

Case Studies Nonlinear Optimization

Open Cast Mining

Final Presentation

July 09, 2016

InYoung Choi, Olivia Kaufmann, Martin Sperr, Florian Wuttke

Table of Contents

- 1 Project Overview
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Identification: Black Box Model
- 5 Summary

Table of Contents

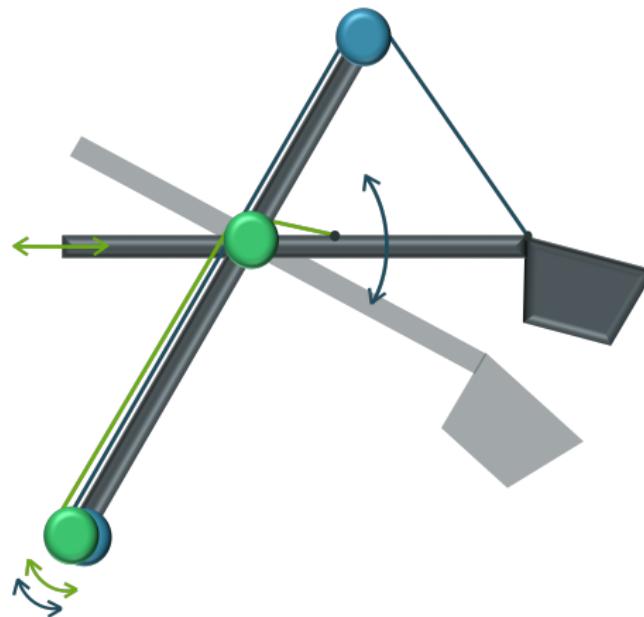
- 1 Project Overview
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Identification: Black Box Model
- 5 Summary



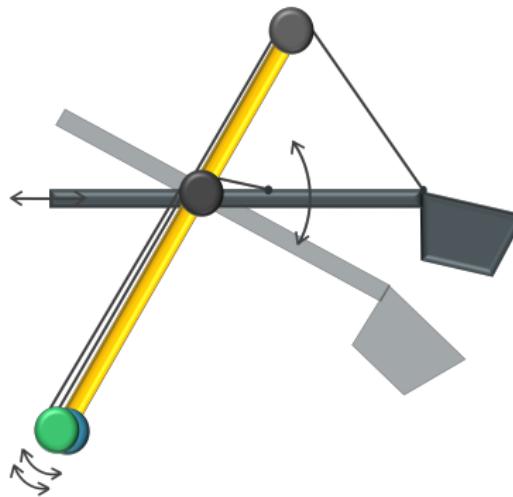
originally posted to Flickr by FAndrey at <http://flickr.com/photos/43301444@N06/4141786255>

- Goal: **Optimization of model parameters**
- Models of technical system = Physical properties + Control properties

Problem Setting

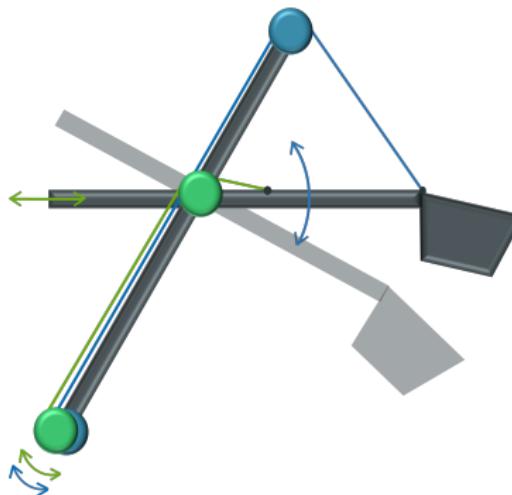


Problem Setting



- Arm element fixed to the base
- Cannot be moved w.r.t. the base

Problem Setting (include videos)



- Green: Shovel motion **back and forth**
- Blue: Shovel motion **up and down**

Procedure

Physical Model

- Rope properties
- Lagrange Formalism



Parameter Identification

Discretization

Procedure

Physical Model

- Rope properties
- Lagrange Formalism

vs

Blackbox Model

- Realistic model
- Confidential information



Parameter Identification

Discretization

Parameter Identification

Derivative-free optimization

Physical Modeling

Why?

Building an
accurate model



Good description of
the effects of control
and motion

Physical Modeling Cont'd

How?

To consider:

- Friction in cable reels
- Deformation of ropes
- Potential/Kinetic energy
- etc

Physical Modeling Cont'd

How?

To consider:

- Friction in cable reels
- Deformation of ropes
- Potential/Kinetic energy
- etc



Lagrange Formalism
(2nd order ODE)

Physical Modeling Visualization

Why is it important?

Performance videos of two different loads

Which color do we want to use?

TUMblue

TUMblue1

TUMblue2

TUMblue3

TUMblue4

TUMblue5

Parameter Identification

What are parameters?

- Friction coefficients
- Mass
- Inertia
- etc.

Parameter Identification

What are parameters?

- Friction coefficients
- Mass
- Inertia
- etc.

Why?

