

Case Studies Nonlinear Optimization

Open Cast Mining

Final Presentation

June 09, 2016

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- 1 Problem Setting
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Optimization
- 5 Summary

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1 Problem Setting

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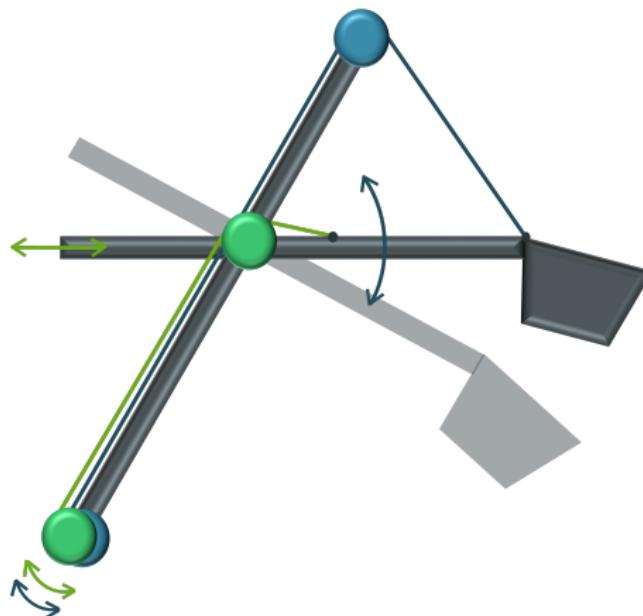
5 Summary



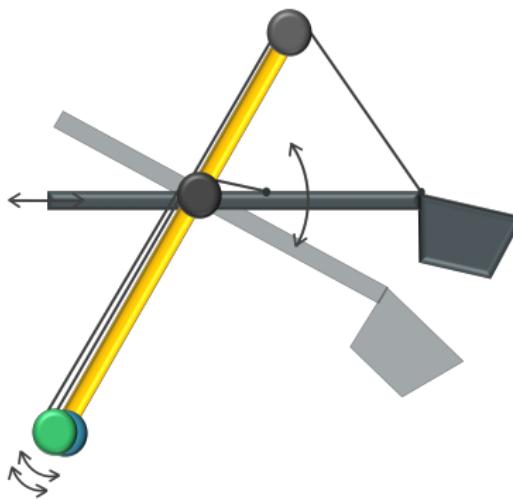
originally posted to Flickr by FAndrey at <http://flickr.com/photos/43301444@N06/4141786255>

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

Problem Setting

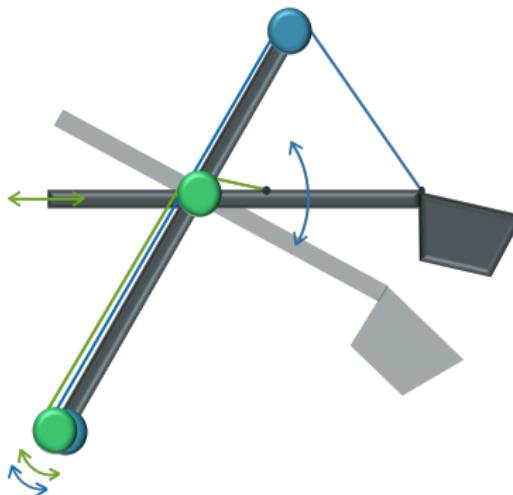


Problem Setting



- 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

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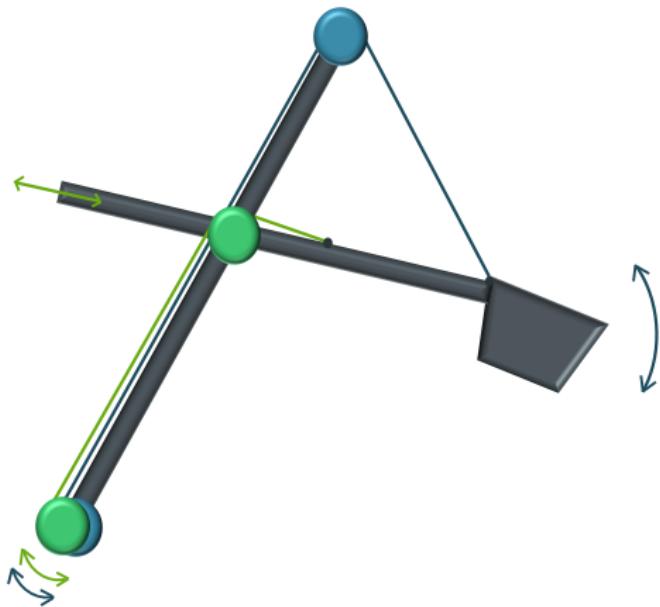
q free variables

