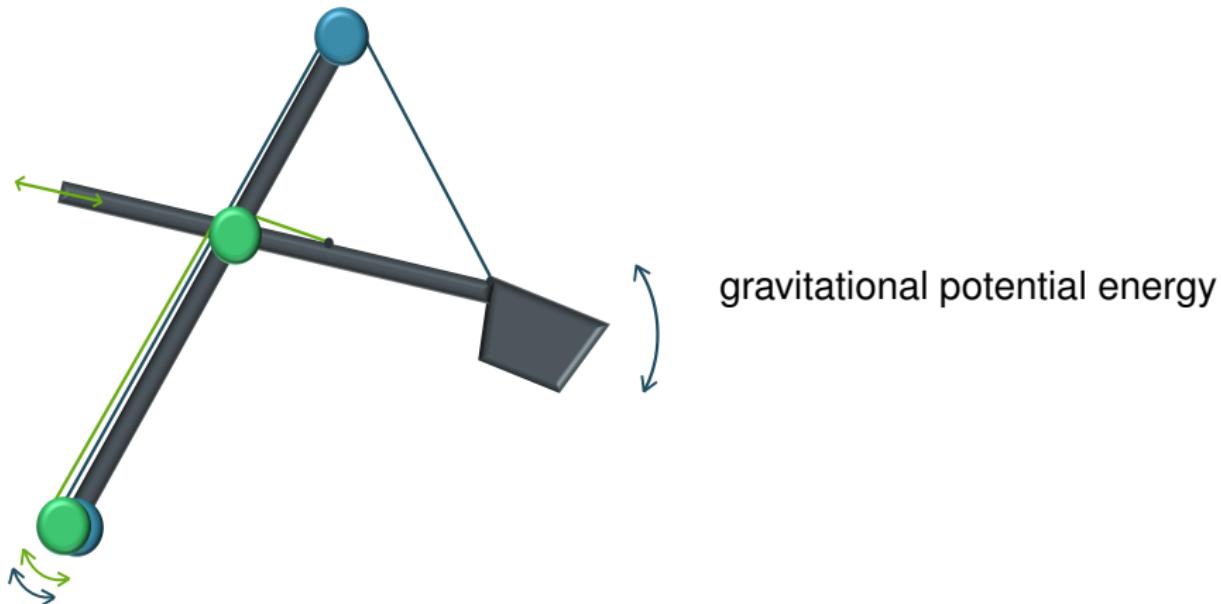
- no mass for the ropes
- shovel as point mass
- no slack/friction between ropes and cable reels

Kinetic Energy

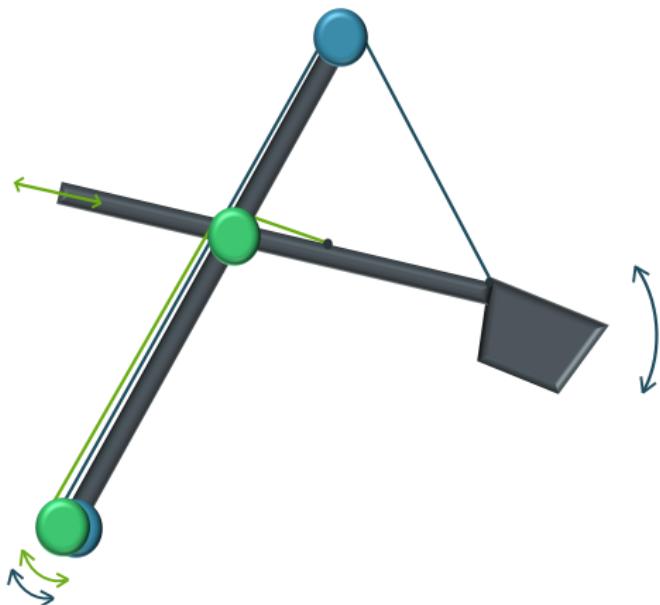


- movement of mass
- rotation of cable reel

Potential Energy



Generalized Forces



- torque on cable reel
- friction of cable reel

Lagrange Formalism

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{s}} \right) - \frac{\partial T}{\partial s} + \frac{\partial V}{\partial s} = Q_s$$