Accurate and
realistic parameters



Better prediction
and planning of
motion

Parameter Optimization Visualization

Two videos carrying the same load, but one with a random motion and the other with optimized parameters

Parameter Identification Two Ways

**Two independent models acquired,
two different computational approaches.**

Physical Model

- Rope properties
- Lagrange Formalism

vs

Blackbox Model

- Realistic model
- Confidential information



Parameter Identification

Discretization

Parameter Identification

Derivative-free optimization

Parameter Identification: Physical Model

Own Physical Model

Lagrange Formalism

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

↓

Parameter Identification

Discretization

$$\min_{x,p} \quad \frac{1}{2} \|\bar{x} - x\|^2$$

Parameter Identification: Physical Model

Own Physical Model

Lagrange Formalism

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

↓

Parameter Identification

Discretization

$$\min_{x,p} \quad \frac{1}{2} \|\bar{x} - x\|^2$$

- All the information needed for calibration is available
- Runge-Kutta method of different orders for discretization
- Parameter computation for a given control and motion

Parameter Identification: Blackbox Model

Siemens Blackbox Model

- **Input:** Joystick commands for up/down/back/forth
- **Output:** Position of the shovel



Parameter Identification

Particle Swarm, Pattern Search,
Genetic Algorithm, ...

Parameter Identification: Blackbox Model

- Almost no information is available except input/output
- Derivative-free optimization methods required
- As a real-life complex system, only a few parameters are studied here

Siemens Blackbox Model

- **Input:** Joystick commands for up/down/back/forth
- **Output:** Position of the shovel



Parameter Identification

Particle Swarm, Pattern Search, Genetic Algorithm, ...

Table of Contents

- 1 Project Overview
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Identification: Black Box Model
- 5 Summary

Lagrange Formalism

Method to describe dynamics of an accelerated system

T kinetic energy
V potentials

Lagrange Formalism

Method to describe dynamics of an accelerated system

T kinetic energy

V potentials

F non-conservative external forces

Lagrange Formalism

Method to describe dynamics of an accelerated system

- T kinetic energy
- V potenitals
- F non-conservative external forces
- r points of actions of forces F
- q free variables
- Q generalized forces

Lagrange Formalism

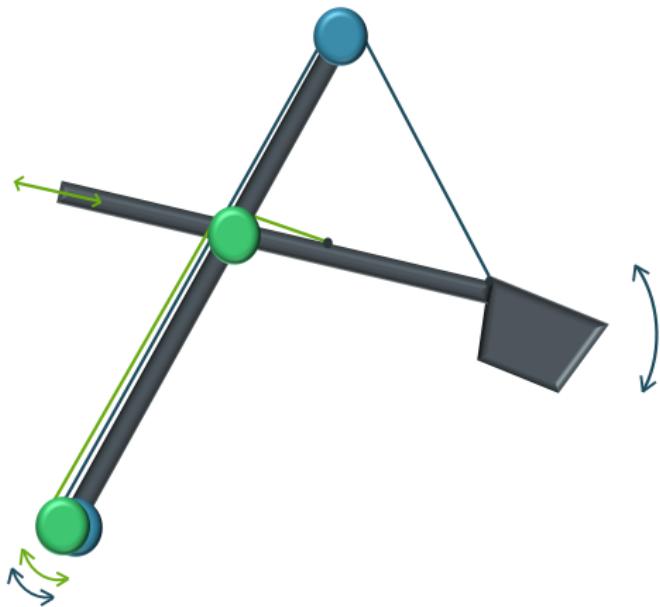
Method to describe dynamics of an accelerated system

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

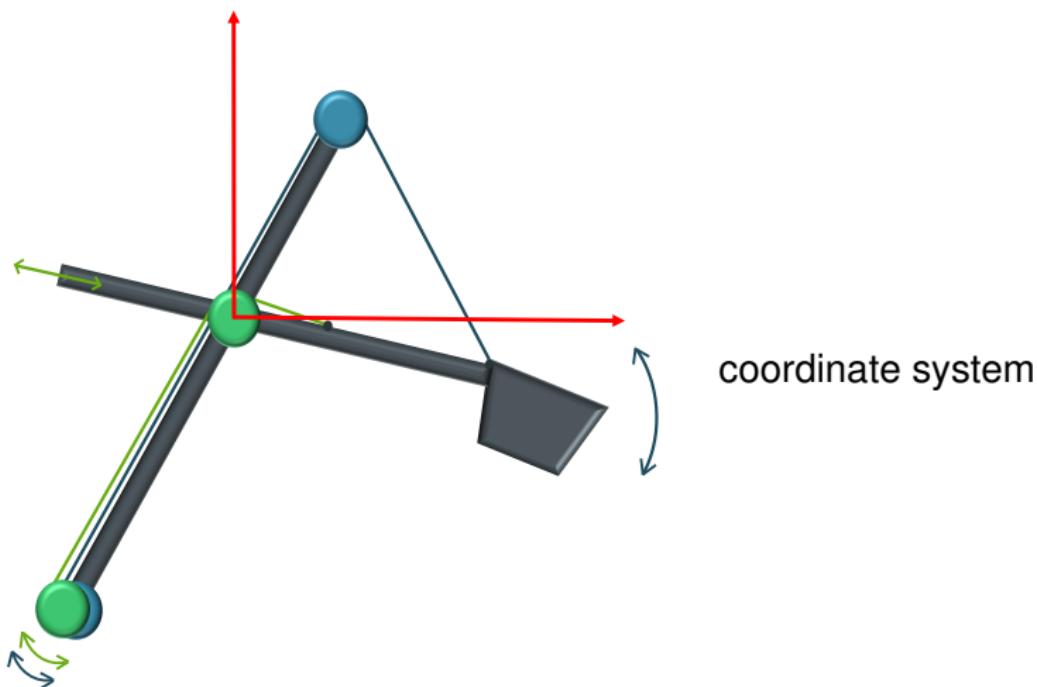
$$Q = \left(\frac{\partial r}{\partial q} \right)^T F$$