Q generalized forces

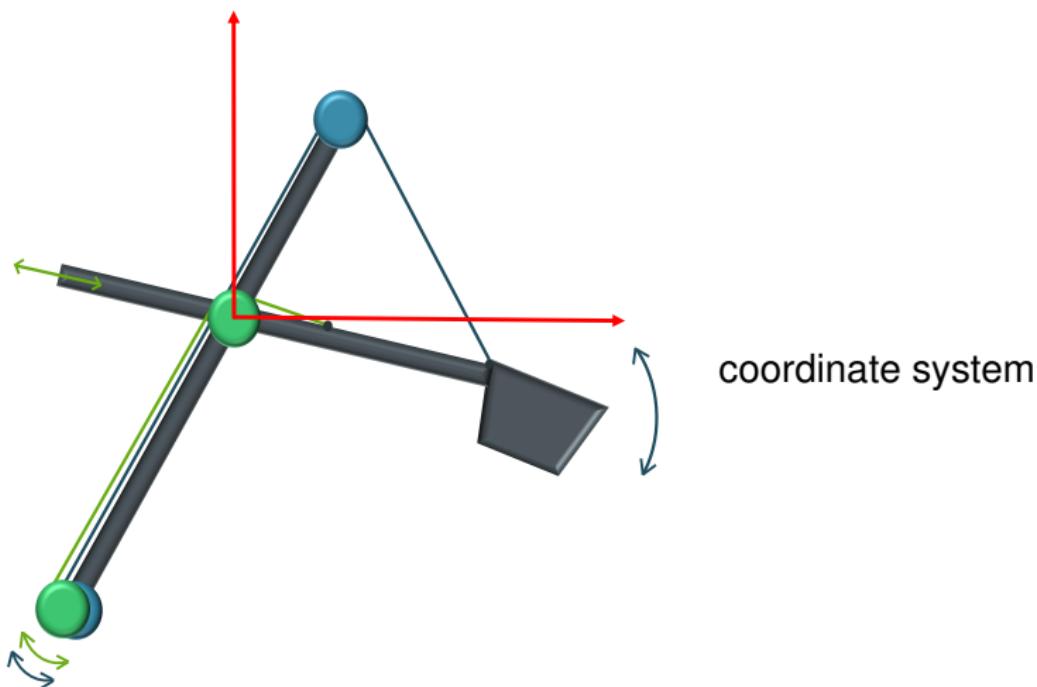
$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i$$

