Co-Design and Control of a Magnetic Microactuator for Freely Moving Platforms

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Motivation I

Objectives in research of microactuators

- Large working ranges
- Fast and precise motion
- Multistability

Stick and Slip [Edeler2011]

Impact mechanism [Mita2003]

Electromagnetic levitation [Poletkin2017]

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- Mechanical limitations
- High dependence on friction
- Permanent energy input

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Magnetic microactuator concept

- Free motion
- Bistability by permanent magnets
- Cooperative actuator mechanism
- Efficient design and control

Motivation II

Design and control goals

- Robust equilibrium positions
- Energy optimal and fast motion
- Opimised cooperation

Problem formulation

- Coupling of design and control
- Contradictory goals

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→ Co-design: Simultaneous design and controller optimisation

Agenda

1 **Motivation**

2 **System description**

3 **Control approach**

4 **Co-design**

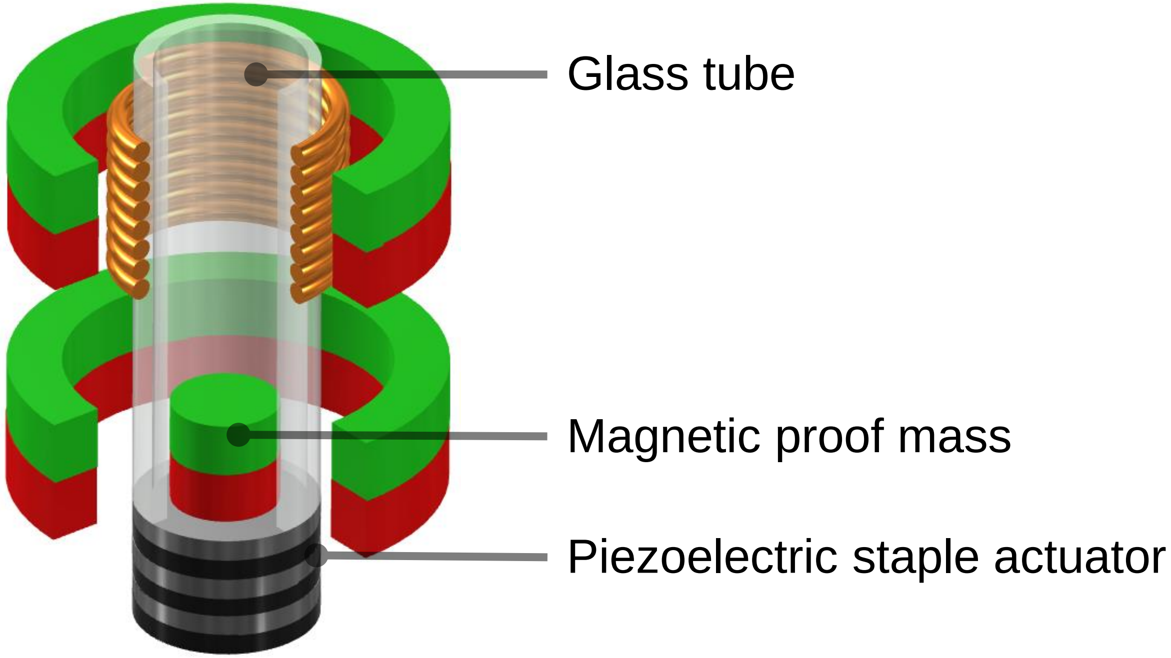
5 **Simulation results**

6 **Summary and Outlook**

System Description

Working Principle

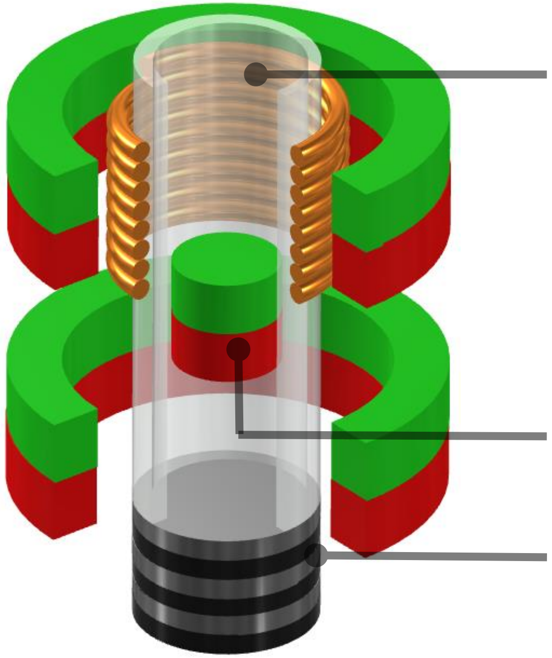
- Proof mass initially on the piezoactuator



System Description

Working Principle

- Proof mass initially on the piezoactuator
- Initial acceleration (Kick) by piezoactuator



