Case Studies Nonlinear Optimization

Open Cast Mining

Final Presentation

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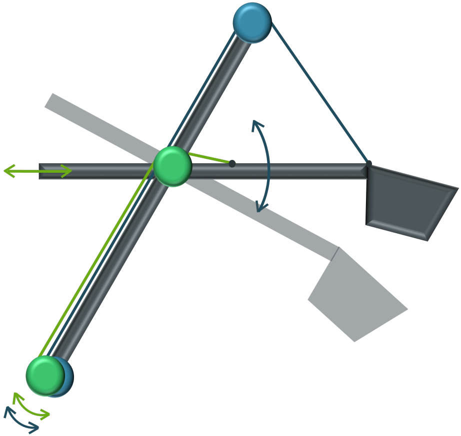
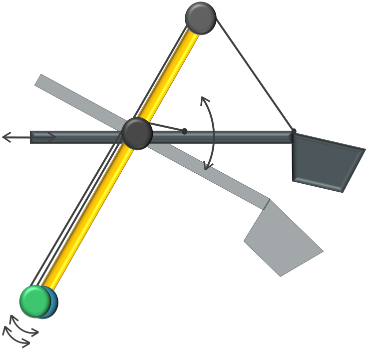
originally posted to Flickr by FAndrey at http://flickr.com/photos/43301444@N06/4141786255

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

Problem Setting

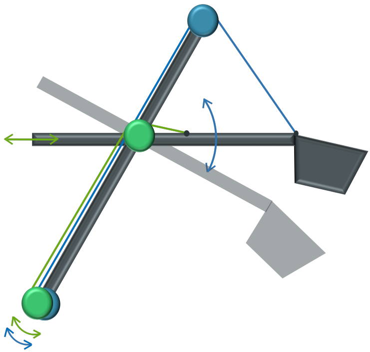


Problem Setting



- Arm element fixed to 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

$\Downarrow$

Parameter Identification

Discretization

Procedure

Physical Model

- Rope properties
- Lagrange Formalism

$\Downarrow$

Parameter Identification

Discretization

vs

Blackbox Model

- Realistic model
- Confidential information

$\Downarrow$

Parameter Identification

Derivative-free optimization

Physical Modeling

Why?

Building an accurate model $\Rightarrow$ 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

$\longrightarrow$

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	$\Rightarrow$	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

$\Downarrow$

Parameter Identification

Discretization

vs

Blackbox Model

- Realistic model
- Confidential information

$\Downarrow$

Parameter Identification

Derivative-free optimization

Parameter Identification: Physical Model

Own Physical Model

Lagrange Formalism

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

$\Downarrow$

Parameter Identification

Discretization

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

Parameter Identification: Physical Model

Own Physical Model

Lagrange Formalism

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

$\Downarrow$

Parameter Identification

Discretization

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

- 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

$\Downarrow$

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

$\Downarrow$

Parameter Identification

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

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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

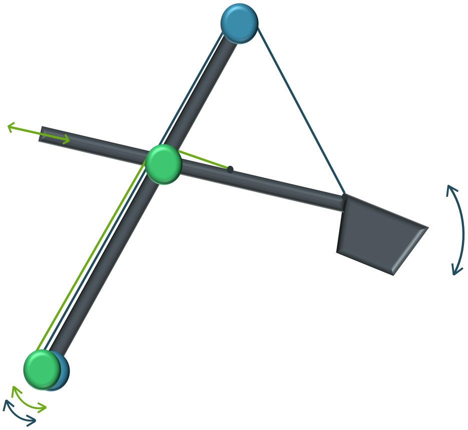
Method to describe dynamics of an accelerated system

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

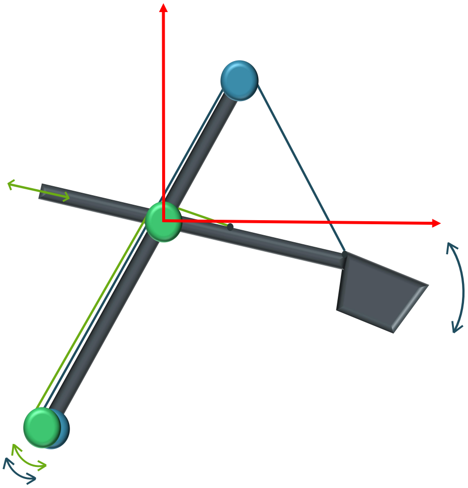
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i$$