- T kinetic energy
- V potentials
- F non-conservative external forces
- r points of actions of forces F
- q free variables
- Q generalized forces

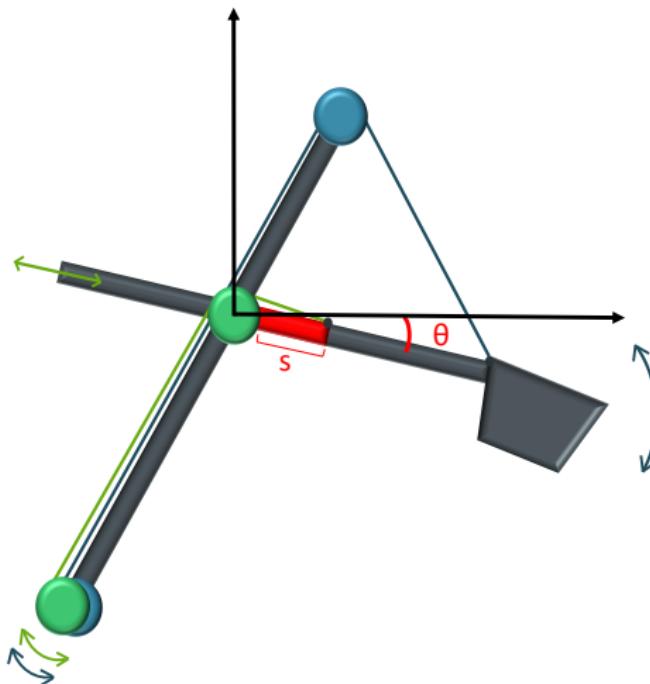
Physical Model of Excavator



Physical Model of Excavator



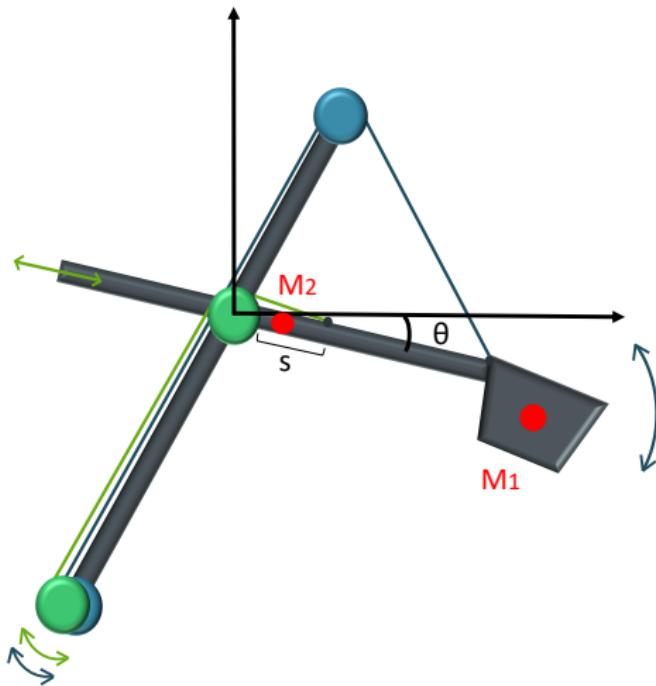
Physical Model of Excavator



degrees of freedom

- length s
- tilt angle θ

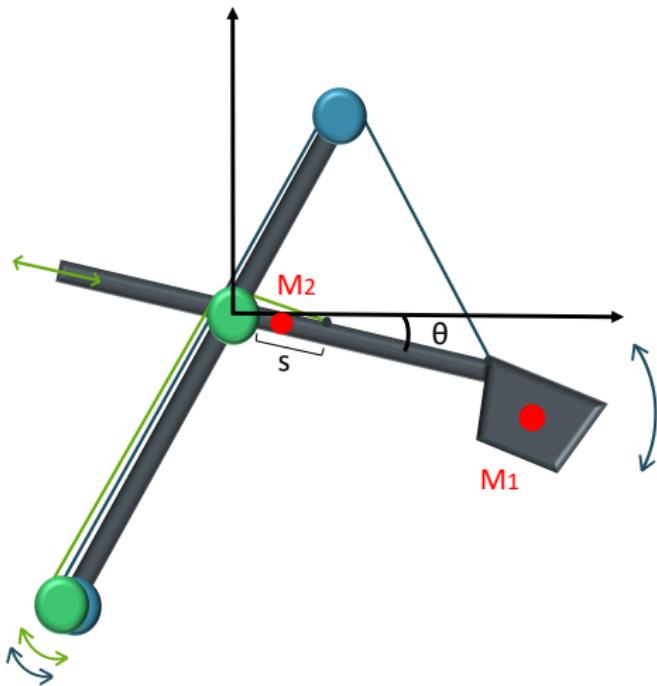
Physical Model of Excavator



movable centers of gravity of

- shovel M_1
- arm M_2

Physical Model of Excavator