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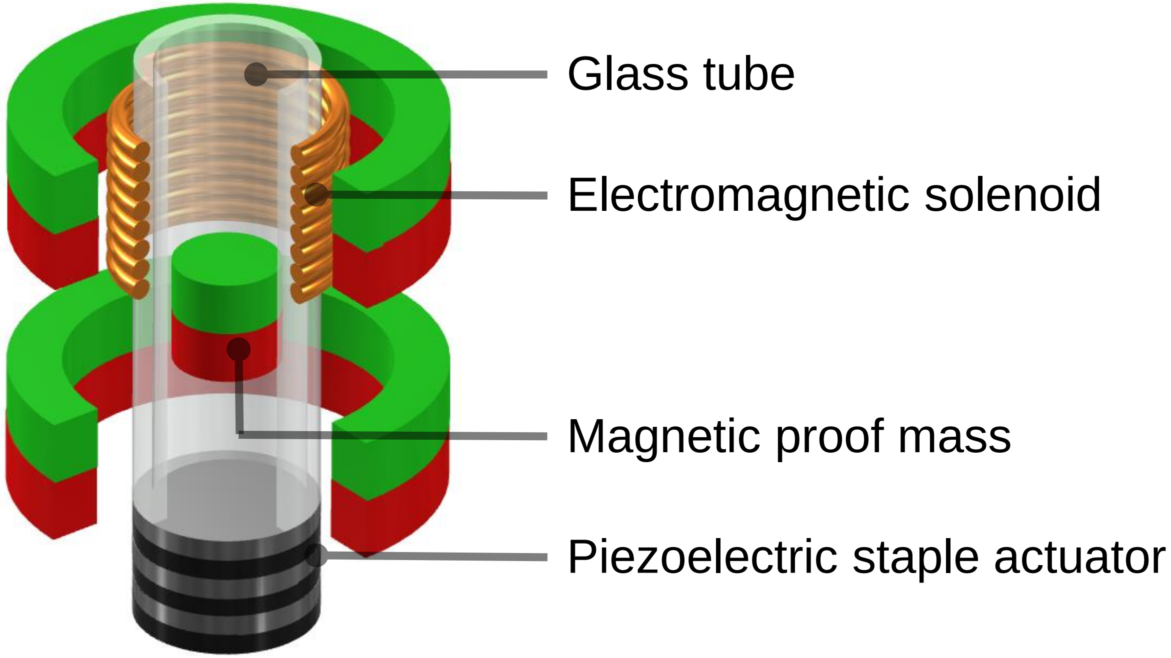
- Proof mass initially on the piezoactuator
- Initial acceleration (Kick) by piezoactuator
- Electromagnetic control (Catch) in upper position



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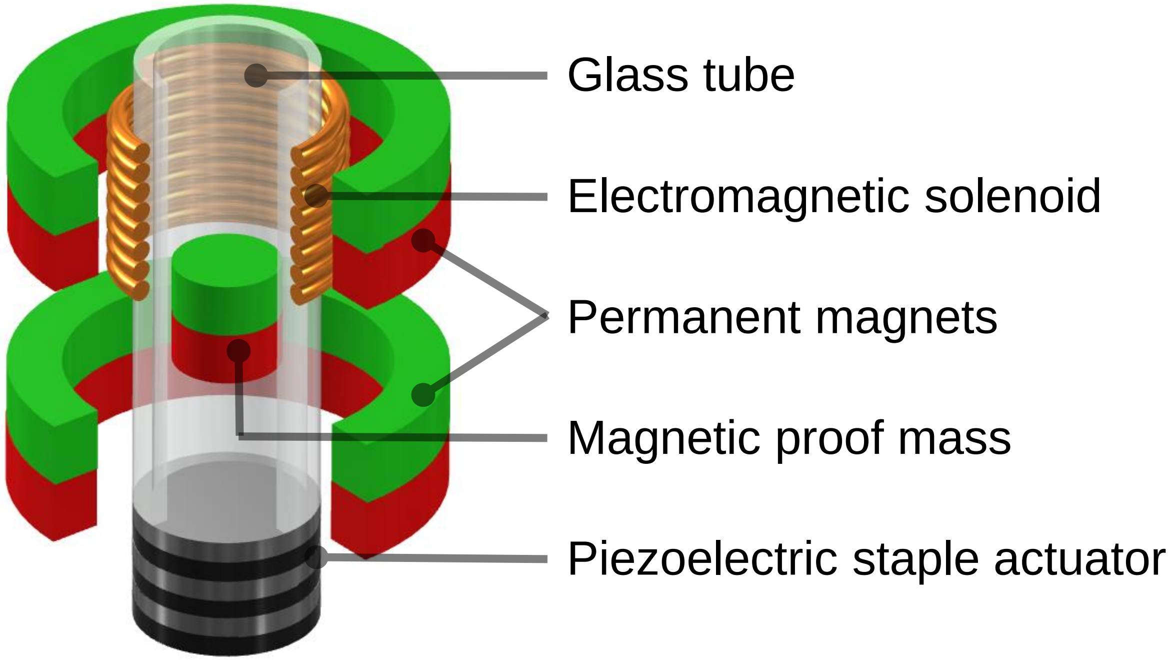
- Stable levitation without input



System Description

Working Principle

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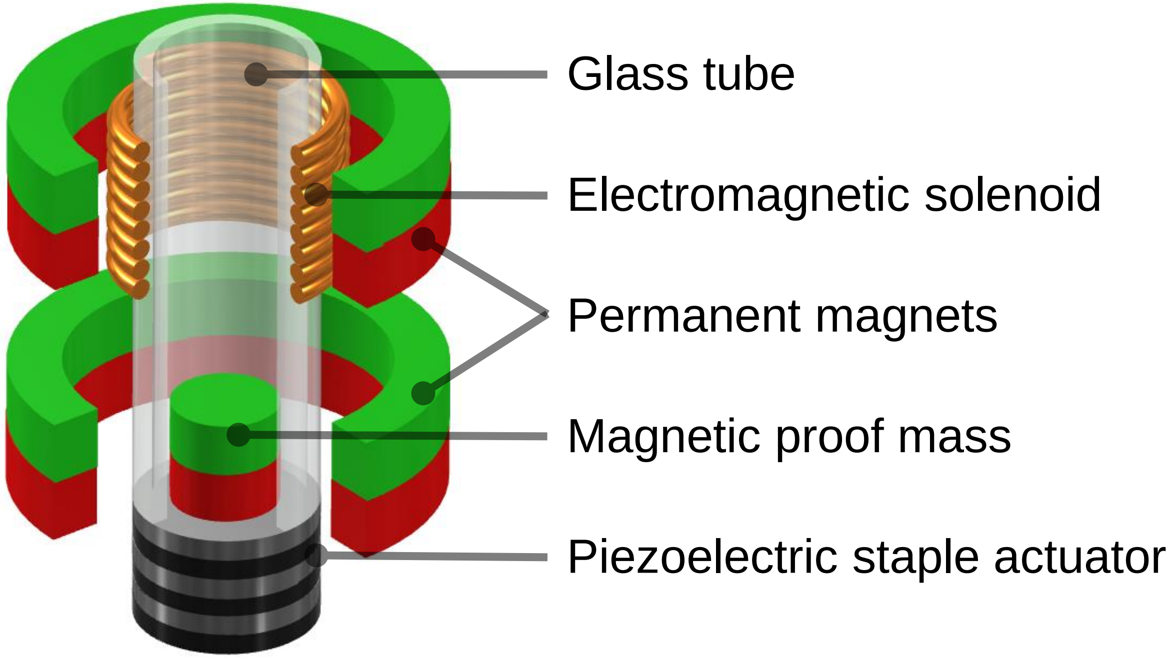
- Initial acceleration (Kick) by piezoactuator
- Electromagnetic control (Catch) in upper position
- Stable levitation without input
- Downwards motion by electromagnetic control



