Case Studies Nonlinear Optimization

Open Cast Mining

Presentation for Siemens

July 20, 2016

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2 Physical Model

3 Parameter Identification: Physical Model

4 Parameter Identification: Black Box Model

5 Summary

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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

Physical Modeling

Why?

Building an accurate model	$\Longrightarrow$	Good description of the effects of control on motion

Physical Modeling

How?

To consider:

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

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- Friction in cable reels
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$\longrightarrow$

Lagrange Formalism
(ODE)

Parameter Identification

What are parameters?

- Friction coefficients
- Mass
- Inertia

Parameter Identification

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- Friction coefficients
- Mass
- Inertia

Why?

Accurate and realistic parameters $\Rightarrow$ Better prediction and planning of motion

Visual Examples

Same parameters except different load weights

vs

Light load

Heavy load

Procedure

Physical Model

Lagrange Formalism

$\Downarrow$

Parameter Identification

Discretization + Optimization

Procedure

Physical Model

Lagrange Formalism

$\Downarrow$

Parameter Identification

Discretization + Optimization

and

Blackbox Model

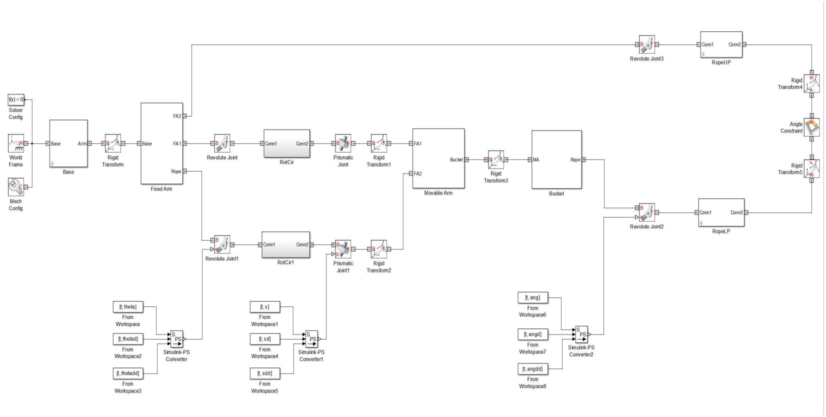
- Realistic model
- Confidential information

$\Downarrow$

Parameter Identification

Derivative-free optimization

Visualization: Simulink



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Lagrange Formalism

Method to describe dynamics of an accelerated system

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Method to describe dynamics of an accelerated system

T	kinetic energy
V	potentials

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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

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

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

T	kinetic energy
V	potentials
F	non-conservative external forces
r	points of actions of forces F
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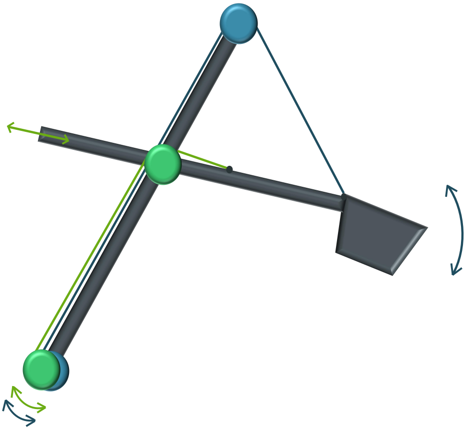
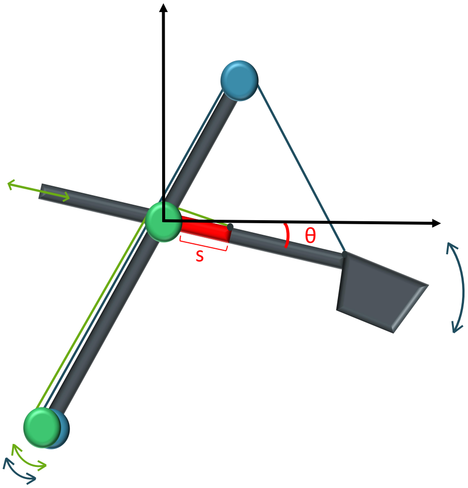
Physical Model of Excavator



