
Case Studies Nonlinear Optimization

Open Cast Mining

Final Presentation

July 09, 2016

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



Procedure

Physical Model

- Rope properties
- Lagrange Formalism



Parameter Identification

Discretization + Optimization

Procedure

Physical Model

- Rope properties
- Lagrange Formalism

Blackbox Model

- Realistic model
- Confidential information

and

Parameter Identification

Discretization + Optimization



Parameter Identification

Derivative-free optimization

Physical Modeling

Why?

Building an
accurate model



Good description of
the effects of control
on motion

Physical Modeling

How?

To consider:

- Friction in cable reels
- Potential/Kinetic energy
- etc

Physical Modeling

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Lagrange Formalism
(ODE)

Parameter Identification

What are parameters?

- Friction coefficients
- Mass
- Inertia

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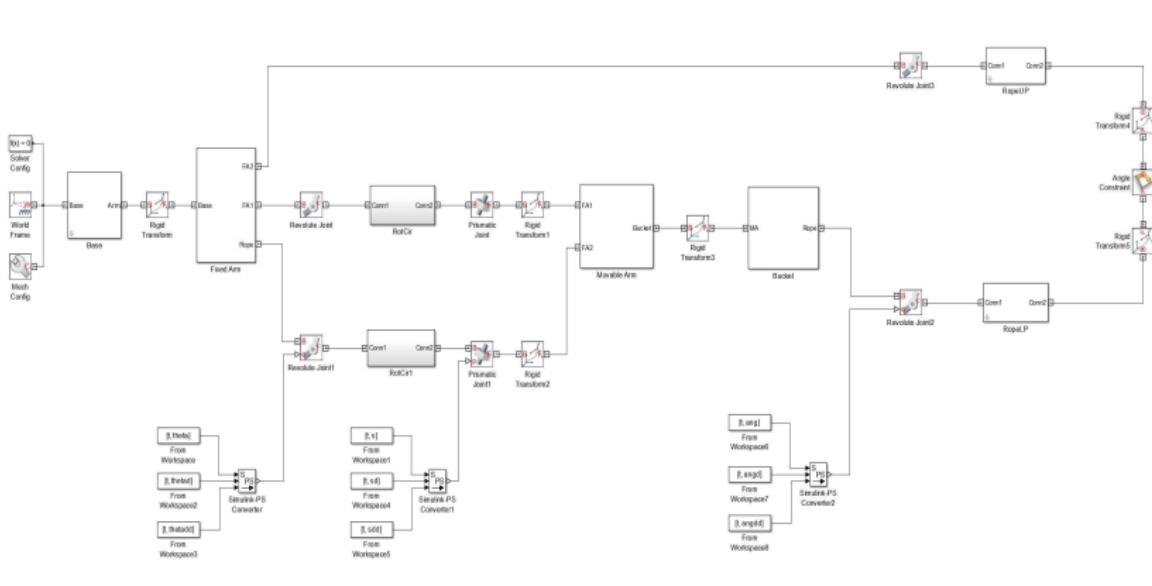
Why?