System Description

Equations of Motion

- Electromagnet
  (current)
- Piezoactuator
  (deflection)
- Proof mass
  (vertical motion)

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$$L\frac{\mathrm{d}i}{\mathrm{d}t} = u_{\mathrm{in}} - Ri$$

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Equations of Motion

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$$L\frac{\mathrm{d}i}{\mathrm{d}t} = u_{\mathrm{in}} - Ri$$

- Piezoactuator (deflection)

$$M\ddot{d} = -Mg - c_{\mathrm{A}}\dot{d} - k_{\mathrm{A}}d - F_{\mathrm{c}}(d,\dot{d},z,\dot{z}) + \frac{F_{\max}}{U_{\max}}u_{\mathrm{A}}$$

- Proof mass (vertical motion)

Contact force $F_{\mathrm{c}}(d,\dot{d},z,\dot{z})$ adapted from [Specker2015]

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- Proof mass (vertical motion)

$$m\ddot{z} = -mg - F_{\mathrm{r}}(\dot{z}) + F_{\mathrm{c}}(d,\dot{d},z,\dot{z}) + F_{\mathrm{em}}(z,i) + \sum_{j} F_{\mathrm{pm},j}(z)$$

Contact force $F_{\mathrm{c}}(d,\dot{d},z,\dot{z})$ adapted from [Specker2015]

Permanent magnetic force $F_{\mathrm{pm},j}(z) \sim B_{\mathrm{p}}\, B_{\mathrm{pm},j}$

Electromagnetic force $F_{\mathrm{em}}(z) \sim B_{\mathrm{p}}\, i$

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Control Approach

Piezoactuator: Feedforward control

Input voltage spike for impulse-like acceleration with $u_{\mathrm{A}} = \frac{u_{\mathrm{p}}}{0.53}\left(\exp\left(\frac{-t}{\tau_2}\right) - \exp\left(\frac{-t}{\tau_1}\right)\right)$

Electromagnet: Flatness-based control

Assumption: The proof mass remains below the solenoid centre

- System model is flat with respect to z

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- Given a trajectory z_{ref}, inversely compute the necessary feedforward input u_{ref}
- Exact feedback linearisation
- Application of a linear quadratic regulator for disturbance compensation

Control Approach

Flatness-based Control

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Flatness-based Control

State transformation

$$\boldsymbol{x} = [z,\ \dot{z},\ i] \rightarrow \boldsymbol{\xi} = [z,\ \dot{z},\ \ddot{z}]$$

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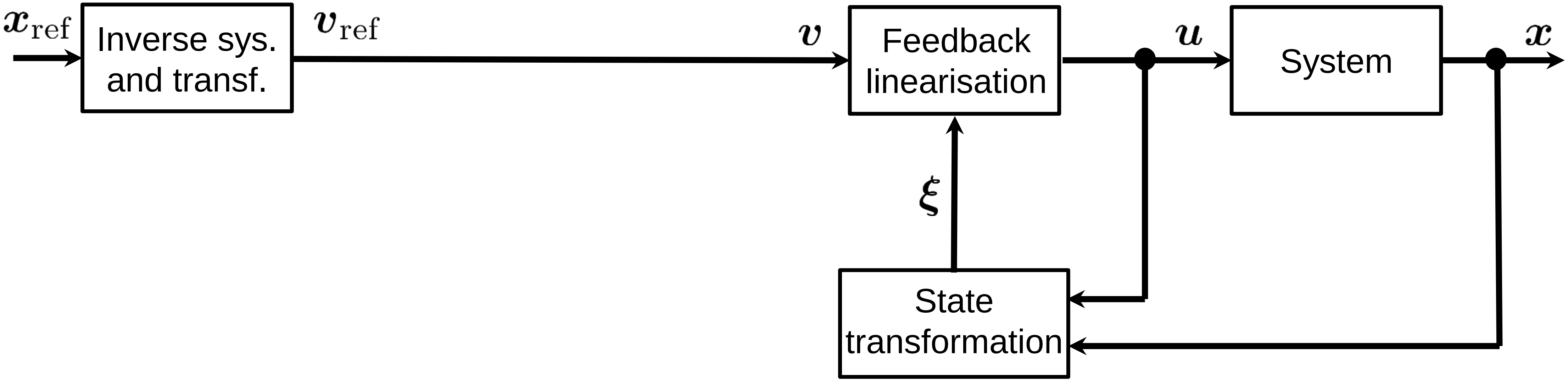