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

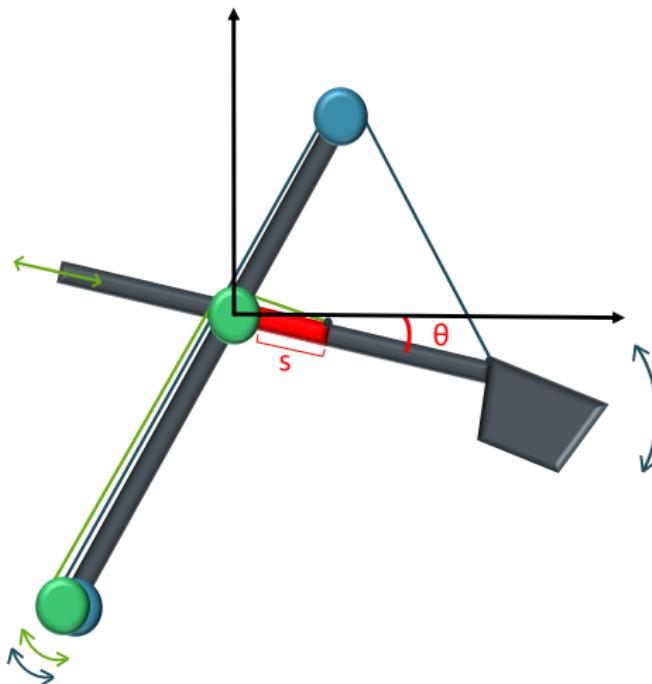
Physical Model of Excavator



Physical Model of Excavator



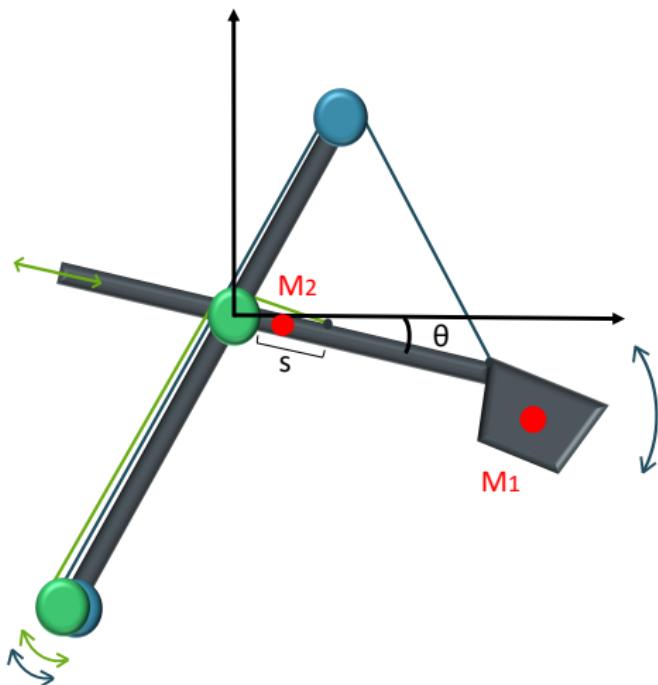
Physical Model of Excavator



degrees of freedom

- length s
- tilt angle θ

Physical Model of Excavator



movable centers of gravity of

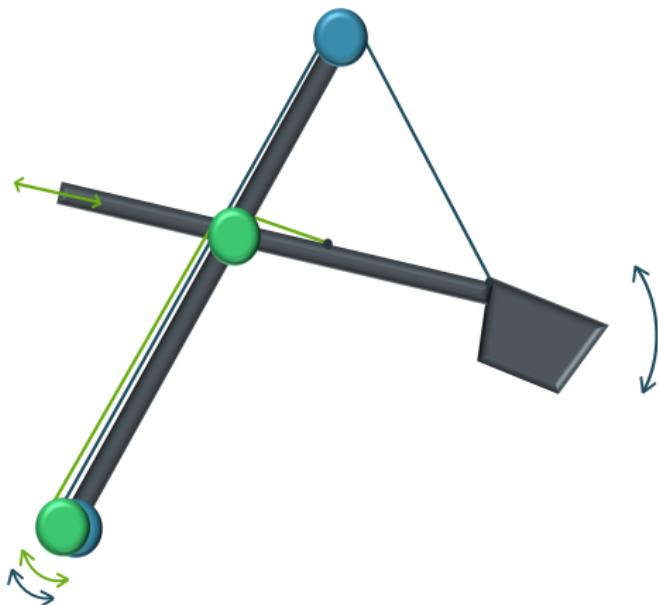
- shovel M_1
- arm M_2

Physical Model of Excavator

Assumptions to the model:

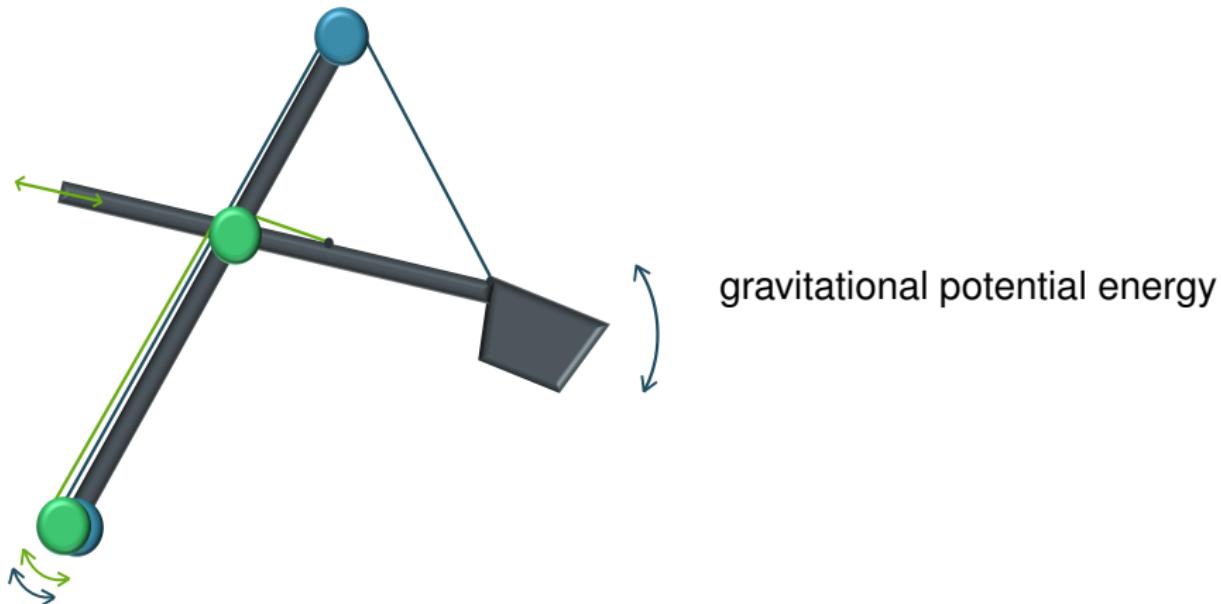
- no mass for the ropes
- shovel as point mass
- no slack/friction between ropes and cable reels

Kinetic Energy

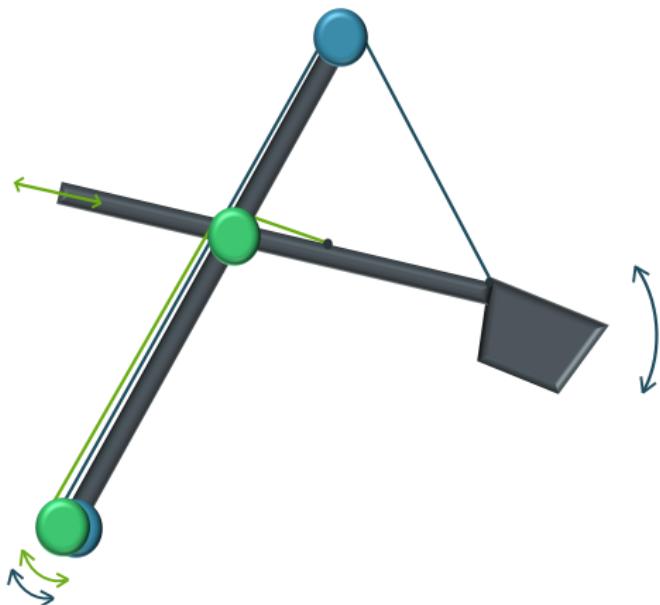


- movement of mass
- rotation of cable reel

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

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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

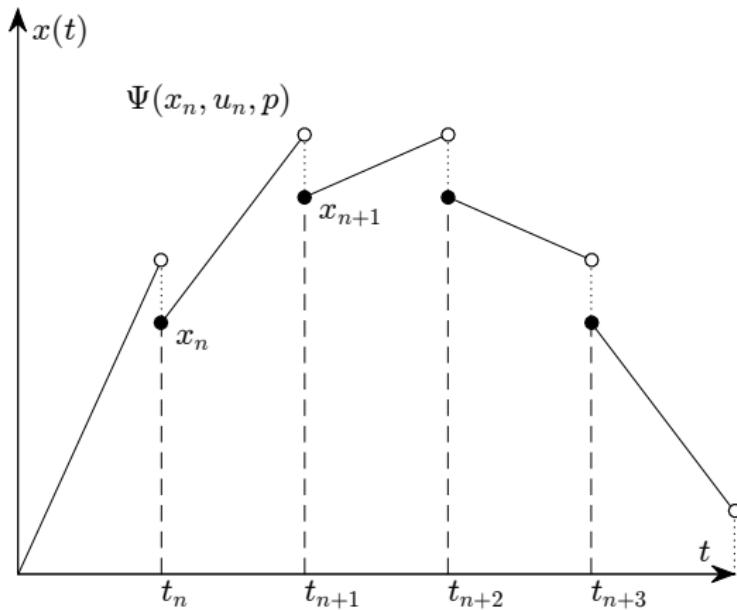
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

$$\Psi(x_n, u_n, p) = x_n + h_n f(x_n, u_n, p)$$

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



Problem Formulation

explaining setting for parameter identification

Problem Formulation

Natural approach: Optimal Control Problem

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

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

Problem Formulation

Input:

- control \bar{u}
- desired motion \bar{x} related to \bar{u}

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Output:

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

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- desired motion \bar{x} related to \bar{u}

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Idea:

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

Problem Formulation

Original Problem

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

Problem Formulation

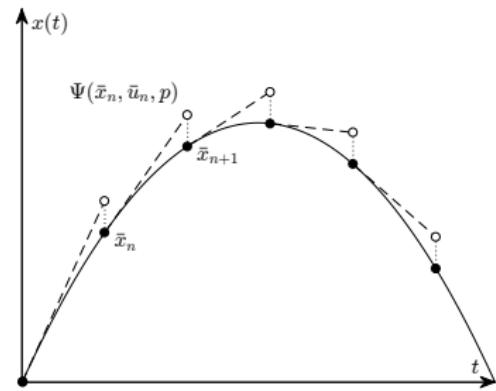
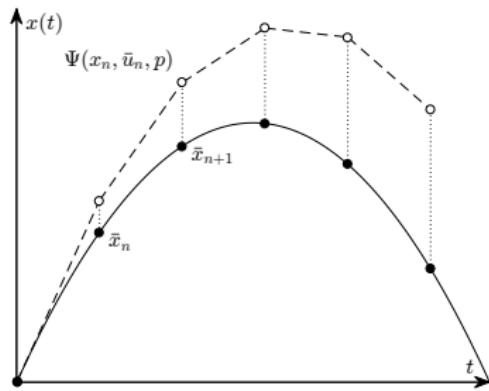
Original Problem

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Reinterpreted Problem

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

Comparison of the Approaches

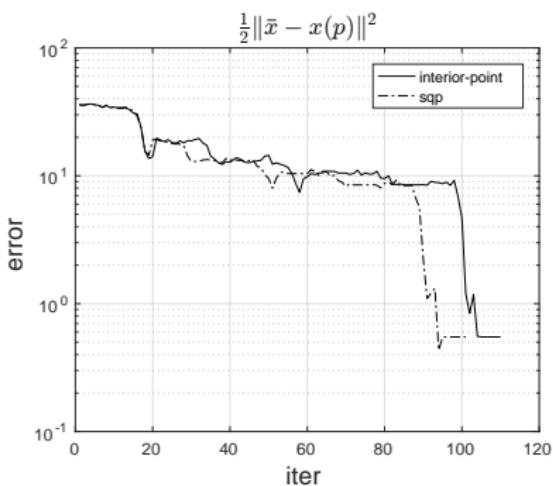
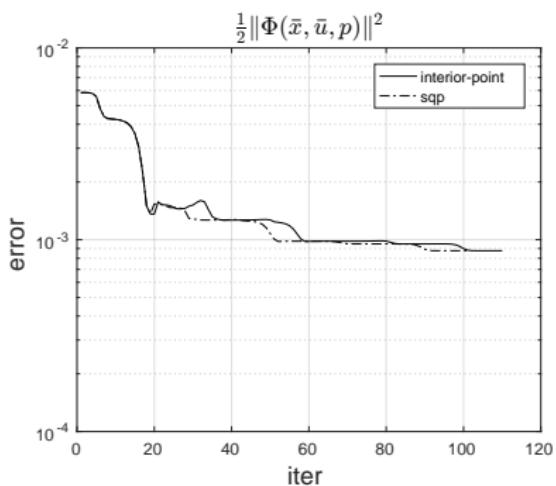