Accurate and
realistic parameters



Better prediction
and planning of
motion

Visualization: Simulink



Visualization Example

Same parameters except different load weights

vs



Light load



Heavy load

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Lagrange Formalism

Method to describe dynamics of an accelerated system

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

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

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

T kinetic energy

V potentials

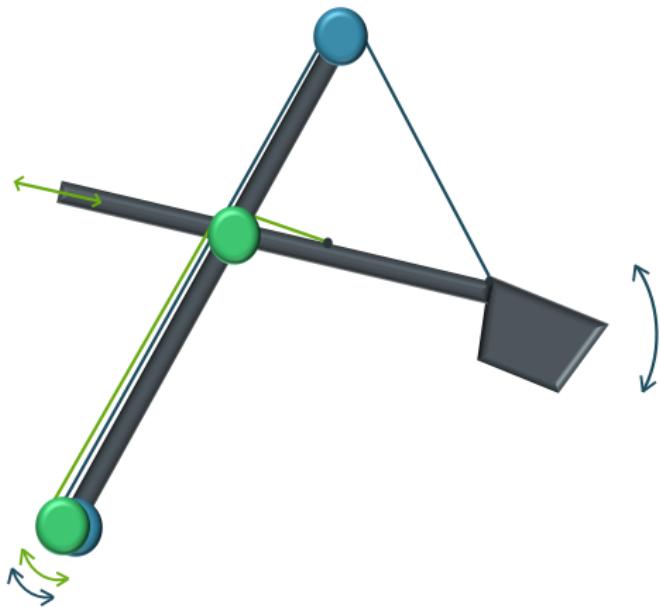
F non-conservative external forces

r points of actions of forces F

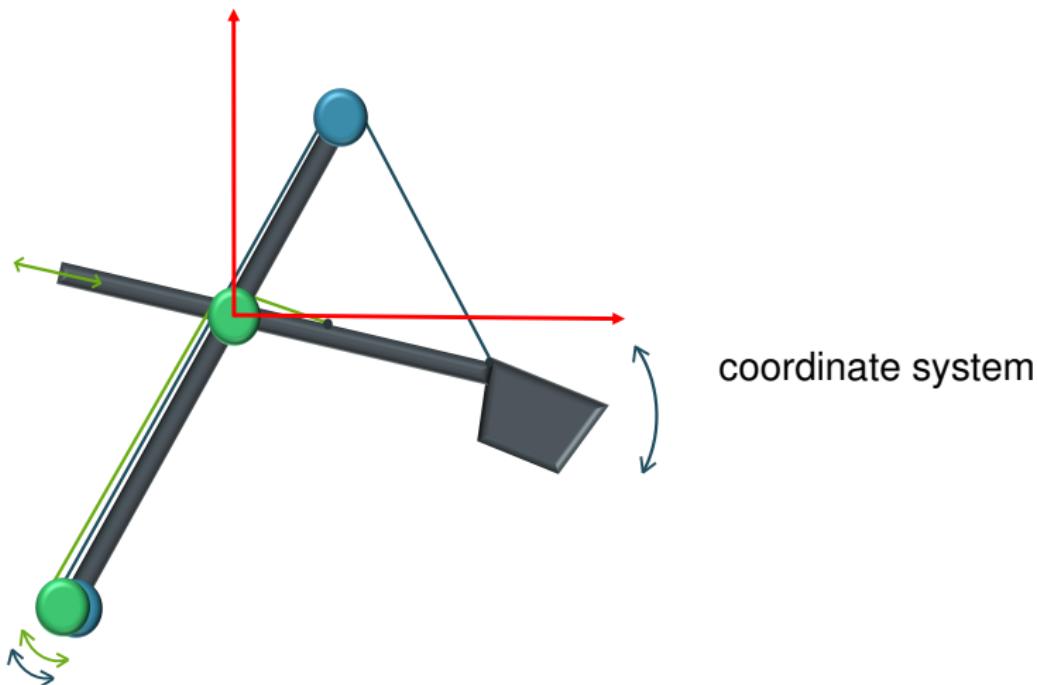
q free variables

Q generalized forces

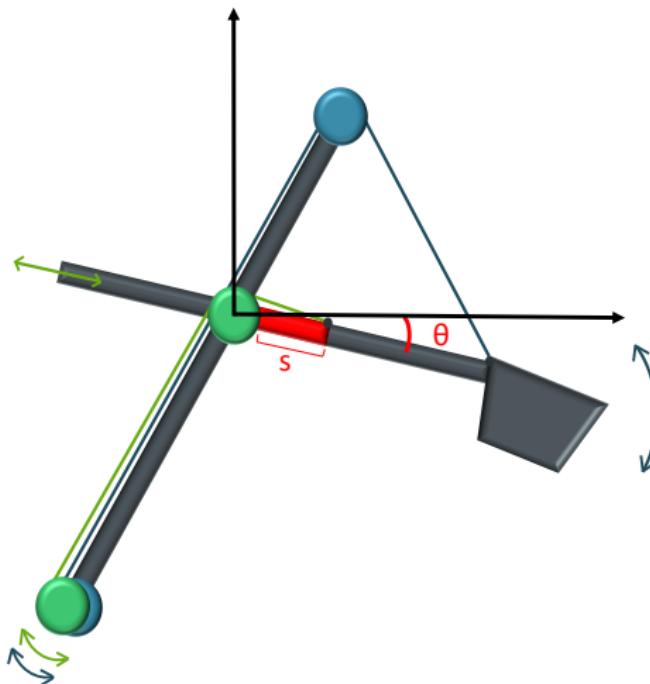
Physical Model of Excavator



Physical Model of Excavator



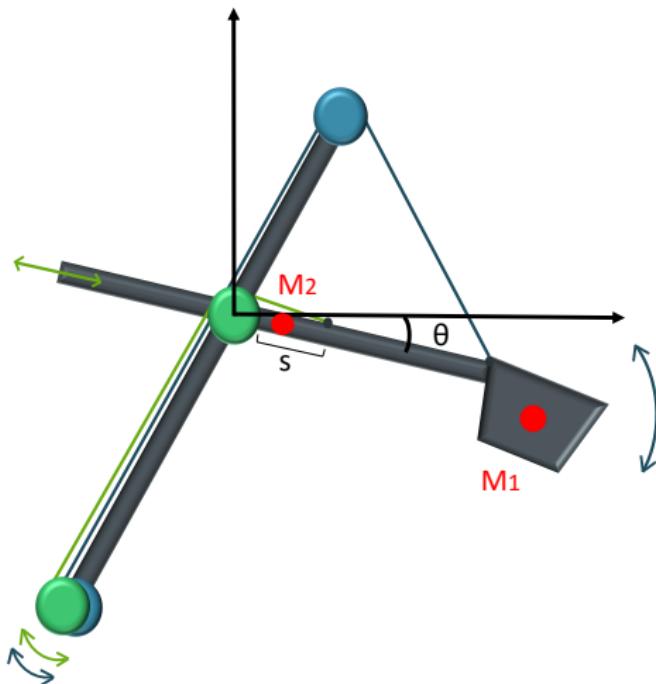
Physical Model of Excavator



degrees of freedom

- length s
- tilt angle θ

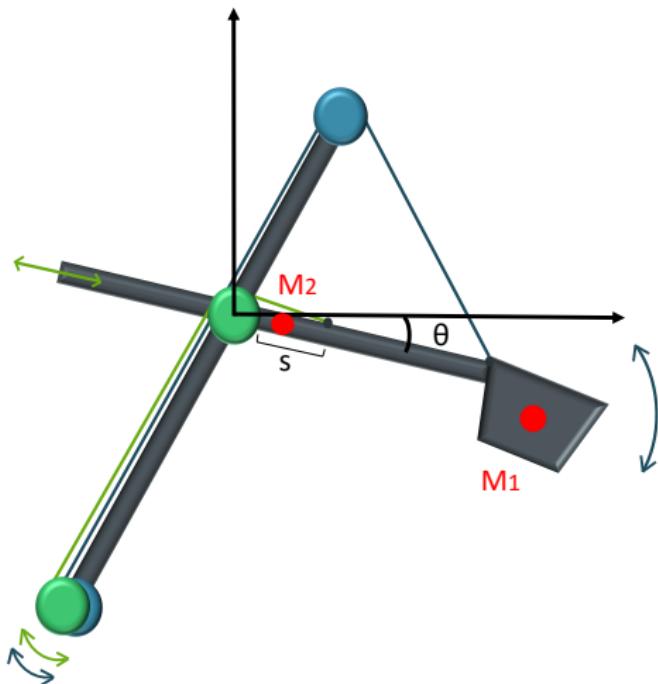
Physical Model of Excavator



movable centers of gravity of

- shovel M_1
- arm M_2

Physical Model of Excavator