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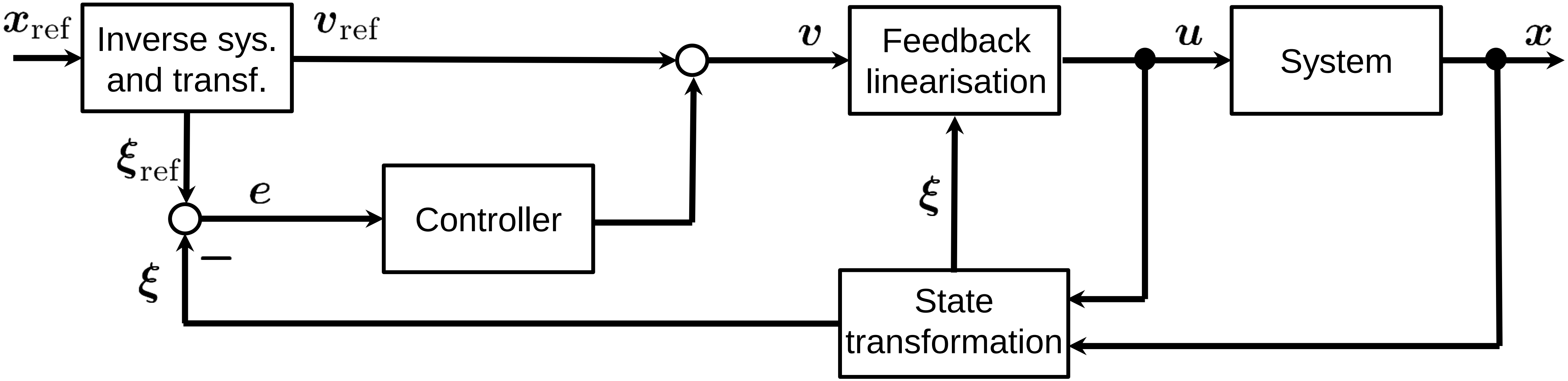

Control Approach

Reference trajectory generation

- Parameterise motion z_{ref} by its third derivative

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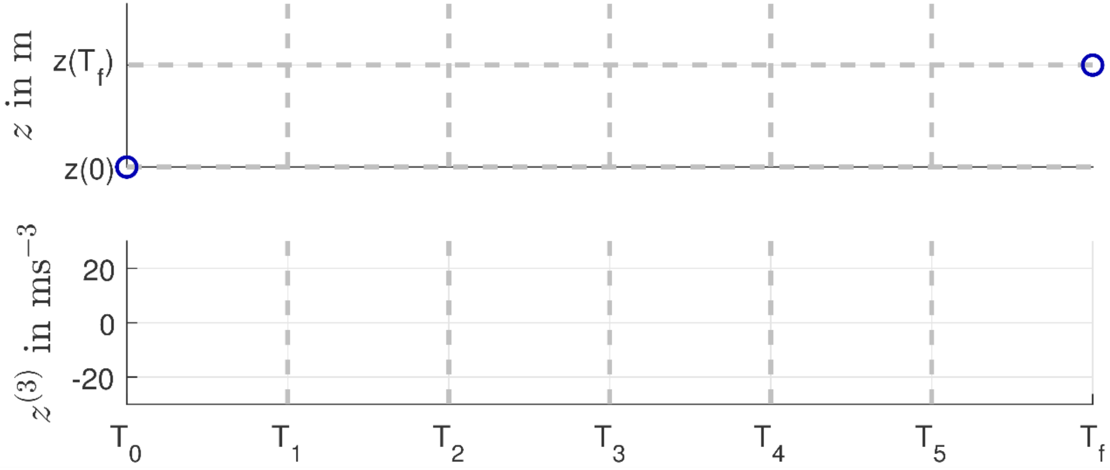

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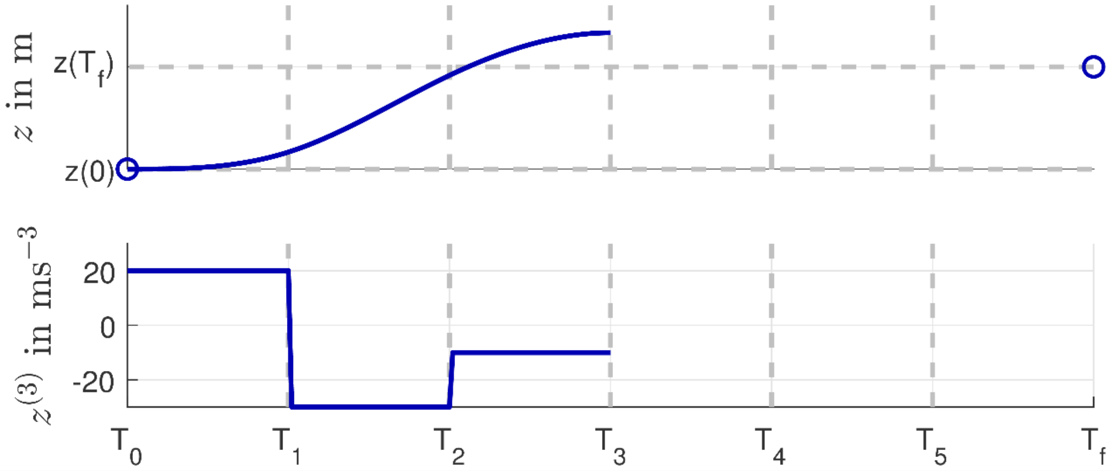
Reference trajectory generation

- Parameterise motion z_{ref} by its third derivative
- Divide transient time T_{f} into equal intervals
- Assign constant trajectory parameters $\dddot{z}_{\mathrm{ref}} = u_i, \quad t \in [T_i, T_{i+1}]$