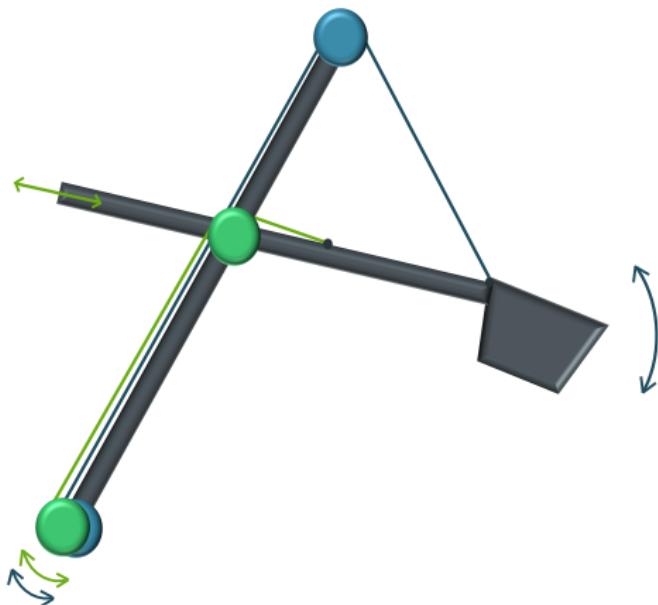
movable centers of gravity of

- shovel M_1
- arm M_2

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

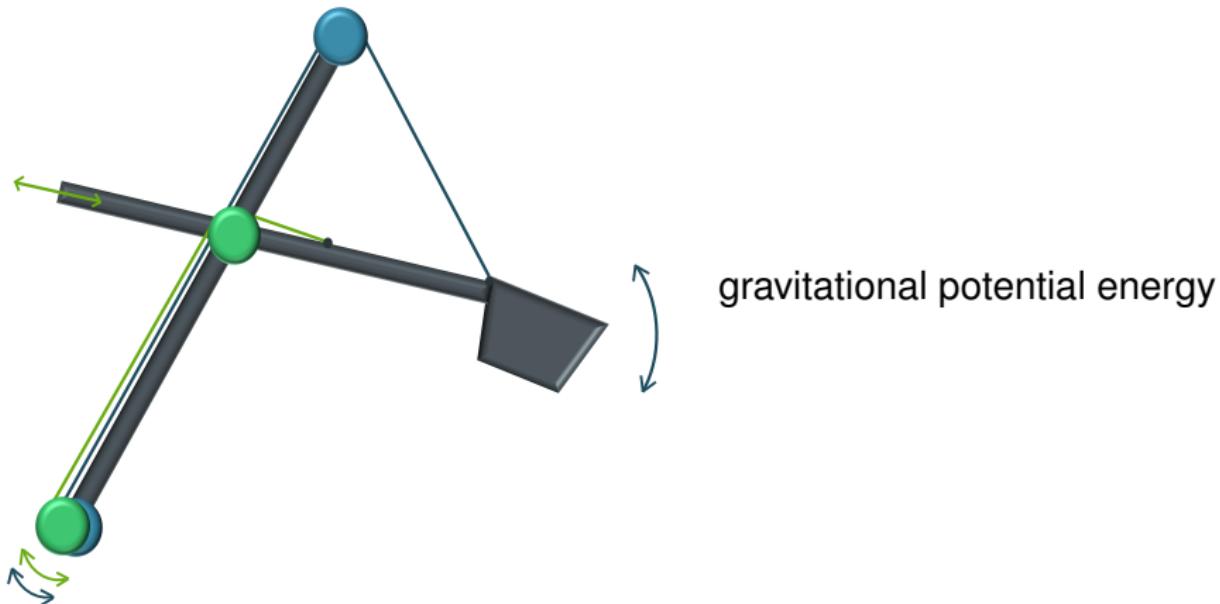
$$Q = \left(\frac{\partial r}{\partial q} \right)^T F$$

Kinetic Energy

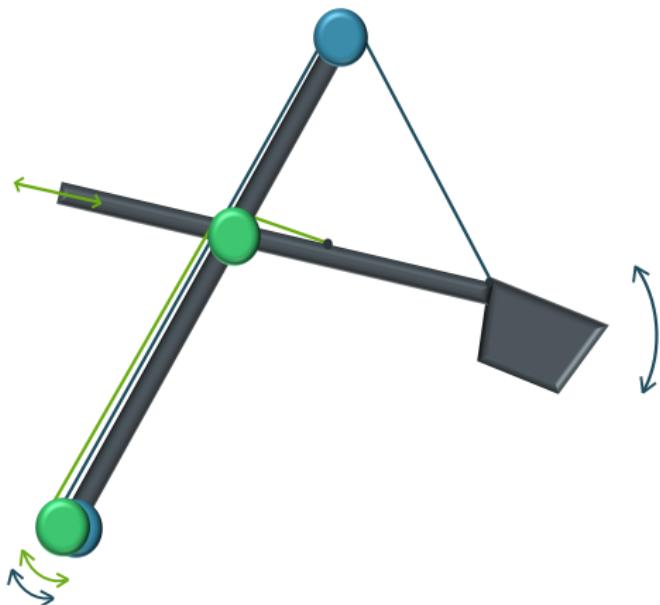


- movement of mass
- rotation of cable reel

Potential Energy



Generalized Forces



- torque on cable reels
- friction of cable reels

Physical Model of Excavator

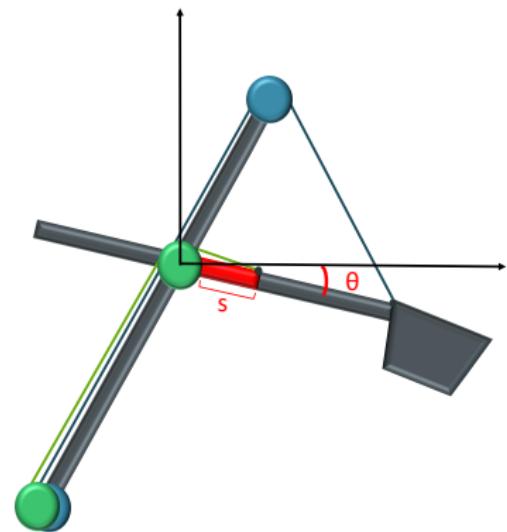
Assumptions to the model:

