Case Studies Nonlinear Optimization

Open Cast Mining

Final Presentation

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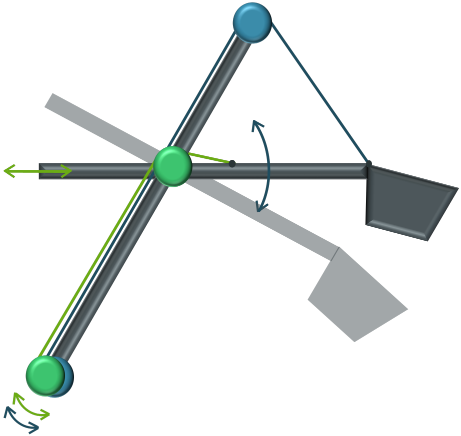
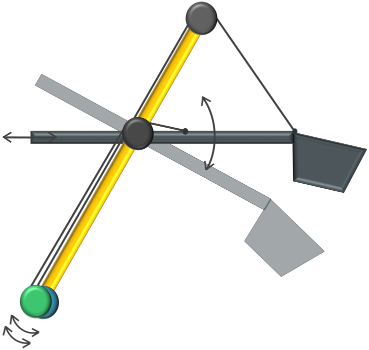
originally posted to Flickr by FAndrey at http://flickr.com/photos/43301444@N06/4141786255

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

Problem Setting

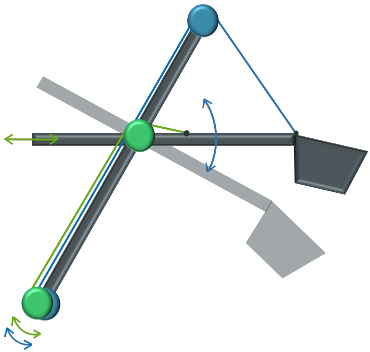


Problem Setting



- 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

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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

$\Rightarrow$

Good description of the effects of control and motion

Physical Modelling

Why?

Building an accurate model $\Rightarrow$ 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 $\Rightarrow$ 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

Method to describe dynamics of an accelerated system

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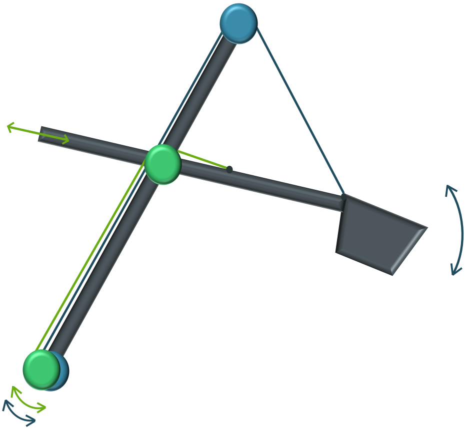
V	potentials
F	non-conservative external forces
r	points of actions of forces F
q	free variables
Q	generalized forces

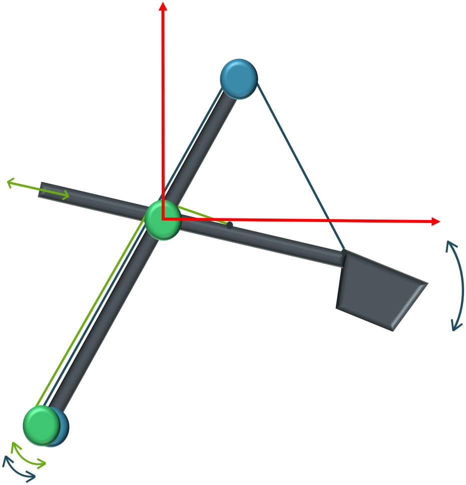
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i$$