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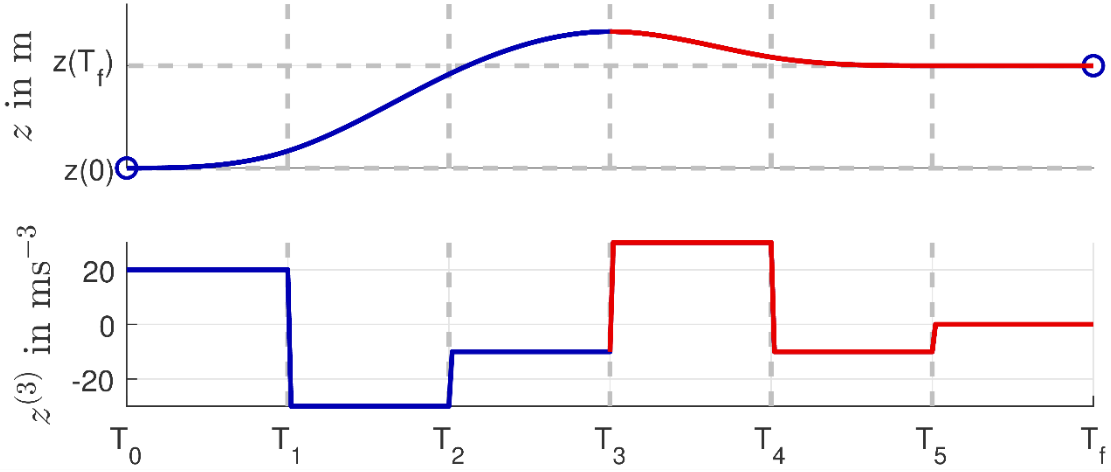
- Satisfy terminal state constraints up to second order
    - ➢ Achieve this with last three parameters

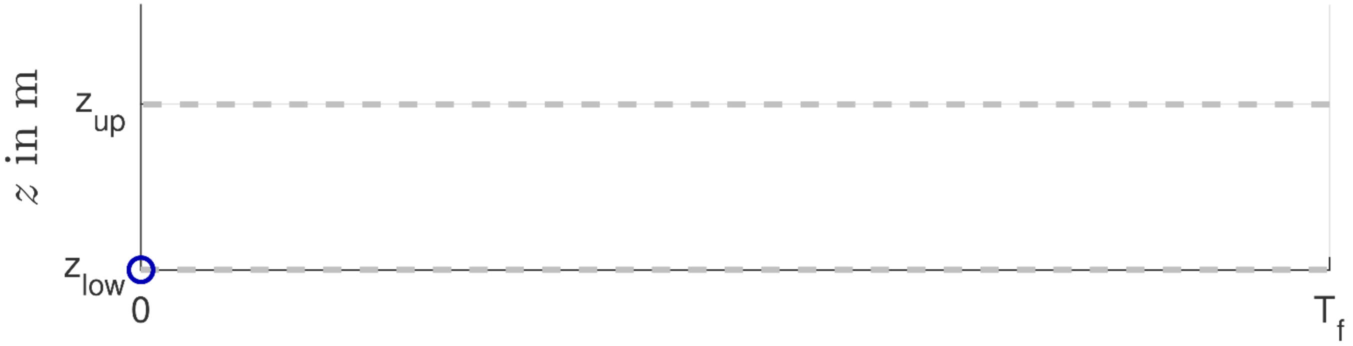


Control Approach

Overall Procedure

- Start at lower position

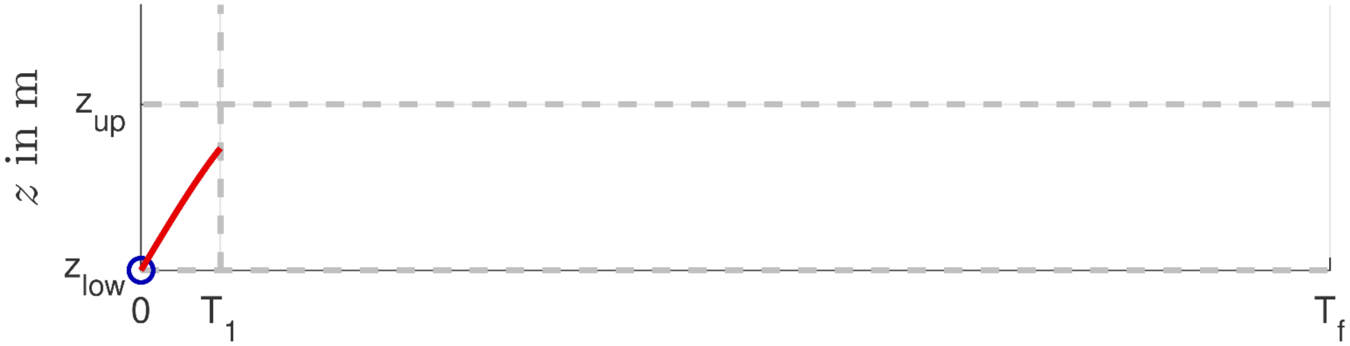
$$t = T_0$$



Control Approach

Overall Procedure

- Start at lower position $t = T_0$
- Kick proof mass upwards (Piezo) $T_0 < t \leq T_1$