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

Physical Model of Excavator

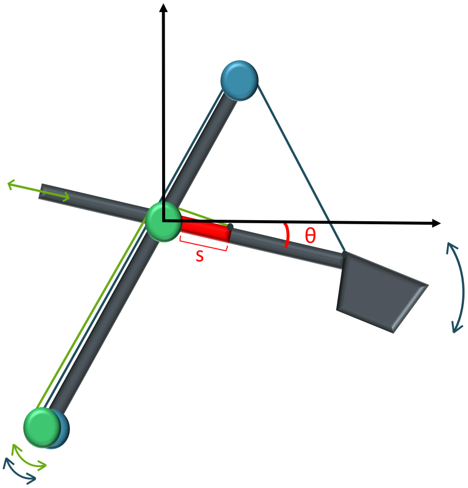


Physical Model of Excavator



coordinate system

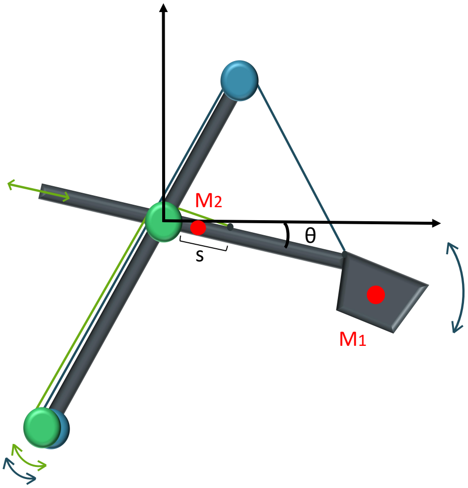
Physical Model of Excavator



degrees of freedom

- length s
- tilt angle θ

Physical Model of Excavator



movable centers of gravity of

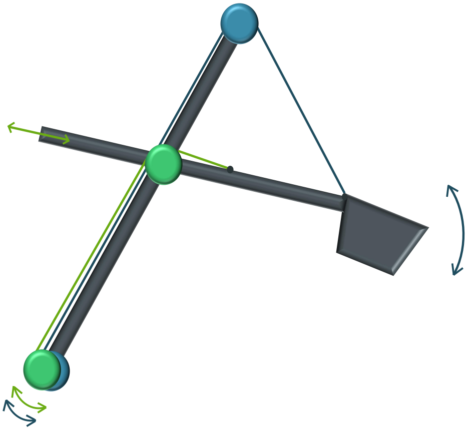
- shovel M_1
- arm M_2

Physical Model of Excavator

Assumptions to the model:

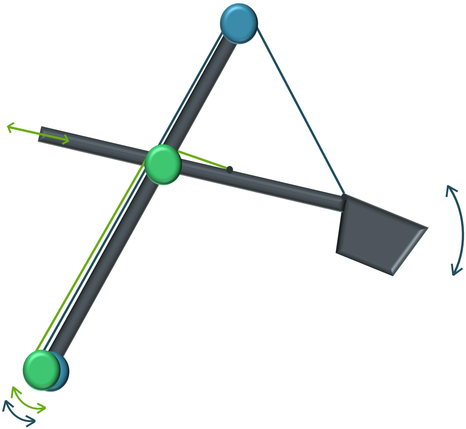
- no mass for the ropes
- shovel as point mass
- no slack/friction between ropes and cable reels

Kinetic Energy



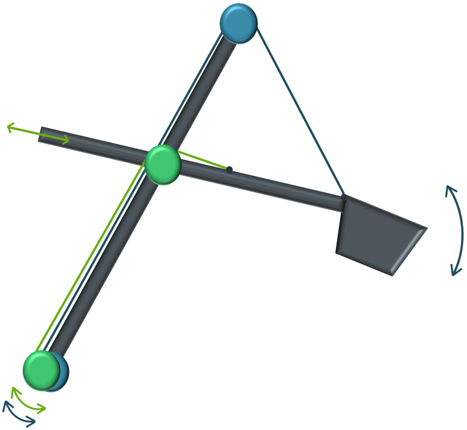
- movement of mass
- rotation of cable reel

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

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Discretization of the ODE

Discretize time interval:

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

Discretize state and control:

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

Discretization of the ODE

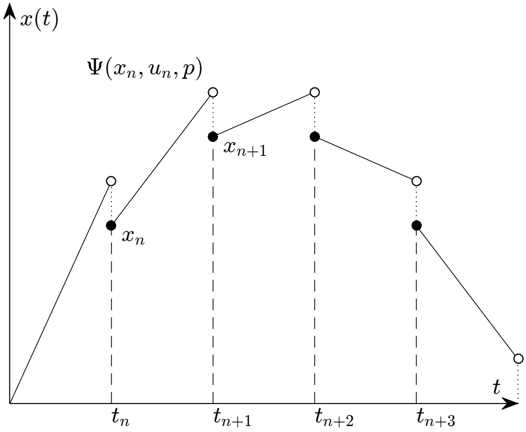
Explicit Euler for every time step $h_n = t_{n+1} - t_n$:

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

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

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

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 \\
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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 $x \leftarrow \bar{x}$

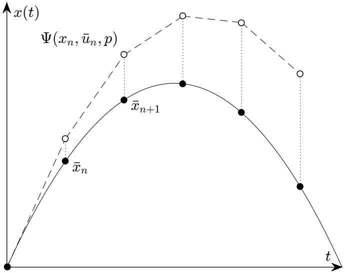
Reinterpreted Problem

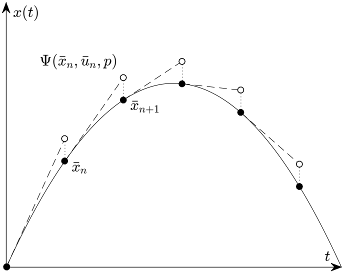
$$\begin{aligned} \min_{p} \quad & \frac{1}{2}\|\Phi(\bar{x}, \bar{u}, p)\|^2 \\ \text{s. t.} \quad & p \geq 0 \end{aligned}$$

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

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

Comparison of the Approaches



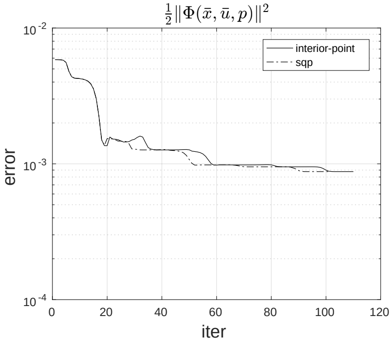


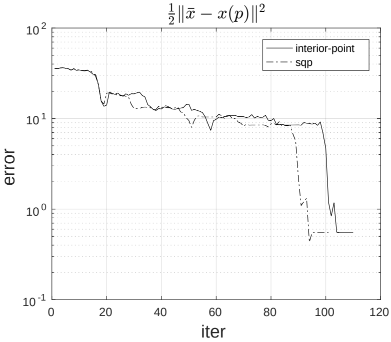
continuous vs. stepwise Approximation

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


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


$\frac{1}{2}\|\bar{x}-x(p)\|^2$
interior-point
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error
iter
10^2
10^1
10^0
10^-1
0
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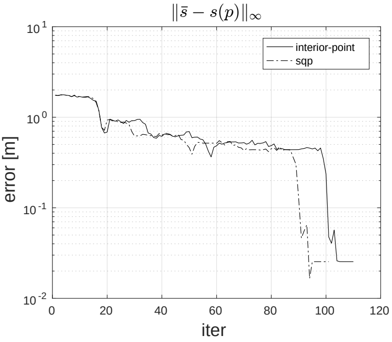
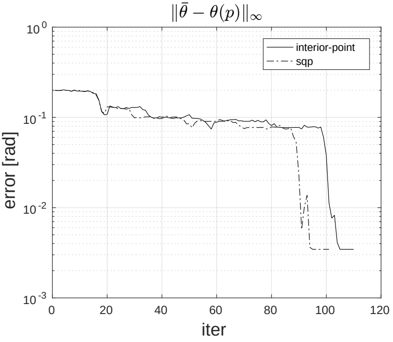
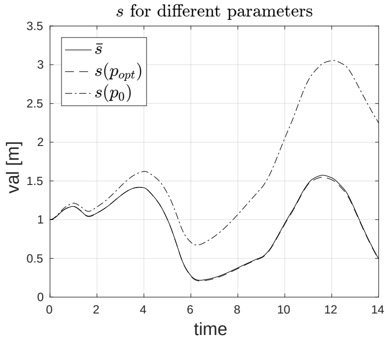
Results

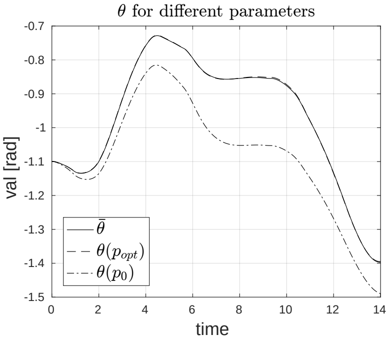




Exact up to 3cm

Results


s for different parameters
val [m]
time
$\bar{s}$
$s(p_{opt})$
$s(p_0)$
0
0.5
1
1.5
2
2.5
3
3.5
0
2
4
6
8
10
12
14


θ for different parameters
val [rad]
time
$\bar{\theta}$
$\theta(p_{opt})$
$\theta(p_0)$
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
-1.5
0
2
4
6
8
10
12
14

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Motivation

Examples

- Friction coefficients
- Masses
- Inertia

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Black box model

- Realistic model from Siemens
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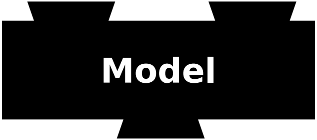