continuous vs. stepwise Approximation

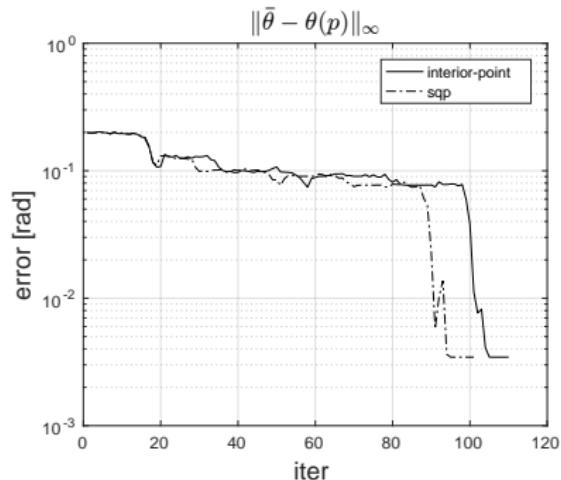
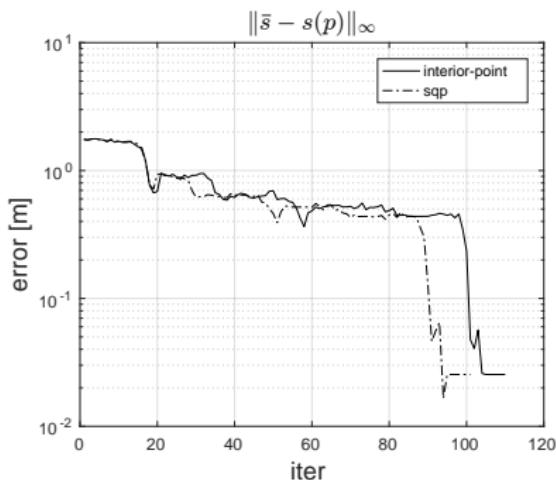
Example Instance

movies: reference and starting trajectory
maybe p0 deviation

Results



Results



Exact up to 3cm

Results

movies: reference and optimizes trajectory

Results

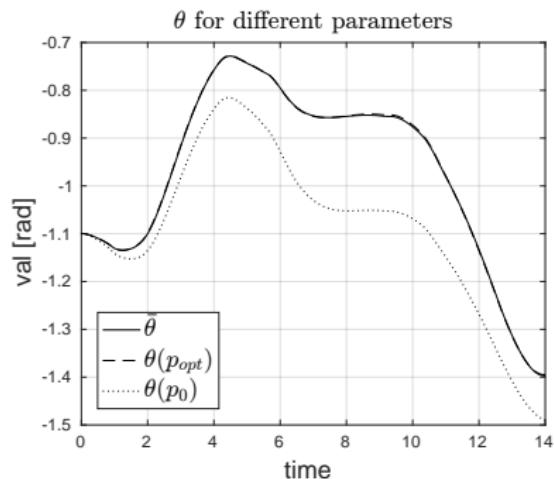
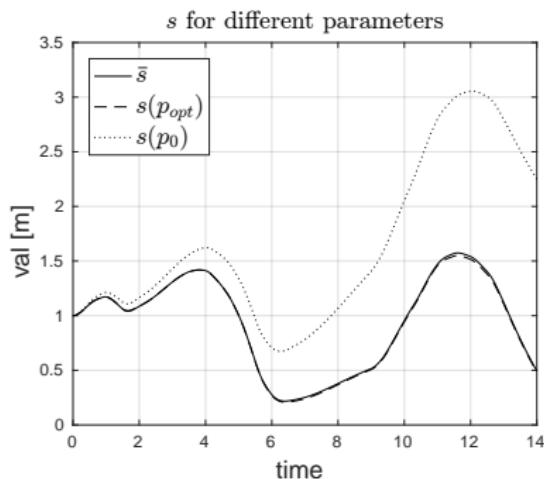


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Motivation

Examples

- Friction coefficients
- Masses
- Inertia

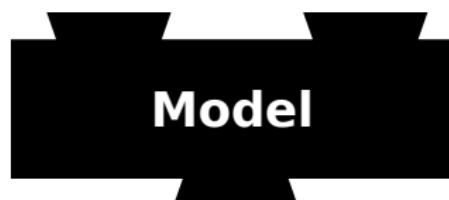
Black box model

- Realistic model from Siemens
- Confidential information

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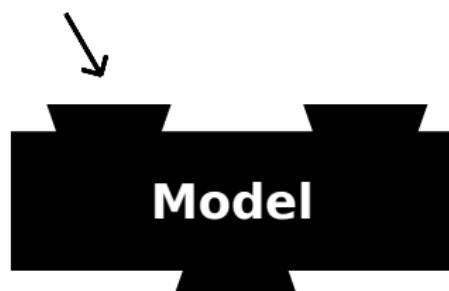
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Control