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- Start at lower position $t = T_0$
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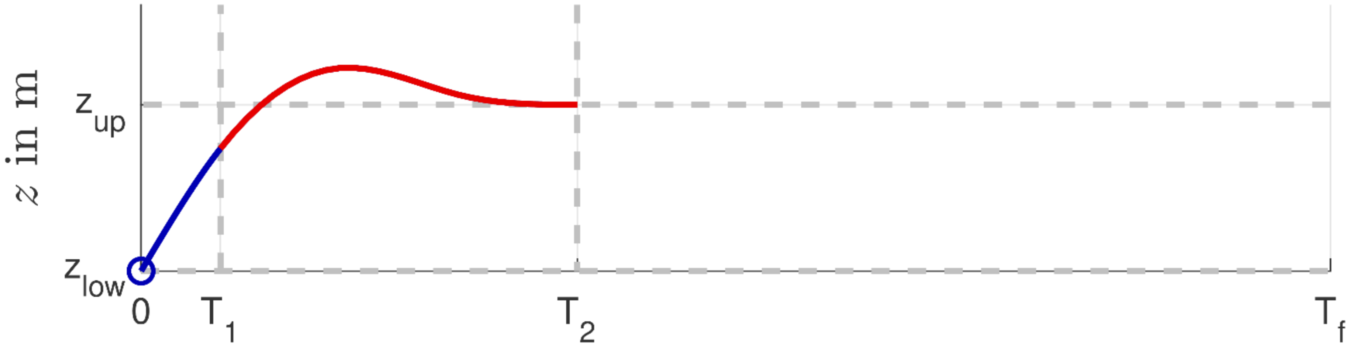
- Controlled catch in upper position (Electromagnet) $T_1 < t \leq T_2$



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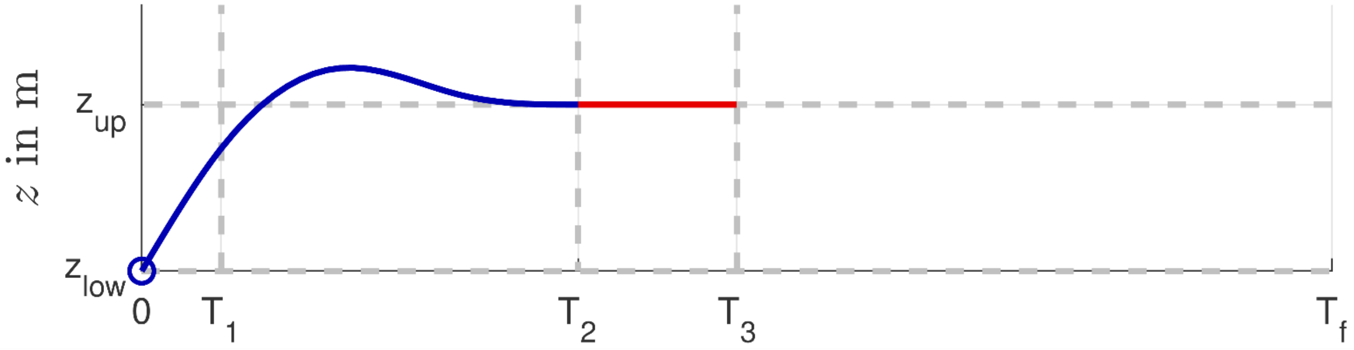

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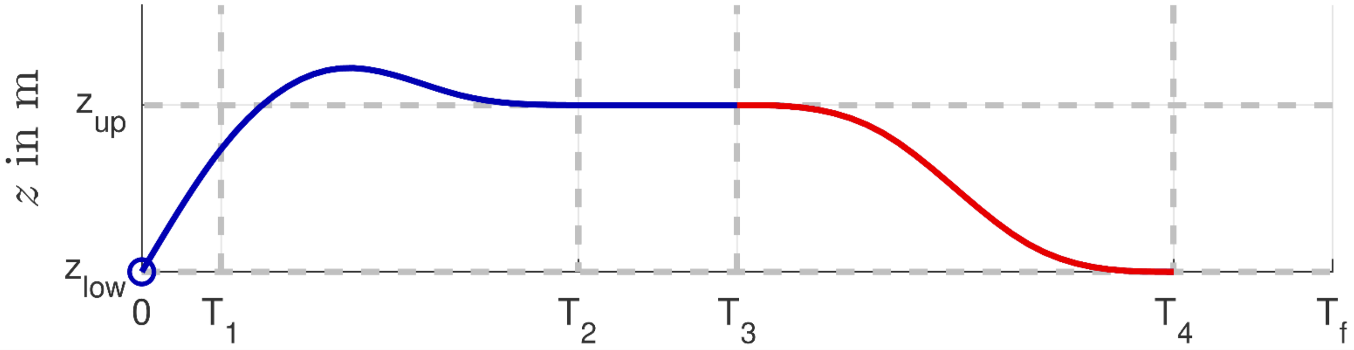

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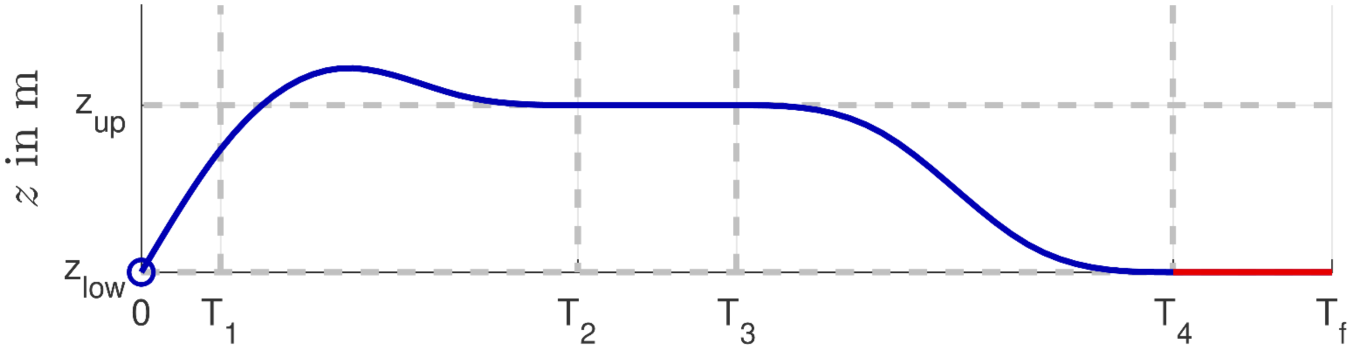
- Controlled motion downwards (Electromagnet) $T_3 < t \leq T_4$
- Hold proof mass without input (Permanent magnets and Piezo) $T_4 < t$