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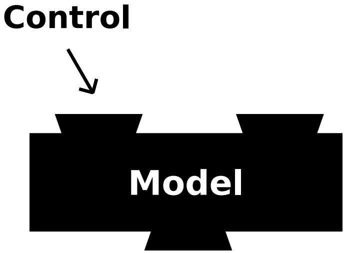

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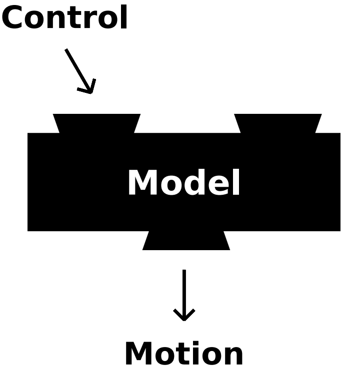

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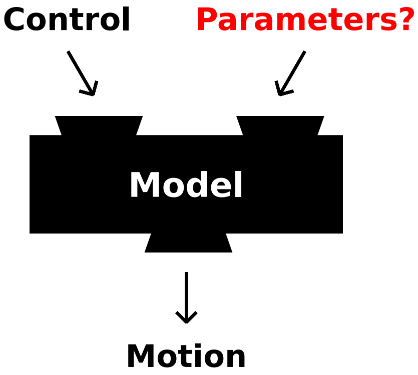

Trajectories

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

Output: Position of the shovel

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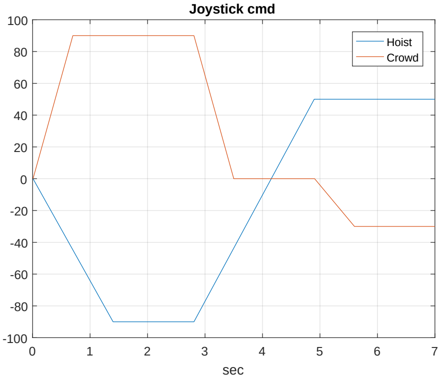

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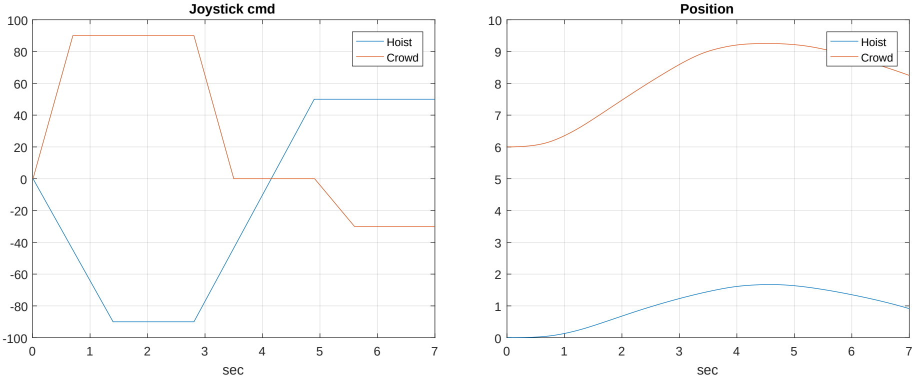

Objective Function

Optimized Parameters:

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

Objective Function

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Penalty Term:

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

Objective Function

Optimized Parameters:

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

Objective Function

Optimized Parameters:

- Inertia (Engine)
- Inertia (Arm)
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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:

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

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

Objective Function

Optimized Parameters:

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

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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Big parameter changes $\Rightarrow$ Small effects

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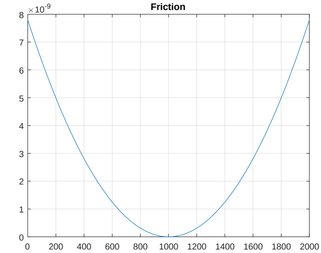

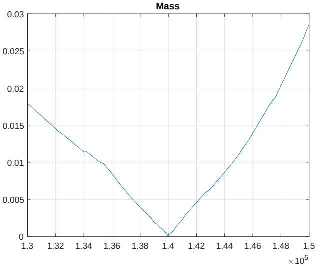

Optimizers

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

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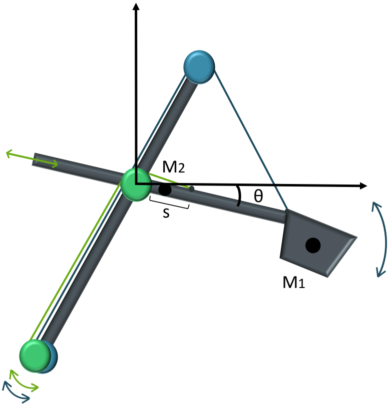
Summary



Summary