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

Physical Model of Excavator

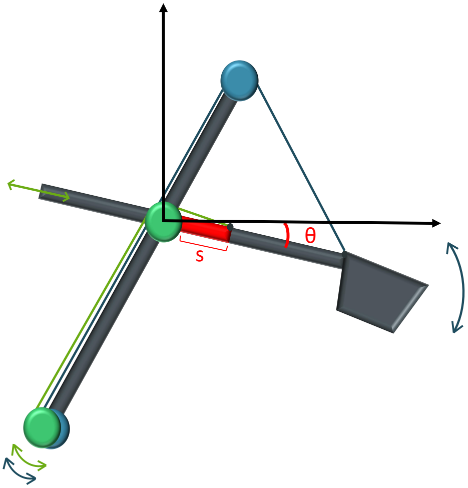


Physical Model of Excavator



coordinate system

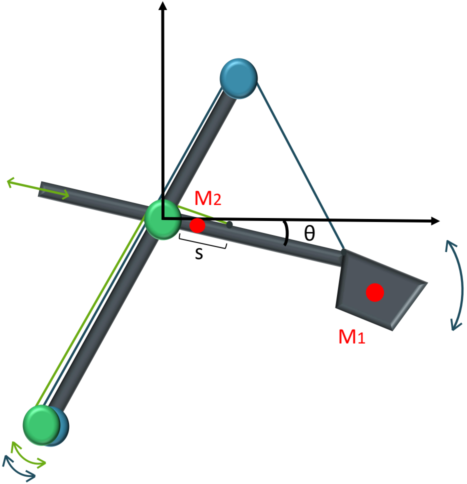
Physical Model of Excavator



degrees of freedom

- length s
- tilt angle θ

Physical Model of Excavator



movable centers of gravity of

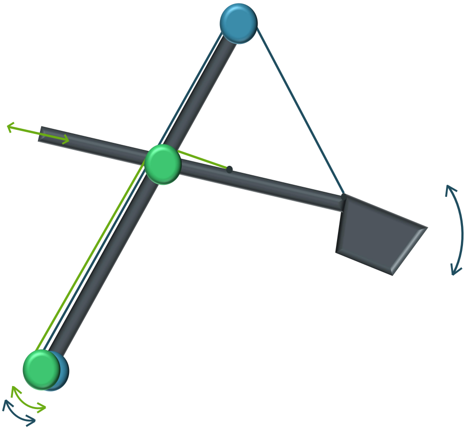
- shovel M_1
- arm M_2

Physical Model of Excavator

Assumptions to the model:

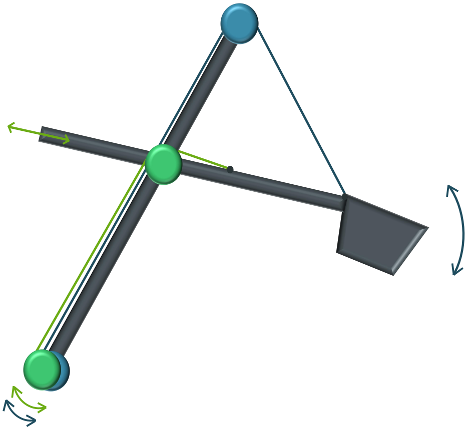
- no mass for the ropes
- shovel as point mass
- no slack/friction between ropes and cable reels

Kinetic Energy



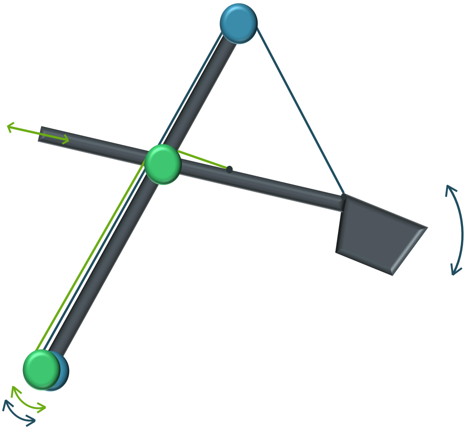
- movement of mass
- rotation of cable reel

Potential Energy



gravitational 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	$p = (p_1, ..., p_k)^T$

Discretization of the ODE

Discretize time interval:

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

Discretize state and control:

$$x_n = x(t_n)$$
$$u_n = u(t_n)$$

Discretization of the ODE

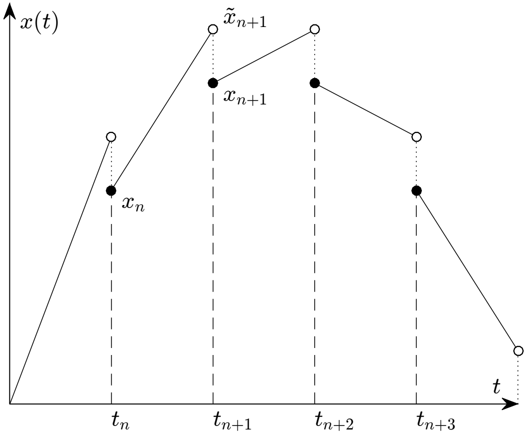
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

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

Discrete constraint:

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

Discretization of the ODE



Problem Formulation

Natural approach: Optimal Control Problem

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

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

Problem Formulation

Input:

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

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Output:

- parameters p of the excavator
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Idea:

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

Problem Formulation

Original Problem

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

Problem Formulation

Original Problem

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

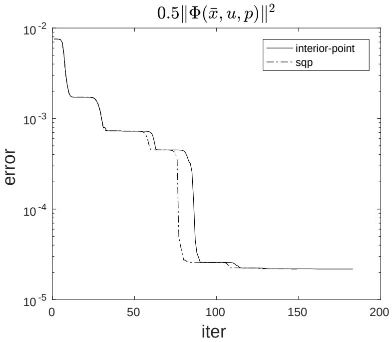
Reinterpreted Problem

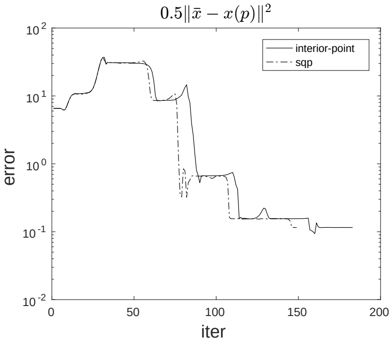
$$\begin{aligned} \min_{p} \quad & \frac{1}{2}\|\Phi(\bar{x}, u, p)\|^2 \\ \text{s. t.} \quad & p \geq 0 \end{aligned}$$

Comparison

plots explaining difference of the approaches

Results


$0.5\|\Phi(\bar{x}, u, p)\|^2$
error
iter
interior-point
sqp
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
50
100
150
200


$0.5\|\bar{x} - x(p)\|^2$
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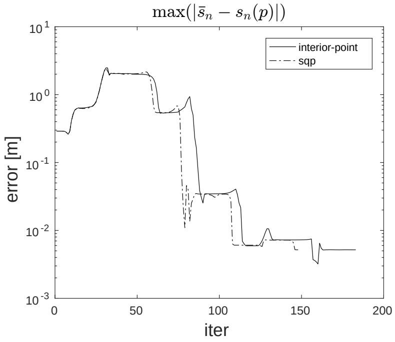
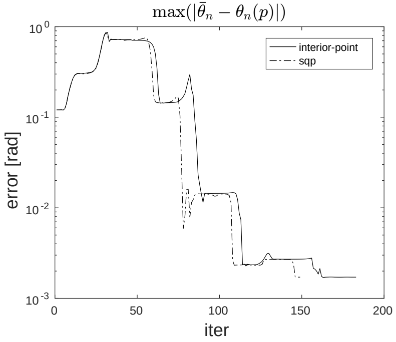
Results





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

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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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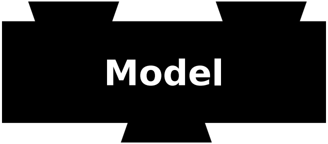

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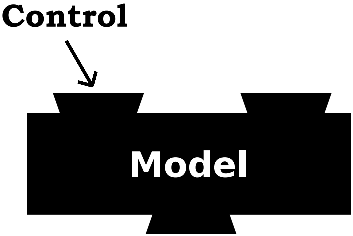

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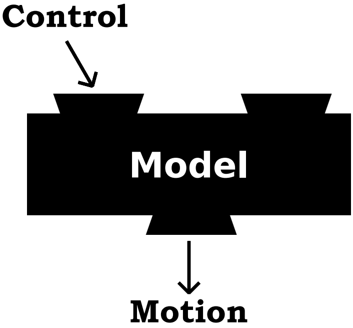

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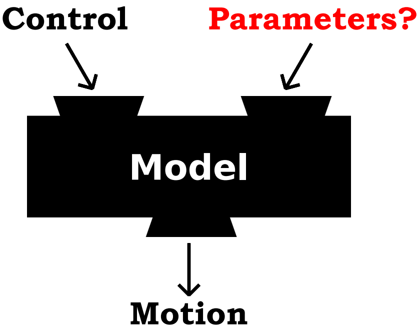

Parameter Optimization

Parameters to optimize:

- Parameters of own model
- Black box model
  $\Rightarrow$ derivative-free optimization

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  $\Rightarrow$ derivative-free optimization

Define penalty terms
$\Rightarrow$ minimize for parameter solutions

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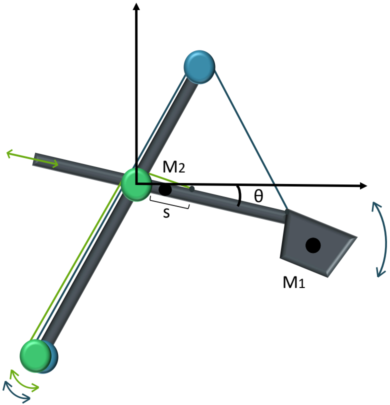
Summary



Summary