Motivation

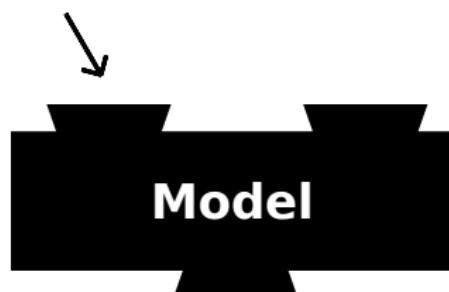
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Control



Motion

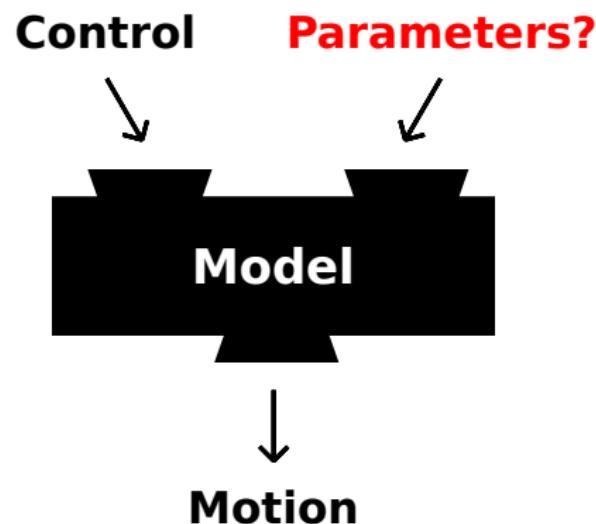
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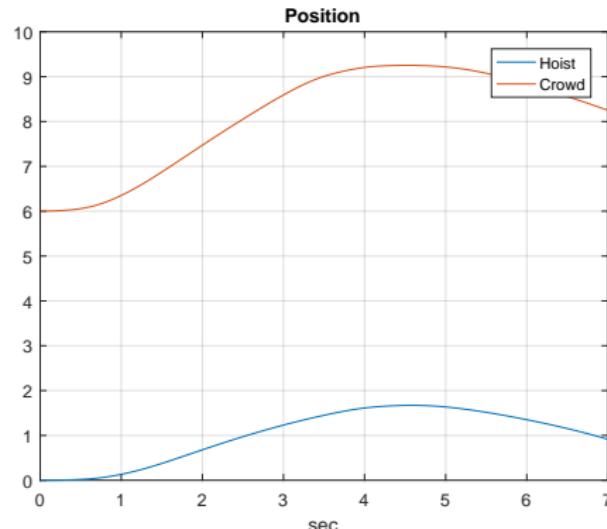
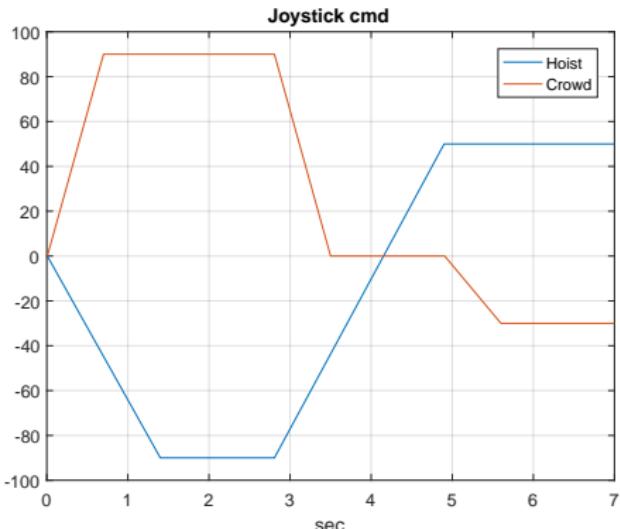
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Trajectories

Input: Joystick commands for Up/Down and Forth/Back

Output: Position of the shovel



Objective Function

Optimized Parameters:

- Inertia (Engine)
- Inertia (Arm)
- Friction
- Mass

Penalty Term:

$$\min_{p \in \mathbb{R}^4} f(p) = \frac{1}{n} \cdot \sum_{i=1}^n \left(\frac{\|\bar{X}_i - X_i(p)\|^2}{\|\bar{X}_i\|^2} + \frac{\|\bar{Y}_i - Y_i(p)\|^2}{\|\bar{Y}_i\|^2} \right)$$

s. t.