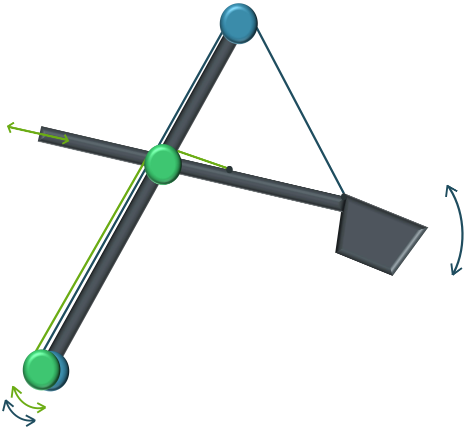
Physical Model of Excavator



degrees of freedom

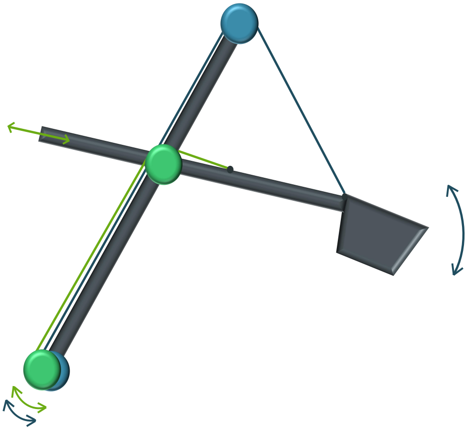
- length s
- tilt angle θ

Kinetic Energy



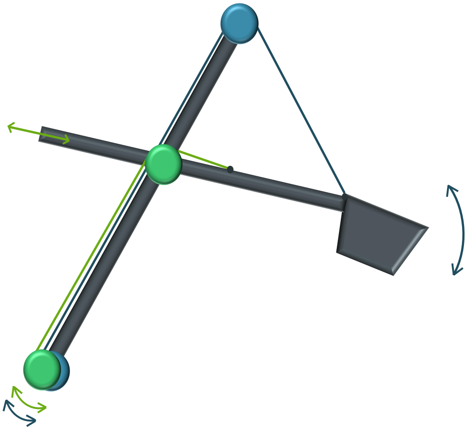
- kinetic energy for shovel and movable arm
- rotation of cable reels

Potential Energy



gravitational energy for shovel and movable arm

Potential Energy



gravitational energy for shovel and movable arm

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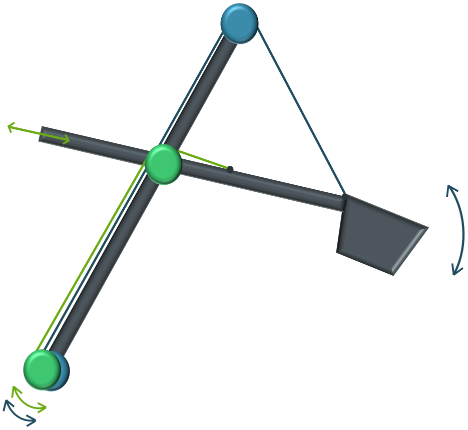
$$Q = \left(\frac{\partial r}{\partial q}\right)^T F$$

Generalized Forces

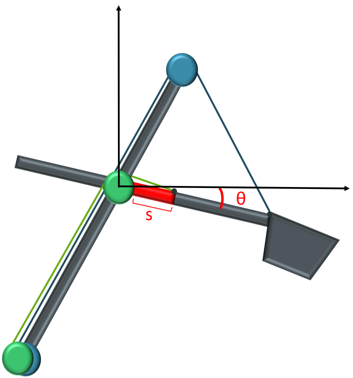


- torque on cable reels
- friction of cable reels

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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$\rightarrow$ Transformation into 1st order ODE

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

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

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Discretization of the ODE

Discretize time interval:

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

Discretize state and control:

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

Discretization of the ODE

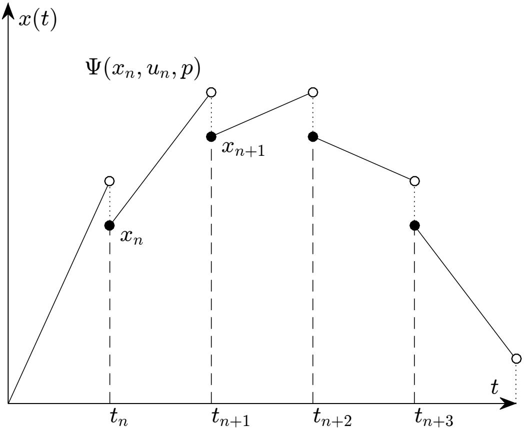
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

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

Discrete constraint:

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

Discretization of the ODE



Problem Setting

Given:

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

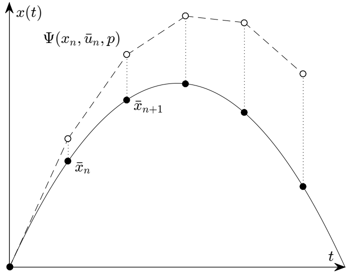
Unknown:

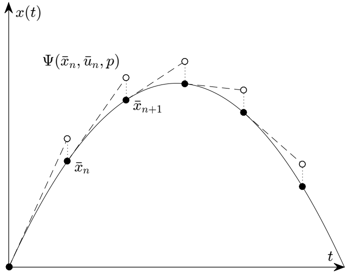
- parameters $\bar{p}$ of the excavator

Output:

- parameters p

Possible Approaches





continuous vs. stepwise Approximation

Problem Formulation

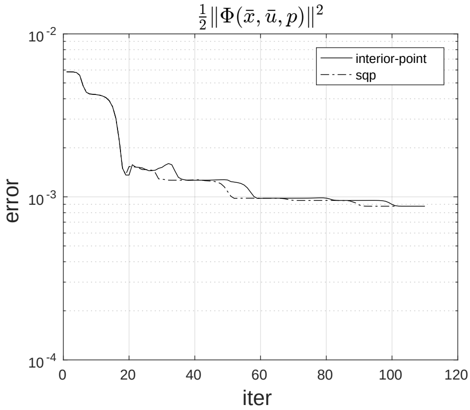
$$\begin{aligned} \min_{p} \quad & \frac{1}{2}\|\Phi(\bar{x}, \bar{u}, p)\|^2 \\ \mathrm{s.\,t.} \quad & p \geq 0 \end{aligned}$$

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

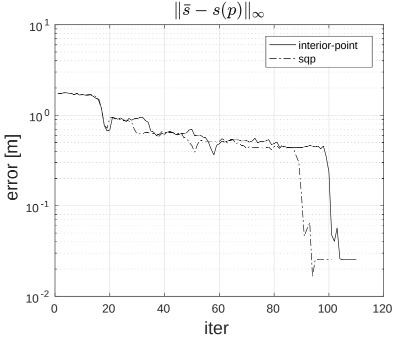
Example Instance

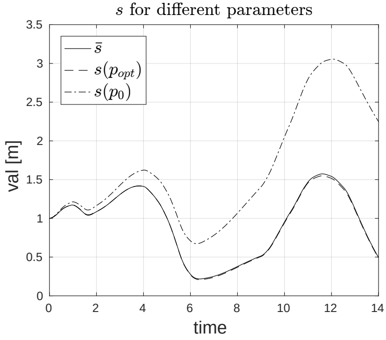
- $[0, T] = [0, 14s]$
- 1500 time steps
- $p_0 \in [0.8\bar{p}, 1.2\bar{p}]$
- internally 5 trajectories in parallel

Results


$\frac{1}{2}\|\Phi(\bar{x}, \bar{u}, p)\|^2$
10^{-2}
10^{-3}
10^{-4}
error
0
20
40
60
80
100
120
iter
interior-point
sqp

Results





In total exact up to 3cm

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- Masses
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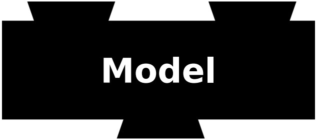

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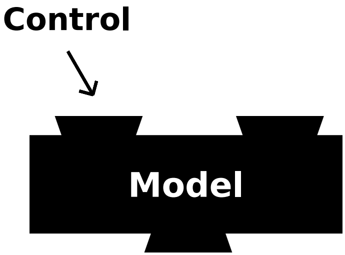