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{\theta}} \right) - \frac{\partial T}{\partial \theta} + \frac{\partial V}{\partial \theta} = Q_\theta$$

Resulting ODE

Second order ODE from Lagrange Formalism:

$$A(x, p) \begin{pmatrix} \ddot{s} \\ \ddot{\theta} \end{pmatrix} = b(x, u, p)$$

Transformed into first order ODE:

$$\frac{d}{dt} \begin{pmatrix} s \\ \theta \\ \dot{s} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \dot{s} \\ \dot{\theta} \\ A^{-1}(x, p)b(x, u, p) \end{pmatrix} = f(x, u, p)$$

state $x = (s, \theta, \dot{s}, \dot{\theta})^T$

control $u = (\tau_1, \tau_2)^T$

parameters $p = (p_1, \dots, p_k)^T$

Discretization of the ODE

Discretize time interval:

$$[0, T] \rightarrow \{0 = t_0, t_1, \dots, t_{m-1}, t_m = T\}$$

Discretize state and control:

$$x_n = x(t_n)$$

$$u_n = u(t_n)$$

Discretization of the ODE

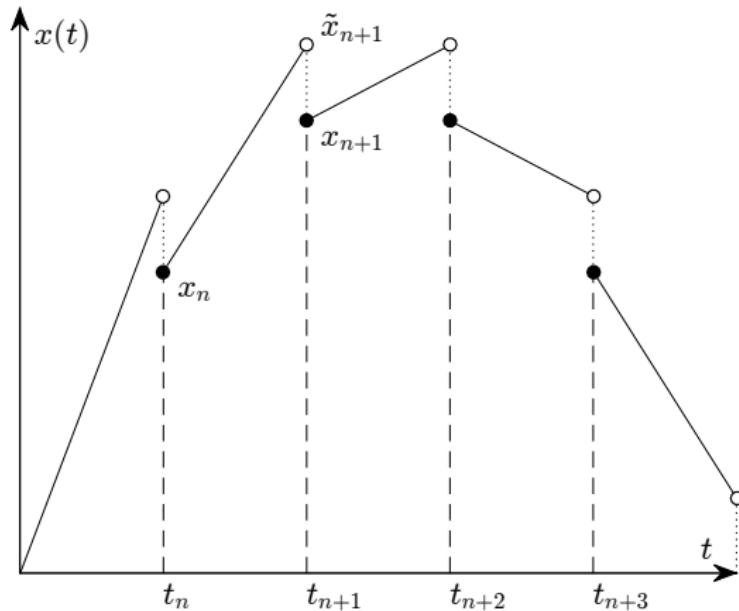
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

$$x_{n+1} \approx \tilde{x}_{n+1} = x_n + h_n f(x_n, u_n, p) =: \Psi(x_n, u_n, p)$$

Discrete constraint:

$$0 = x_{n+1} - \Psi(x_n, u_n, p) =: \Phi_n(x, u, p) \quad \forall n = 0, \dots, m-1$$

Discretization of the ODE



Multiple Shooting

Natural approach: Optimal Control Problem

$$\begin{aligned} \min_{x,p} \quad & \frac{1}{2} \|\bar{x} - x\|^2 \\ \text{s. t.} \quad & \Phi(x, u, p) = 0 \\ & p \geq 0 \end{aligned}$$

state	$x = (s, \theta, \dot{s}, \dot{\theta})^T$
control	$u = (\tau_1, \tau_2)^T$
parameters	$p = (p_1, \dots, p_k)^T$
reference	\bar{x}

Multiple Shooting

Input:

- control u
- reference trajectory \bar{x} related to u

Multiple Shooting

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Output:

- parameters p of the excavator
- x , but not of interest

Multiple Shooting

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- control u
- reference trajectory \bar{x} related to u

Output:

- parameters p of the excavator
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Idea:

- get rid of variable x
- set $x := \bar{x}$
- solve a relaxed problem

Multiple Shooting

Original Problem

$$\begin{aligned} \min_{x,p} \quad & \frac{1}{2} \|\bar{x} - x\|^2 \\ \text{s. t.} \quad & \Phi(x, u, p) = 0 \\ & p \geq 0 \end{aligned}$$