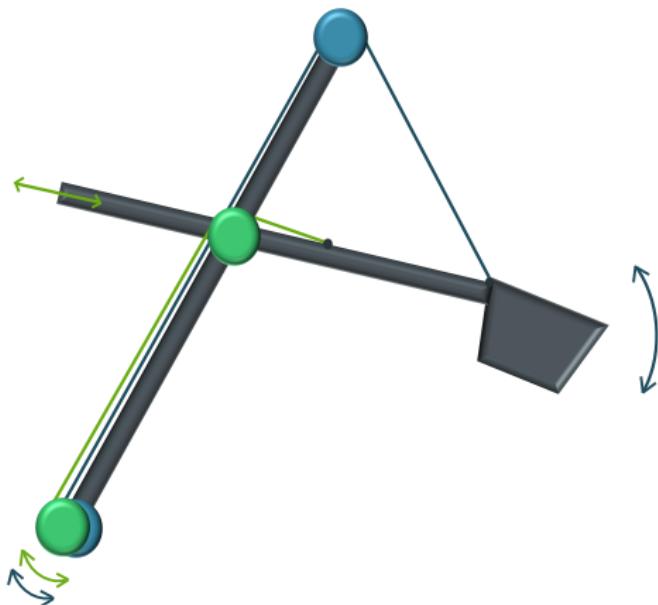
movable centers of gravity of

- shovel M₁
- arm M₂

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

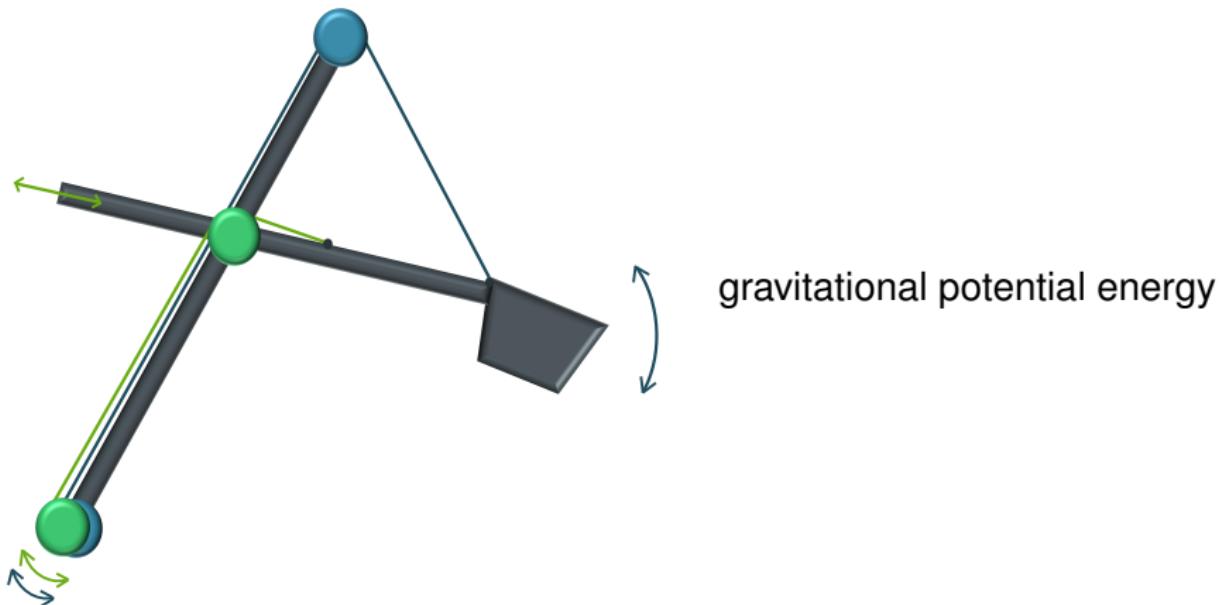
$$Q = \left(\frac{\partial r}{\partial q} \right)^T F$$

Kinetic Energy

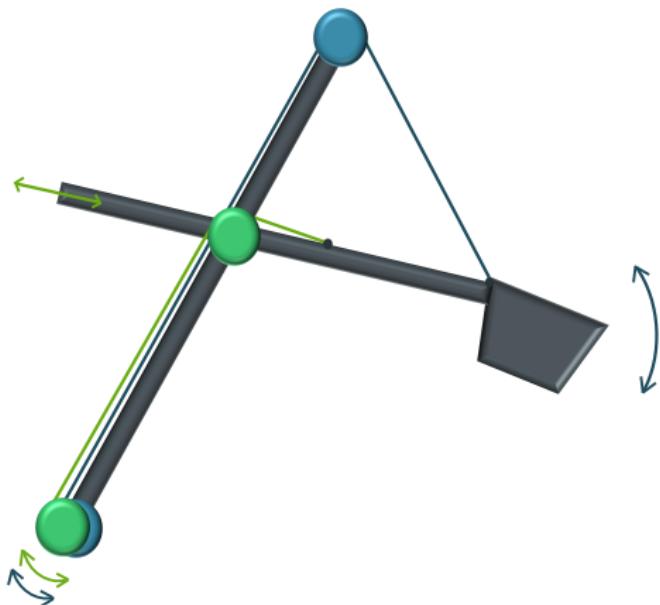


- movement of mass
- rotation of cable reel

Potential Energy



Generalized Forces



- torque on cable reels
- friction of cable reels

Physical Model of Excavator

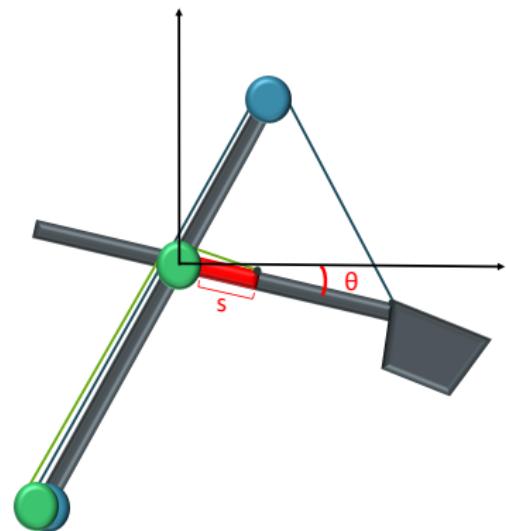
Assumptions to the model:

- 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

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

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

→ 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	$p = (p_1, \dots, p_k)^T$

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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

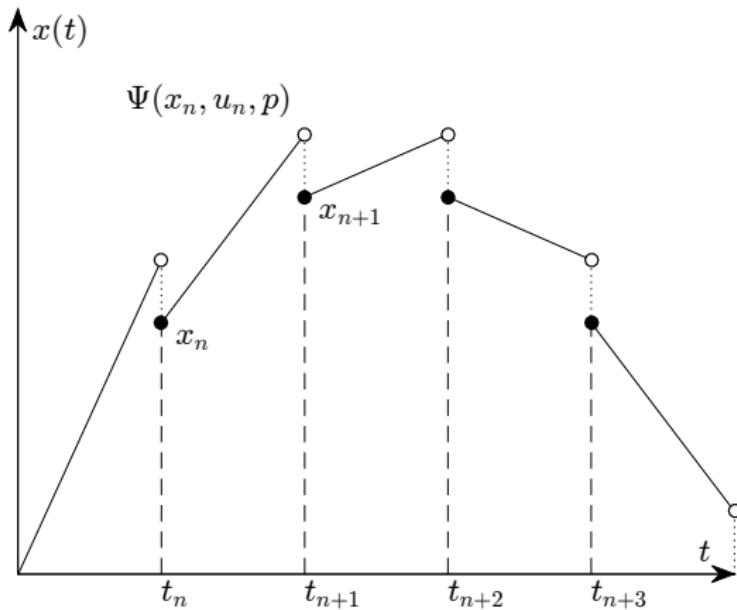
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

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

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 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

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

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Set $x \leftarrow \bar{x}$

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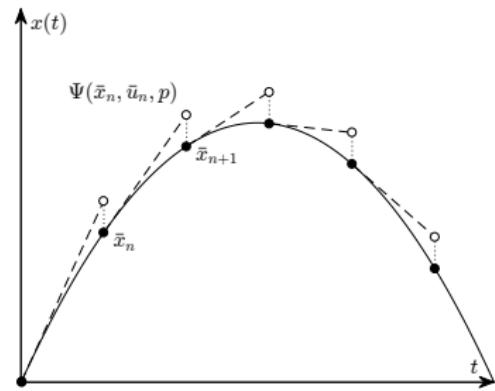
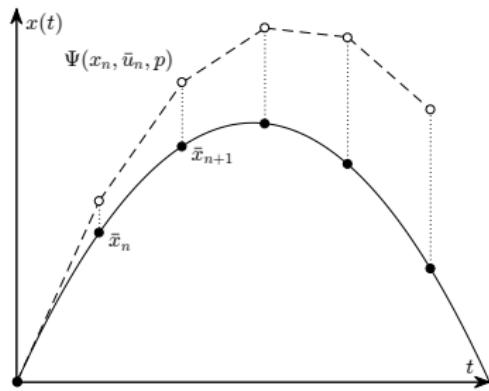
Reinterpreted Problem

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

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

- \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

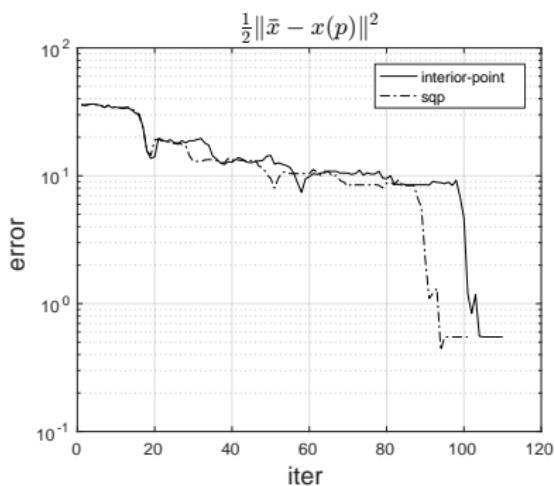
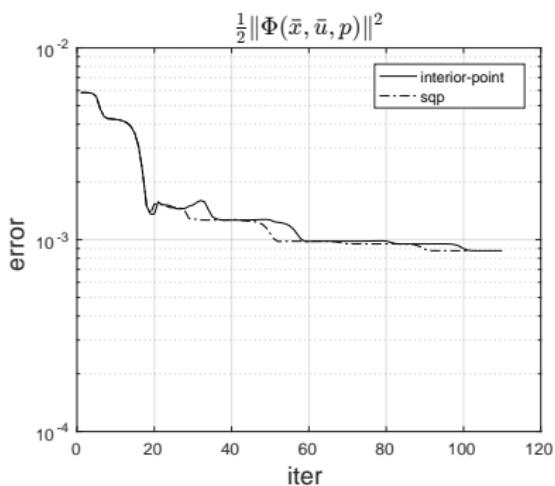