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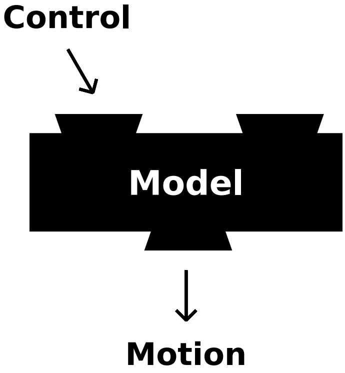

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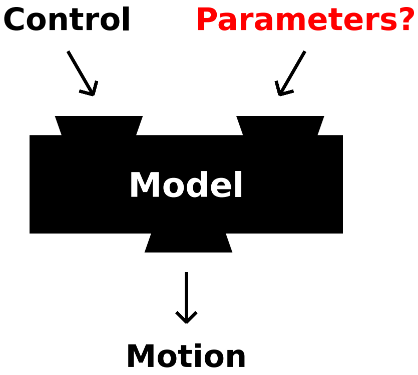

Trajectories

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

Output: Position of the shovel

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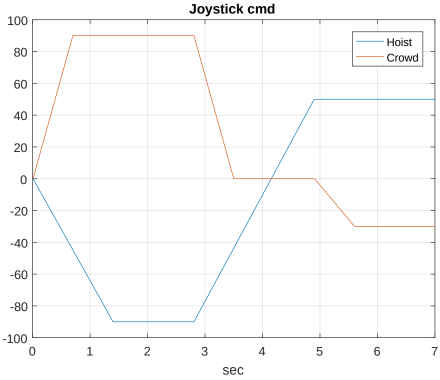

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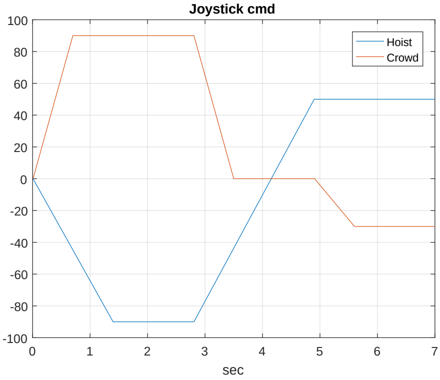

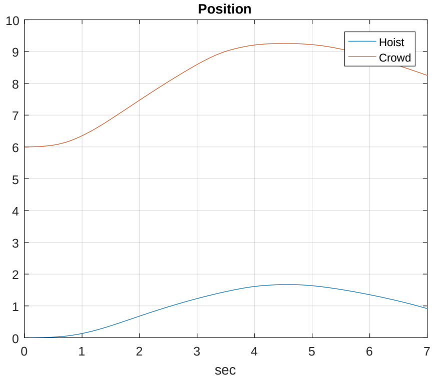

Objective Function

Optimized Parameters:

- Inertia (Engine)
- Inertia (Arm)
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$$\|\overline{X}_i - X_i\,(p)\,\|^2$$

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$$\frac{\|\overline{X}_i - X_i\left(p\right)\|^2}{\|\overline{X}_i\|^2}$$

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Optimized Parameters:

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

$\overline{X}_i$, $\overline{Y}_i$ reference trajectories

Objective Function

Optimized Parameters:

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

Penalty Term:

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

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Objective Function

Optimized Parameters:

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Penalty Term:

$$\begin{aligned} \min_{p \in \mathbb{R}^4} f(p) = \quad & \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{\|\overline{X}_i - X_i(p)\|^2}{\|\overline{X}_i\|^2} + \frac{\|\overline{Y}_i - Y_i(p)\|^2}{\|\overline{Y}_i\|^2} \right) \\ \text{s.t.} \quad & p_j \geq 0 \end{aligned}$$

$\overline{X}_i, \overline{Y}_i$ 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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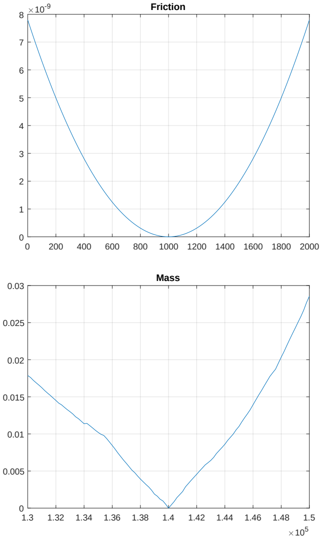