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

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

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

Resulting ODE

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

→ Transformation into 1st 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	$p = (p_1, \dots, p_k)^T$

Table of Contents

- 1 Project Overview
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Identification: Black Box Model
- 5 Summary

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

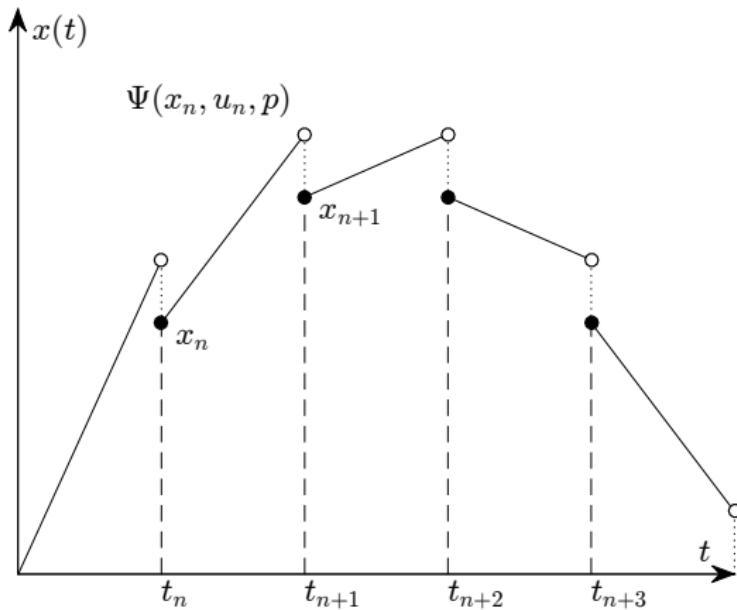
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

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

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 Setting

Given:

- control \bar{u}
- motion \bar{x} related to \bar{u} and \bar{p}

Unknown:

- parameters \bar{p} of the excavator

Output:

- parameters p

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

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

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

Set $x \leftarrow \bar{x}$

Problem Formulation

Original Problem

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

Set $x \leftarrow \bar{x}$

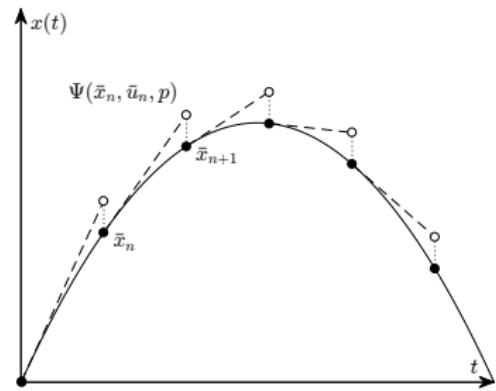
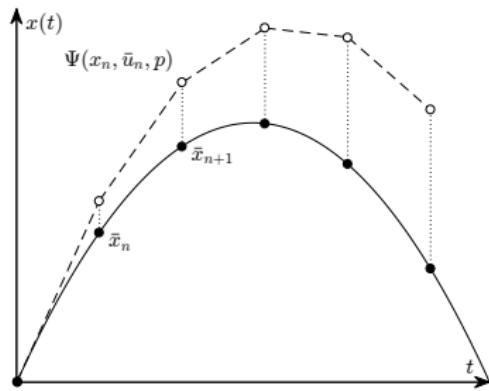
Reinterpreted Problem

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

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

- \bar{x} solves ODE for \bar{p}
- $\Phi(\bar{x}, \bar{u}, \bar{p}) \rightarrow 0$ for discretization $m \rightarrow \infty$
- number of parameters fix

Comparison of the Approaches

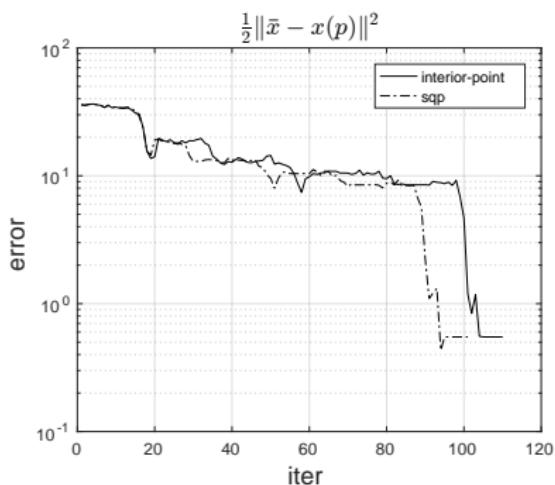
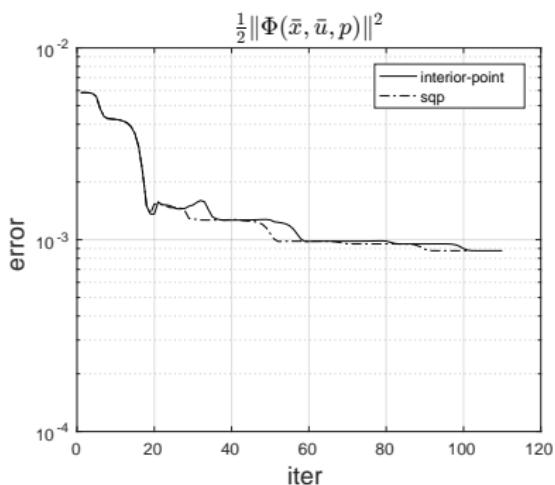