Multiple Shooting

Original Problem

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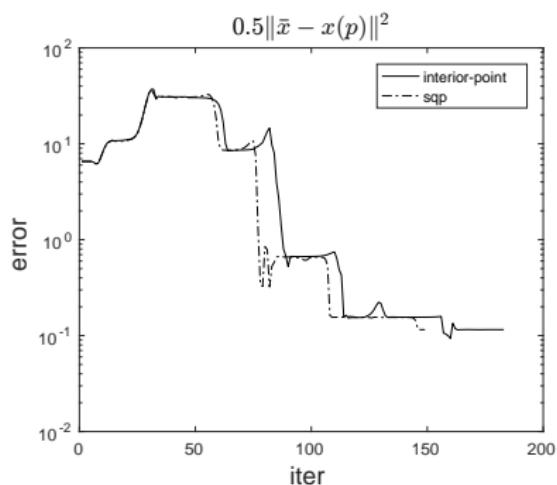
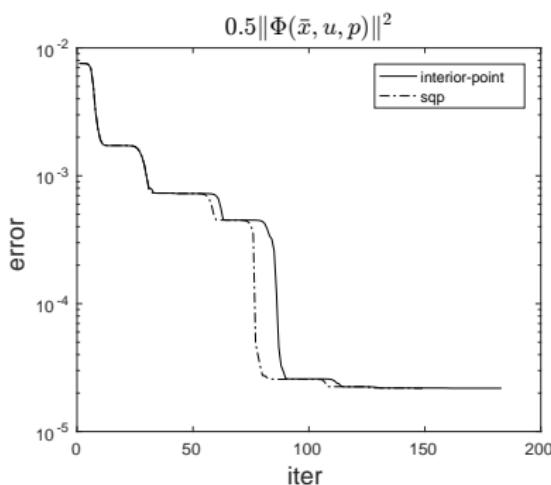
Reinterpreted Problem

$$\begin{aligned} \min_p \quad & \frac{1}{2} \|\Phi(\bar{x}, u, p)\|^2 \\ \text{s. t.} \quad & p \geq 0 \end{aligned}$$

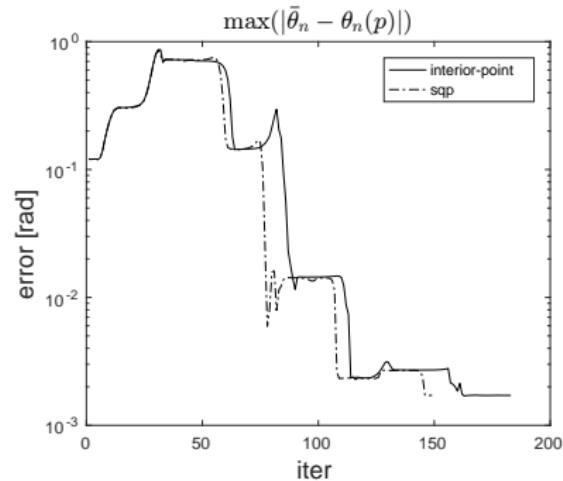
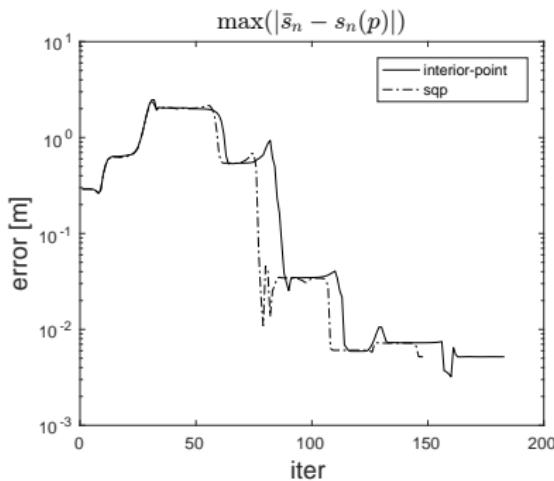
Comparison

plots explaining difference of the approaches

Results



Results



Exact up to 1cm

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Parameters

Examples:

- Friction coefficients $\mu_{B_1}, \mu_{B_2}, \mu_{P_1}, \mu_{P_2}$
- Masses M_1, M_2
- Inertia $I_{B_1}, I_{B_2}, I_{P_1}, I_{P_2}$

Parameters

Examples:

- Friction coefficients $\mu_{B_1}, \mu_{B_2}, \mu_{P_1}, \mu_{P_2}$
- Masses M_1, M_2
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Why do we need parameter optimization?