Agenda

Co-Design

Simultaneous Design and Controller Optimisation

Controller objective: $\min_{p_\mathrm{t}} J_\mathrm{t}$

- Short transient times
- Low input effort
- Small overshoot

Design objective: $\min_{p_\mathrm{d}} J_\mathrm{d}$

- Stable equilibrium positions
- Robustness

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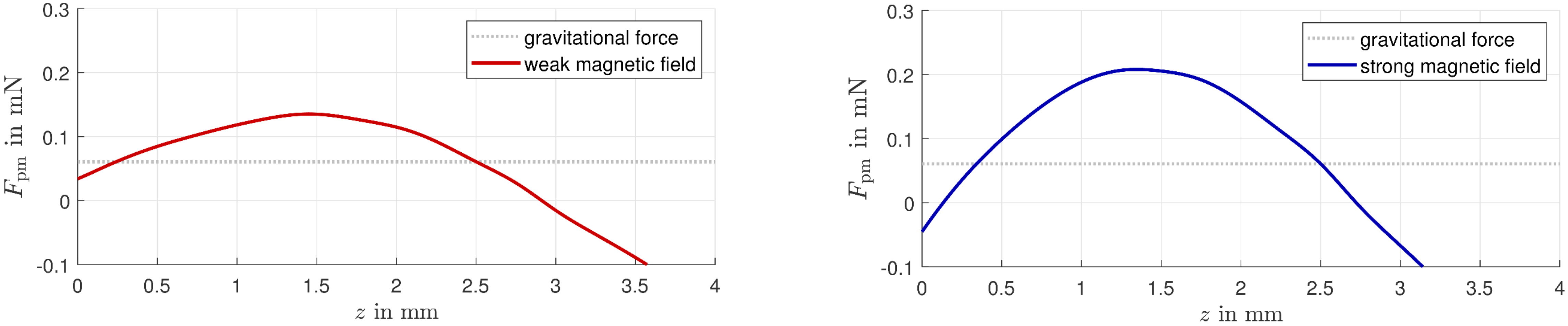

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Optimal trade-off by minimising a common cost function

$$\min_{p_\mathrm{d}, p_\mathrm{t}} w_\mathrm{d} J_\mathrm{d} + w_\mathrm{t} J_\mathrm{t}$$

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$$J_\mathrm{t} = \sum w_1 (z_\mathrm{eq} - z)^2 + w_2 \dot{z}^2 + w_3 i^2 + w_4 u^2$$

$$J_\mathrm{d} = (F_\mathrm{pm}(0) - F_\mathrm{ref})^2 + (F_\mathrm{pm}(z_\mathrm{eq}) - F_\mathrm{g})^2 + (\nabla F_\mathrm{pm}(z_\mathrm{eq}) - \nabla F_\mathrm{ref})^2$$

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$$\min_{p_\mathrm{d}, p_\mathrm{t}} w_\mathrm{d} J_\mathrm{d} + w_\mathrm{t} J_\mathrm{t}$$

Co-Design

Optimisation Variables

Design parameters p_d

- Remanence values $B_\mathrm{p},\ B_{\mathrm{pm},j}$
- Permanent magnet centres $z_{\mathrm{pm},j}$

Stability and robustness

- Solenoid centre z_em

Controlability and efficiency

Control parameters p_t

- Piezo voltage spike u_p
- Controller switch on time T_kick

Cooperation

- Trajectory parameters u_i
- Transient time T_t

Energy and time efficiency

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Simulation Results

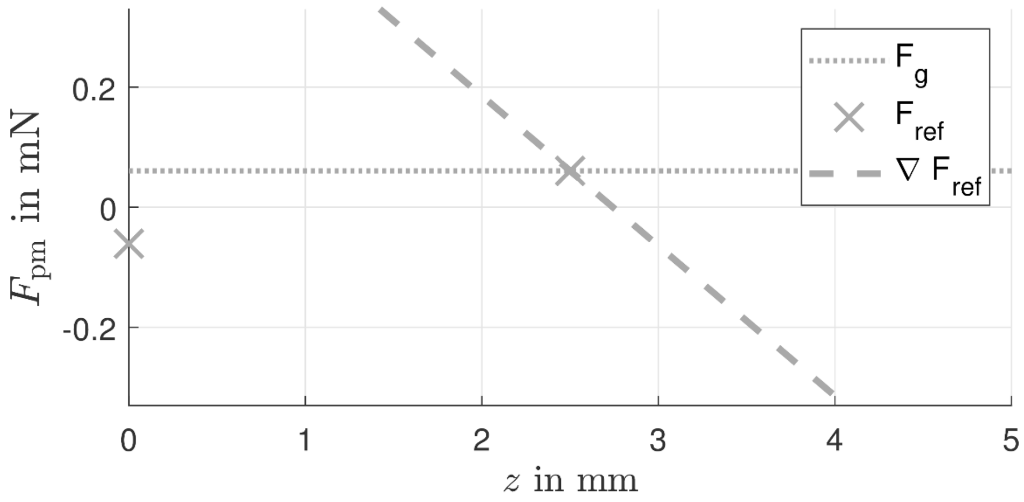
Co-Design

- Optimise motion from lower to upper equilibrium and back
- Maximum allowed time for each direction: 0.15s
- Transient time is divided into 9 intervals with individual u_i
- Use genetic algorithm due to non-convexity and discontinuity