continuous vs. stepwise Approximation

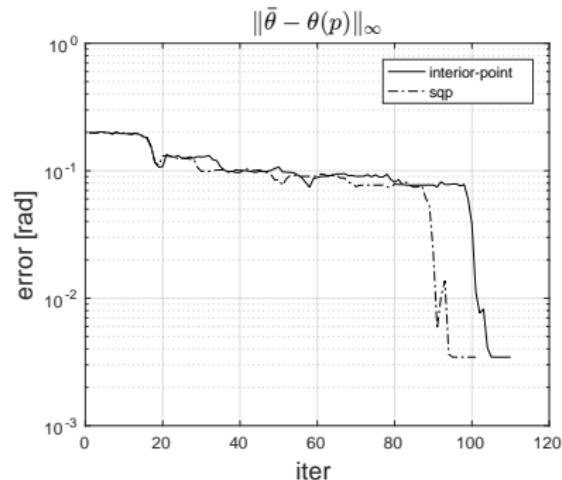
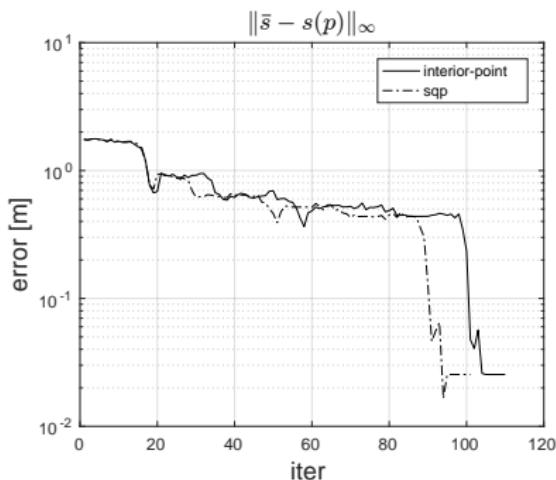
Example Instance

- $[0, T] = [0, 14s]$
- 1500 time steps
- $p_0 \in [0.8\bar{p}, 1.2\bar{p}]$
- $x(p)$ solution of ODE for given p
- internally 5 trajectories in parallel

Results



Results



Exact up to 3cm

Results

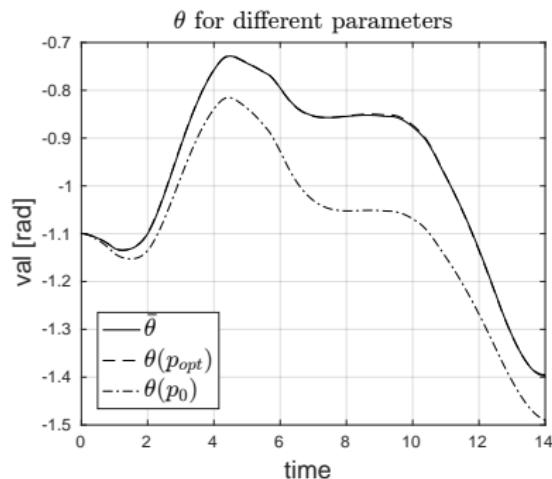
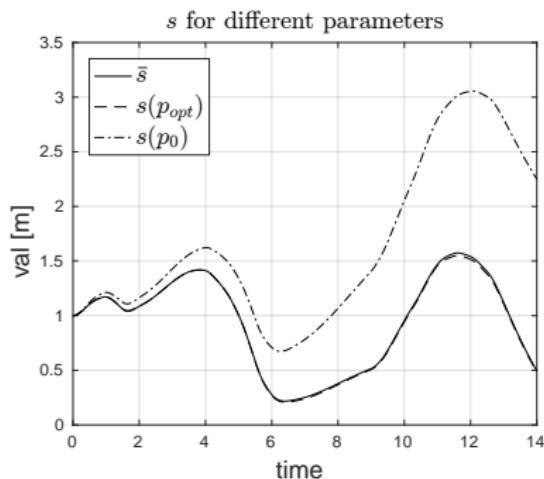


Table of Contents

- 1 Project Overview
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Identification: Black Box Model
- 5 Summary