continuous vs. stepwise Approximation

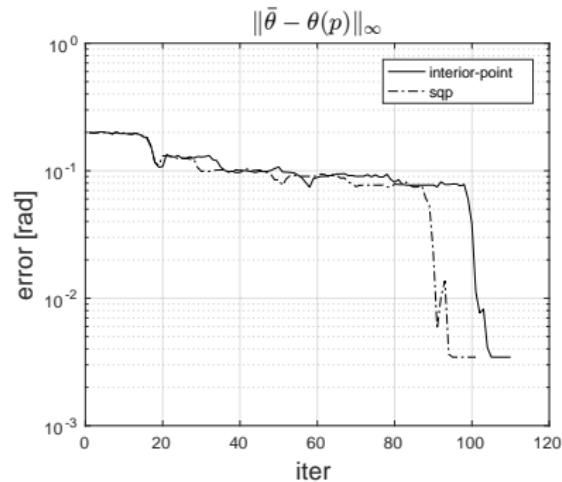
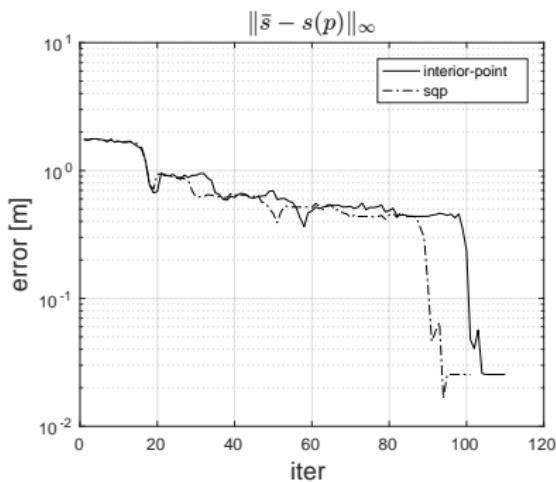
Example Instance

- $[0, T] = [0, 14s]$
- 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

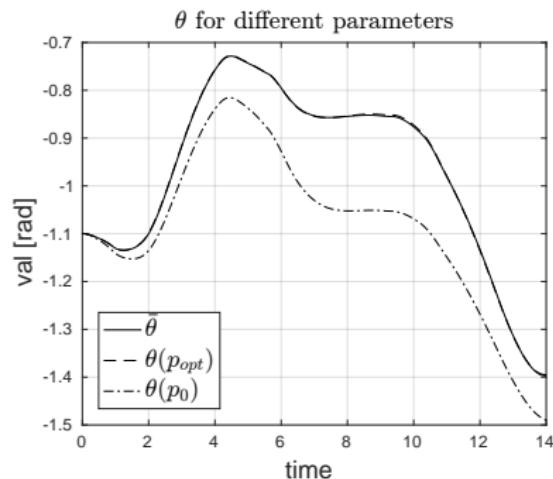
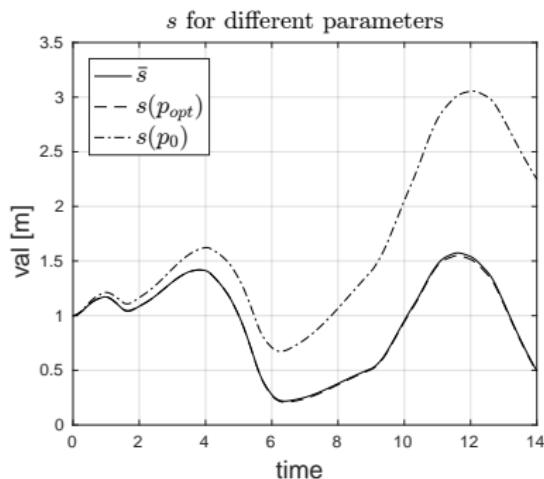


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- Masses
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Black box model

- Realistic model from Siemens
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Control