Optimizers

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

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	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	$10^{-0.3}$	$10^{-0.6}$

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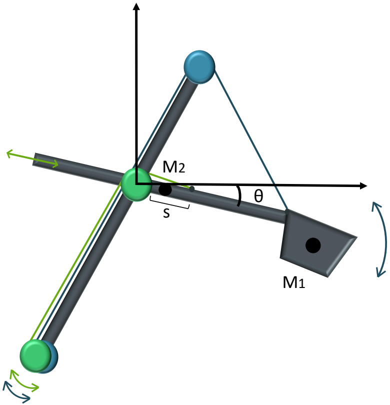

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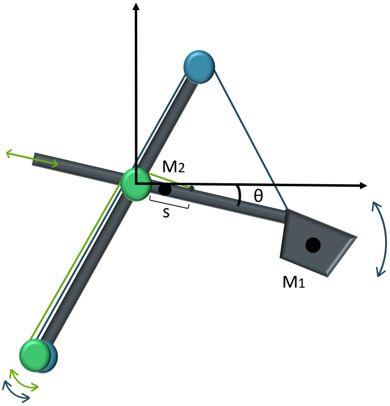
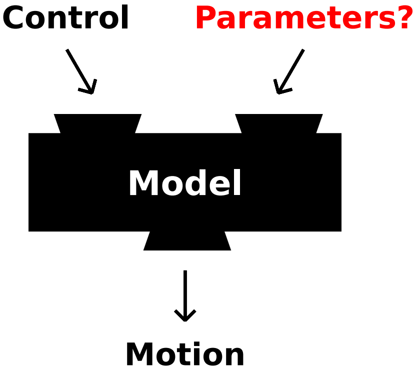




Appendix

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

Problem Formulation

Input:

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

Output:

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

Idea:

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

Problem Formulation

Original Problem

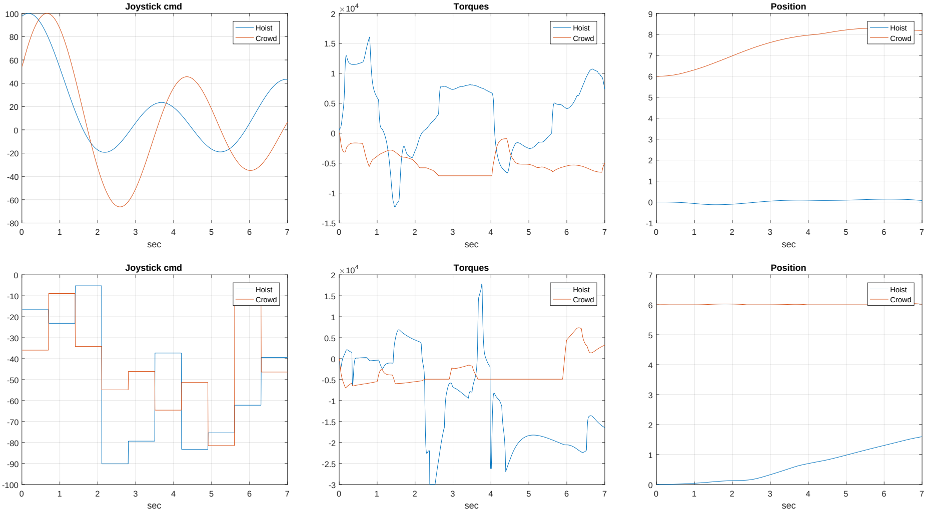
$$\begin{aligned} \min_{x,p} \quad & \frac{1}{2}\|\bar{x} - x\|^2 \\ \text{s.t.} \quad & \Phi(x, \bar{u}, p) = 0 \\ & p \geq 0 \end{aligned}$$

Set $x \leftarrow \bar{x}$

Reinterpreted Problem

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

Example Trajectories



Influence of the Parameters