Motivation

Examples

- Friction coefficients
- Masses
- Inertia

Motivation

Examples

- Friction coefficients
- Masses
- Inertia

Black box model

- Realistic model from Siemens
- Confidential information

Motivation

Examples

- Friction coefficients
- Masses
- Inertia



Black box model

- Realistic model from Siemens
- Confidential information

Motivation

Examples

- Friction coefficients
- Masses
- Inertia

Control



Model

Black box model

- Realistic model from Siemens
- Confidential information

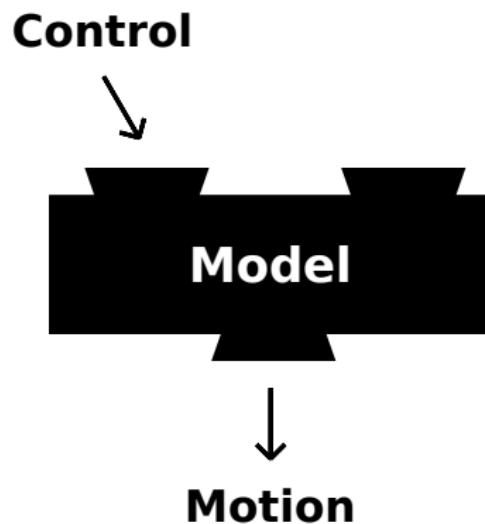
Motivation

Examples

- Friction coefficients
- Masses
- Inertia

Black box model

- Realistic model from Siemens
- Confidential information



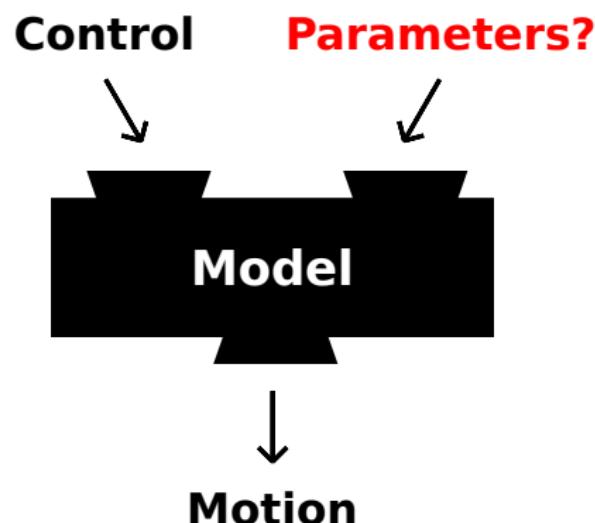
Motivation

Examples

- Friction coefficients
- Masses
- Inertia

Black box model

- Realistic model from Siemens
- Confidential information



Trajectories

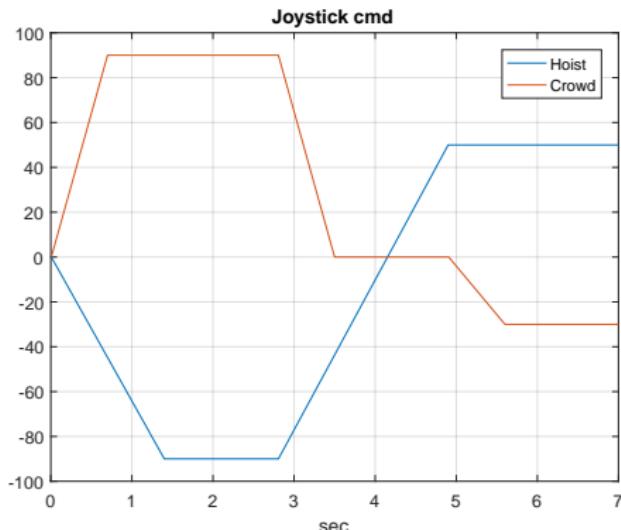
Input: Joystick commands for Up/Down and Forth/Back

Output: Position of the shovel

Trajectories

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

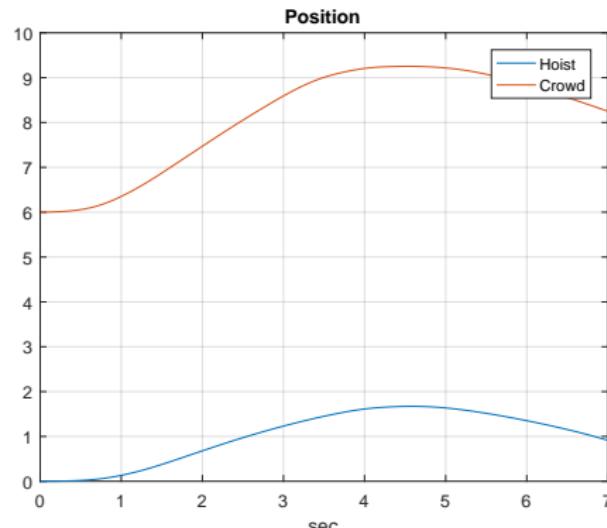
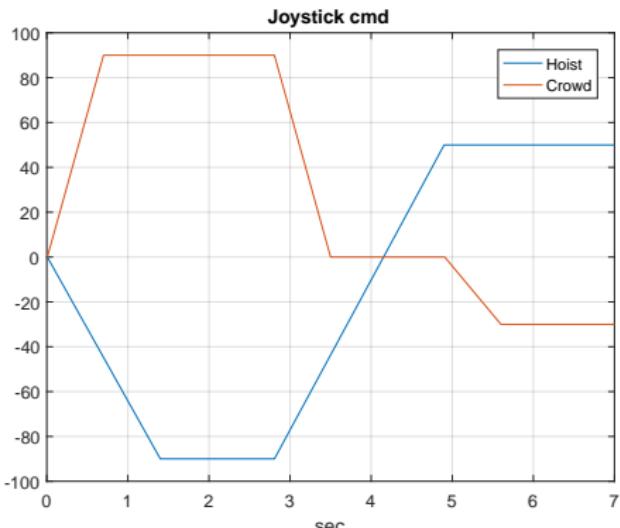
Output: Position of the shovel



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

Objective Function

Optimized Parameters:

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

Penalty Term:

$$\|\bar{X}_i - X_i(p)\|^2$$

Objective Function

Optimized Parameters:

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

Penalty Term:

$$\frac{\|\bar{X}_i - X_i(p)\|^2}{\|\bar{X}_i\|^2}$$

Objective Function

Optimized Parameters:

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

Penalty Term:

$$\frac{\|\bar{X}_i - X_i(p)\|^2}{\|\bar{X}_i\|^2} + \frac{\|\bar{Y}_i - Y_i(p)\|^2}{\|\bar{Y}_i\|^2}$$

\bar{X}_i, \bar{Y}_i reference trajectories

Objective Function

Optimized Parameters:

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

Penalty Term:

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

\bar{X}_i, \bar{Y}_i reference trajectories

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, \bar{Y}_i reference trajectories

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: $5 \cdot 10^{-2}$

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: $5 \cdot 10^{-2}$

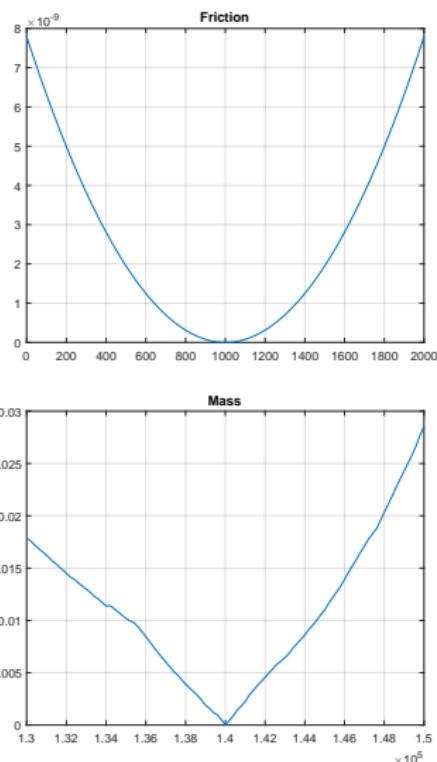
Big parameter changes \Rightarrow Small effects

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: $5 \cdot 10^{-2}$

Big parameter changes \Rightarrow Small effects



Optimizers

- Derivative free optimization
- Deterministic or stochastic
- Decrease function value by evaluating systematically

Optimizers

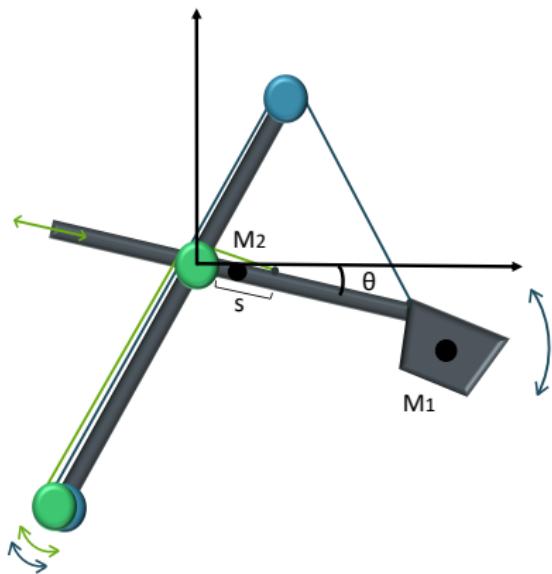
- Derivative free optimization
- Deterministic or stochastic
- Decrease function value by evaluating systematically

	value	evaluations	time	dev_{\max}	dev_{mean}
Particle Swarm	10^{-12}	2200	6 min	$10^{-1.0}$	$10^{-3.8}$
Pattern Search	10^{-11}	6500	17 min	$10^{-1.3}$	$10^{-3.7}$
Genetic Algorithm	10^{-4}	5500	14 min	$10^{-0.5}$	$10^{-1.0}$
Simulated Annealing	10^{-3}	4200	11 min	$10^{-0.3}$	$10^{-0.6}$

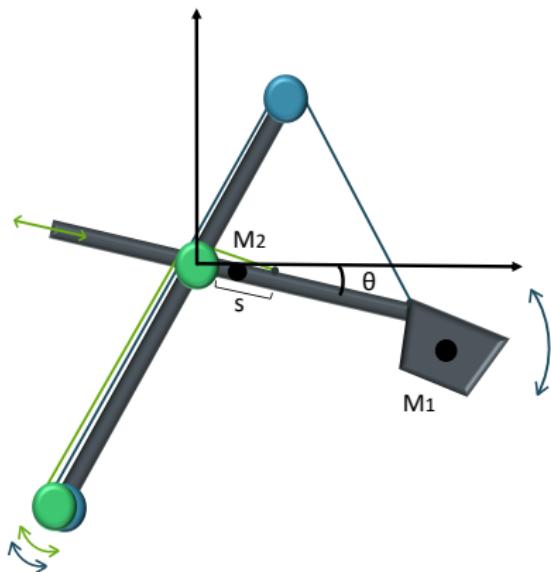
Table of Contents

- 1 Project Overview
- 2 Physical Model
- 3 Parameter Identification: Physical Model
- 4 Parameter Identification: Black Box Model
- 5 Summary

Summary

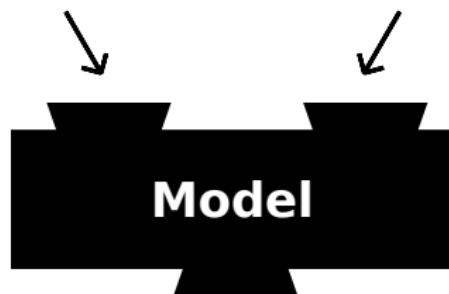


Summary



Control

Parameters?



Motion