Model

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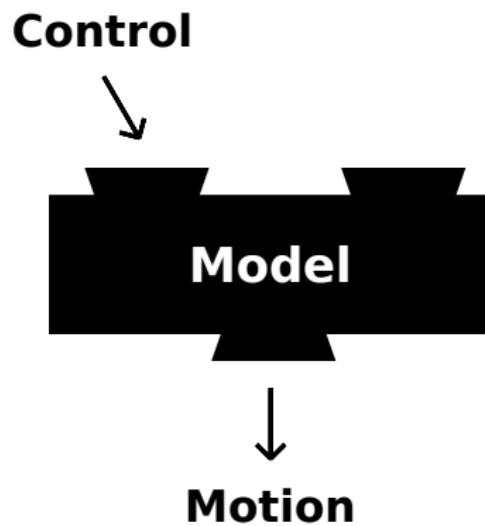
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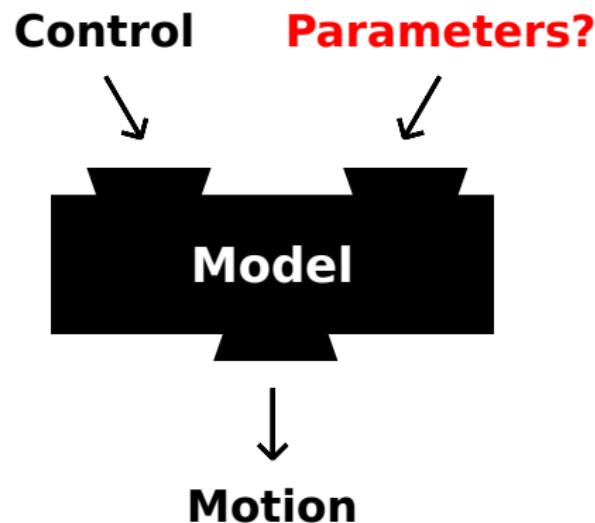
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Trajectories

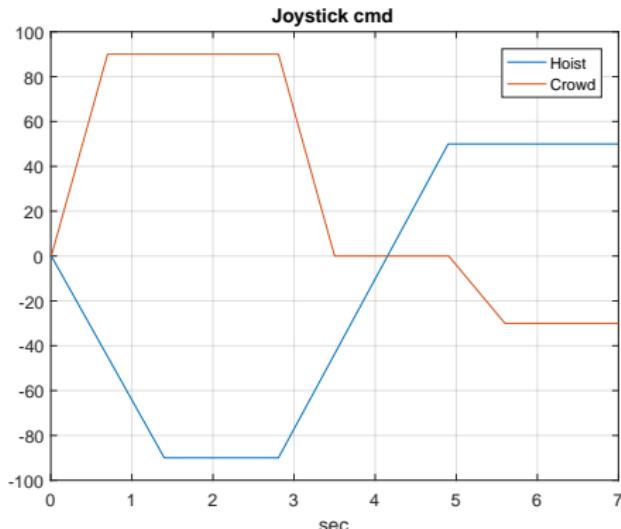
Input: Joystick commands for Up/Down and Back/Forth

Output: Position of the shovel

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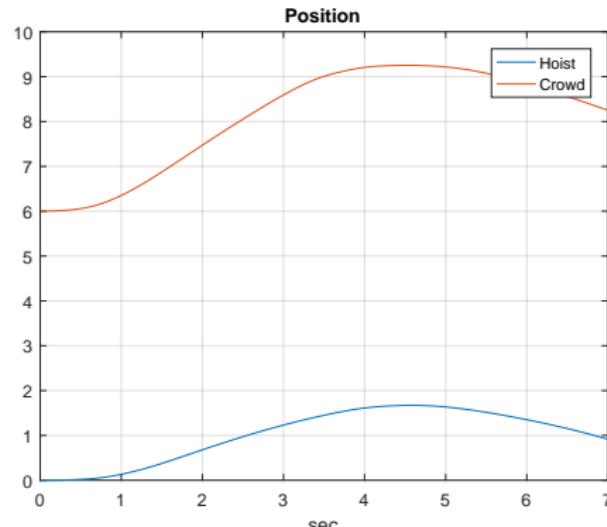
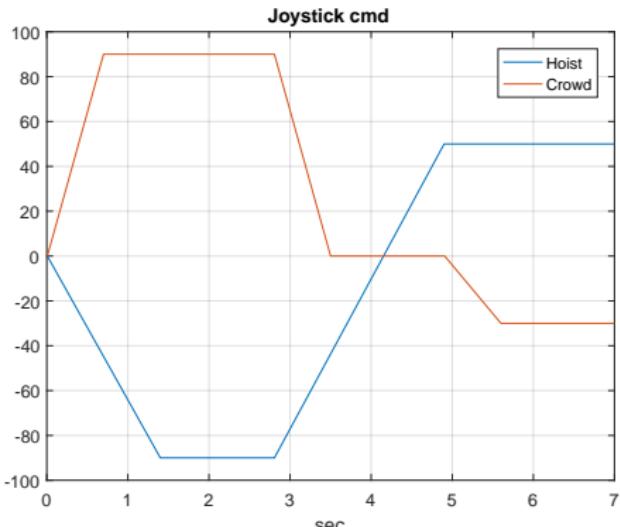
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Trajectories