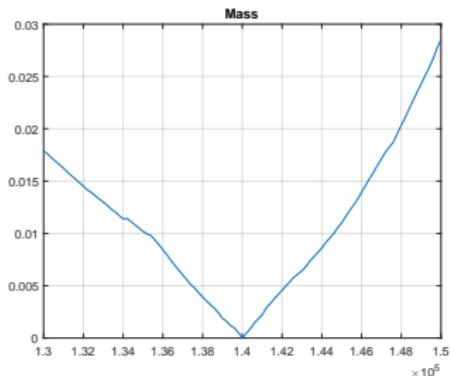
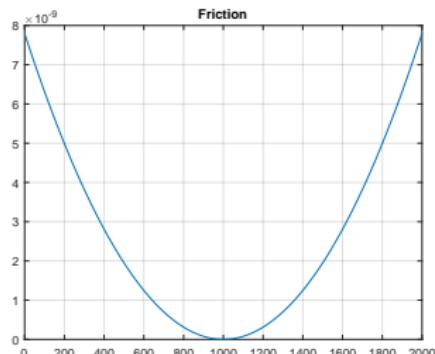
$$p_j \geq 0$$

\bar{X}_i reference trajectory

Influence of the Parameters

10% parameter deviation:

- Inertia (Engine): $1 \cdot 10^{-3}$
- Inertia (Arm): $3 \cdot 10^{-3}$
- Friction: $8 \cdot 10^{-11}$
- Mass: $5 \cdot 10^{-2}$



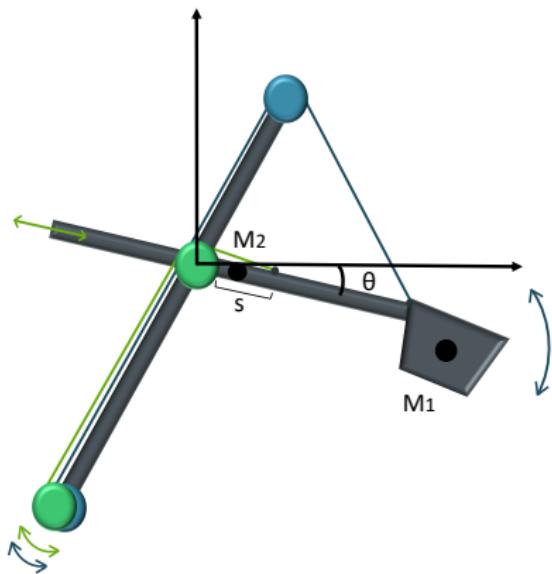
Solvers

| | value | evaluations | time |
|---------------------|------------|-------------|--------|
| Particle Swarm | 10^{-12} | 2200 | 6 min |
| Pattern Search | 10^{-11} | 6500 | 17 min |
| Genetic Algorithm | 10^{-4} | 5500 | 14 min |
| Simulated Annealing | 10^{-3} | 4200 | 11 min |

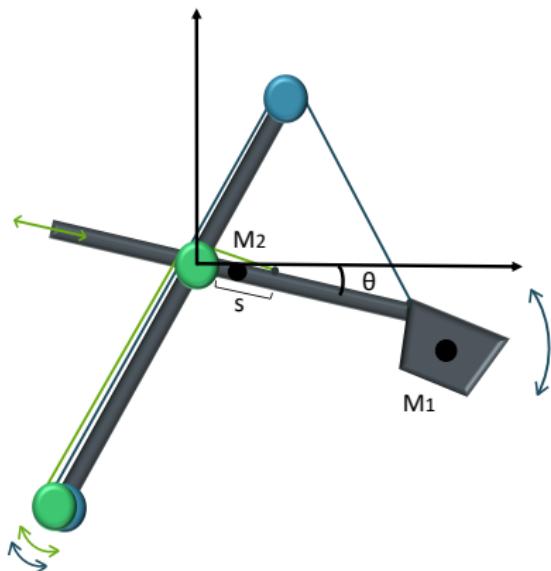
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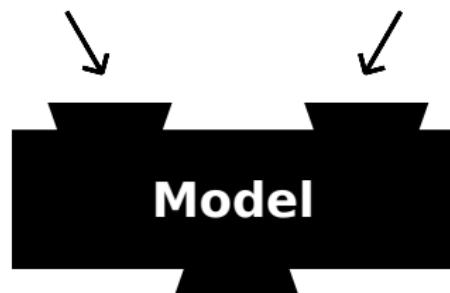


Summary



Control

Parameters?



Motion