- Hard to measure
- May change over time

Blackbox Model

- Contains a realistic model from Siemens
- Confidential information

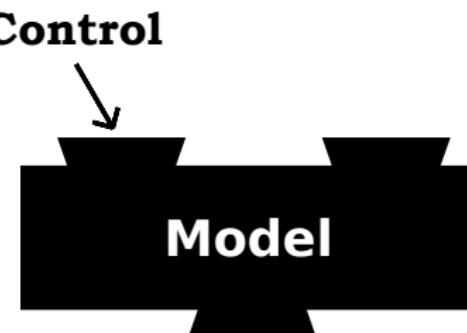
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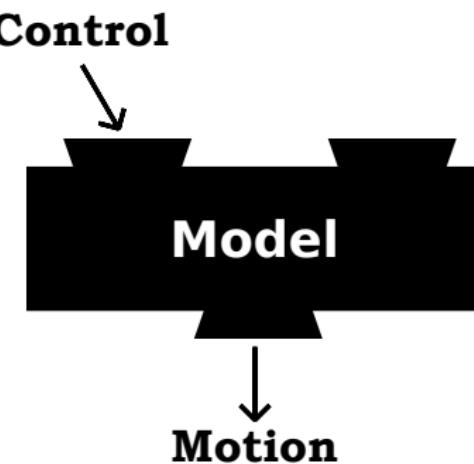
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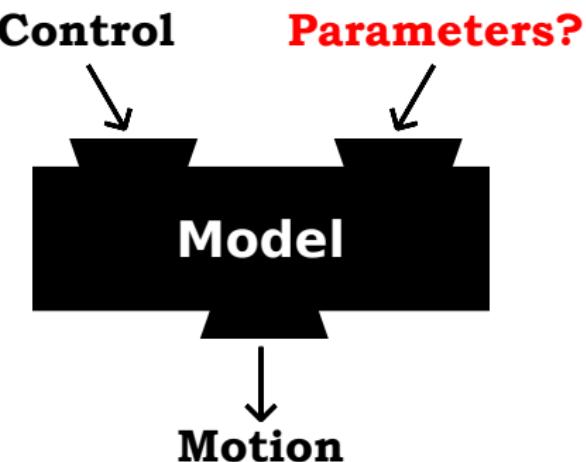
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Blackbox Model

- Contains a realistic model from Siemens
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Parameter Optimization

Parameters to optimize:

- Parameters of own model
- Black box model
 - ⇒ derivative-free optimization

Parameter Optimization

Parameters to optimize:

- Parameters of own model
- Black box model
 - ⇒ derivative-free optimization

Define penalty terms

⇒ minimize for parameter solutions

Table of Contents

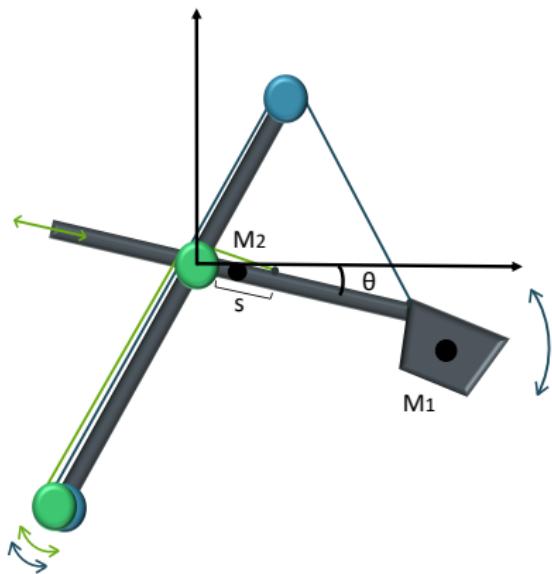
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