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Objective Function

Optimized Parameters:

- Inertia (Engine)
- Inertia (Arm)
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Penalty Term:

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

Objective Function

Optimized Parameters:

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

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

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

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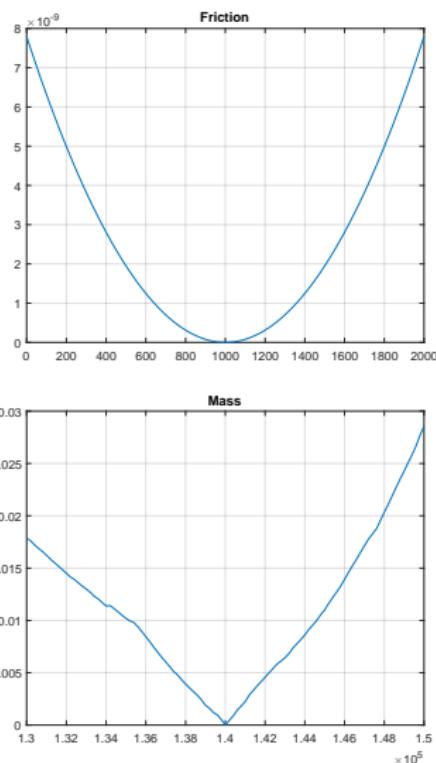
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Optimizers

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

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Pattern Search	10^{-11}	6500	17 min	$10^{-1.3}$	$10^{-3.7}$
Genetic Algorithm	10^{-4}	5500	14 min	$10^{-0.5}$	$10^{-1.0}$
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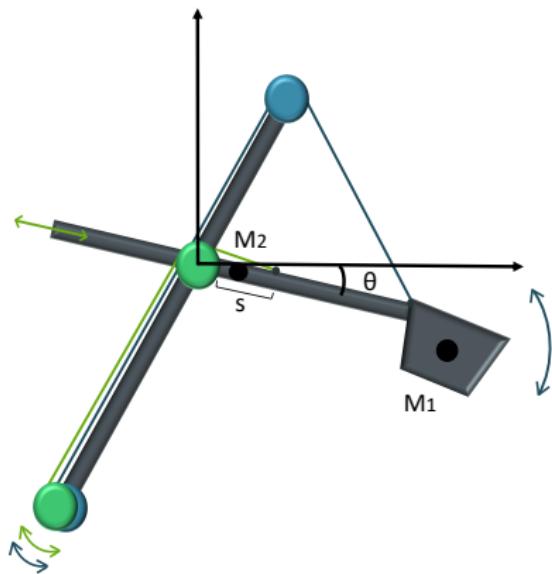
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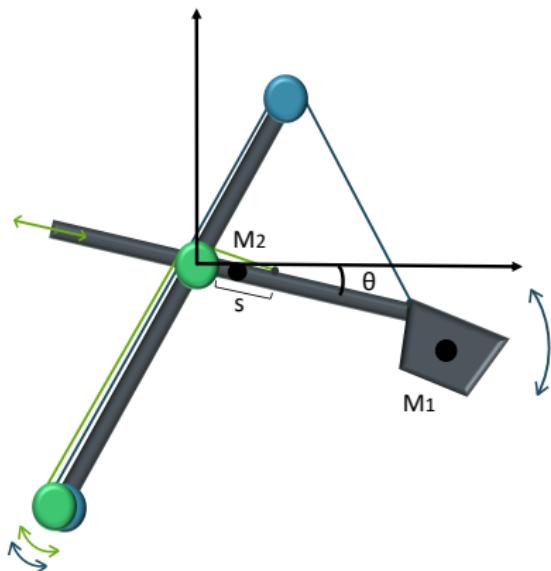
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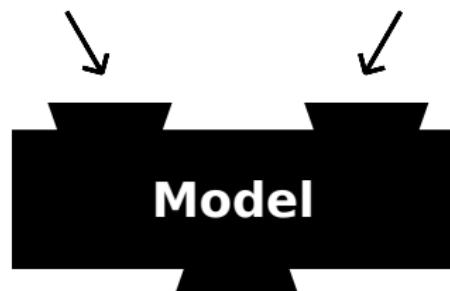


Summary



Control

Parameters?



Motion