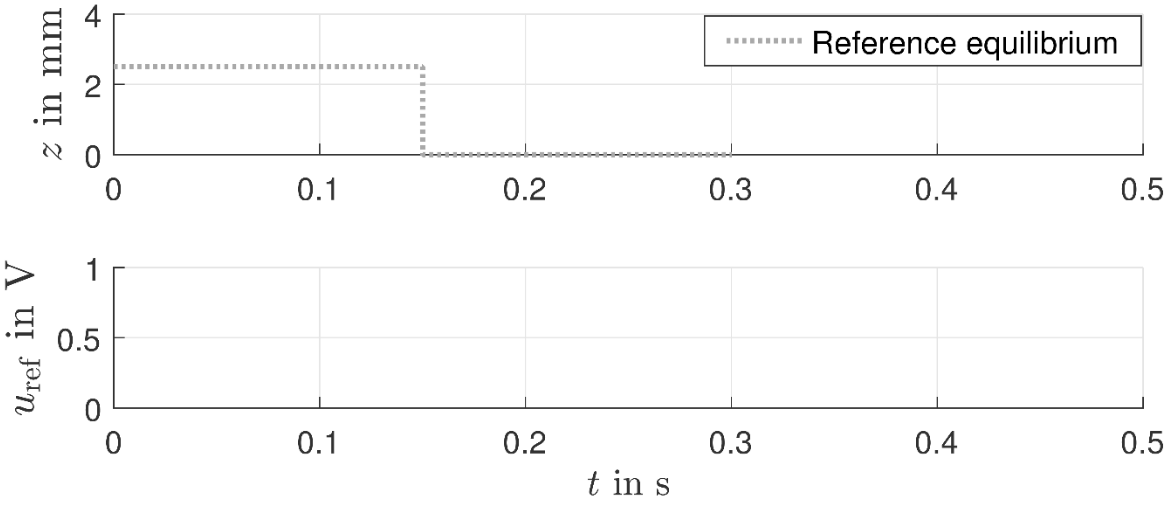
Simulation Results

Co-Design

Superimposed magnetic field



Optimised trajectory

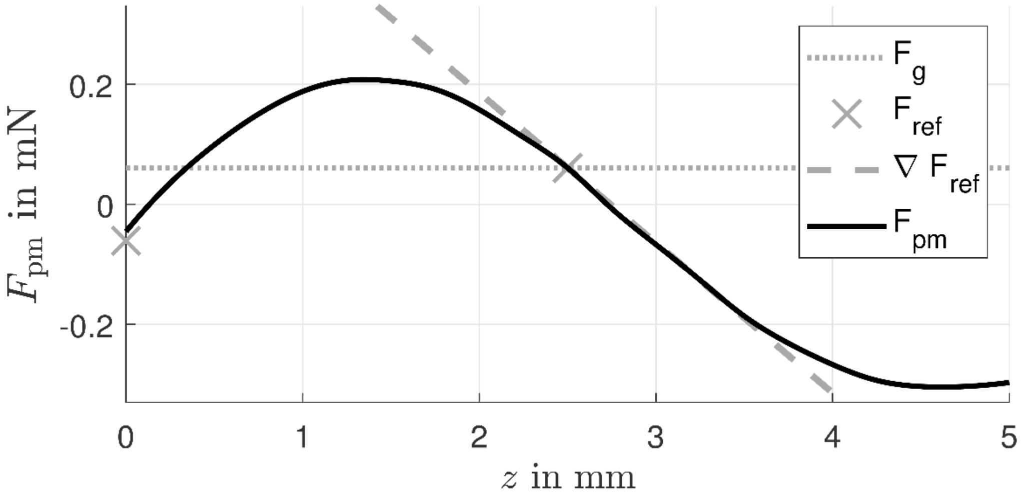


Simulation Results

Co-Design

Superimposed magnetic field

- Close to reference gradient and forces
- Results in robust equilibria



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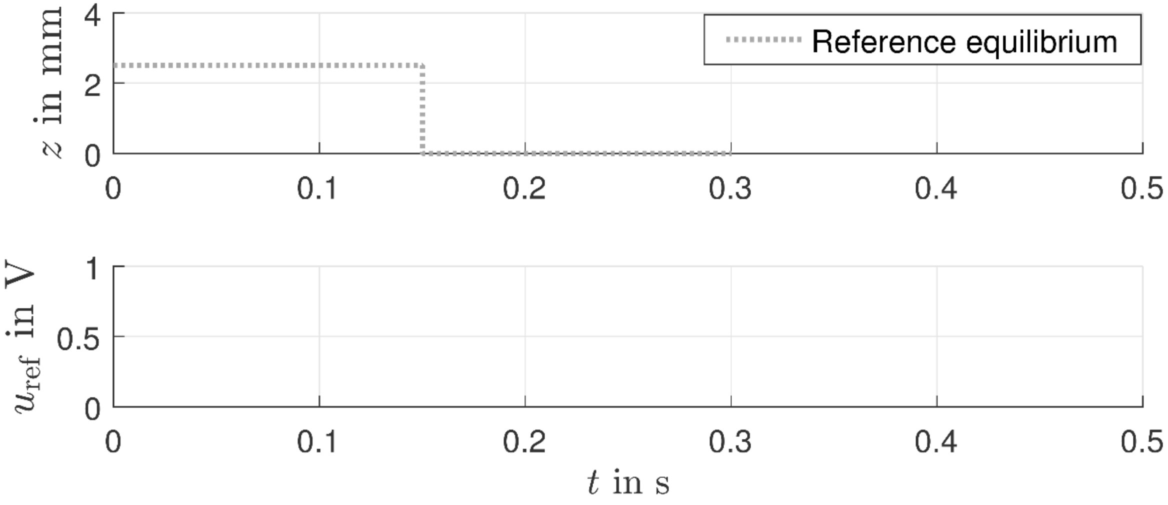
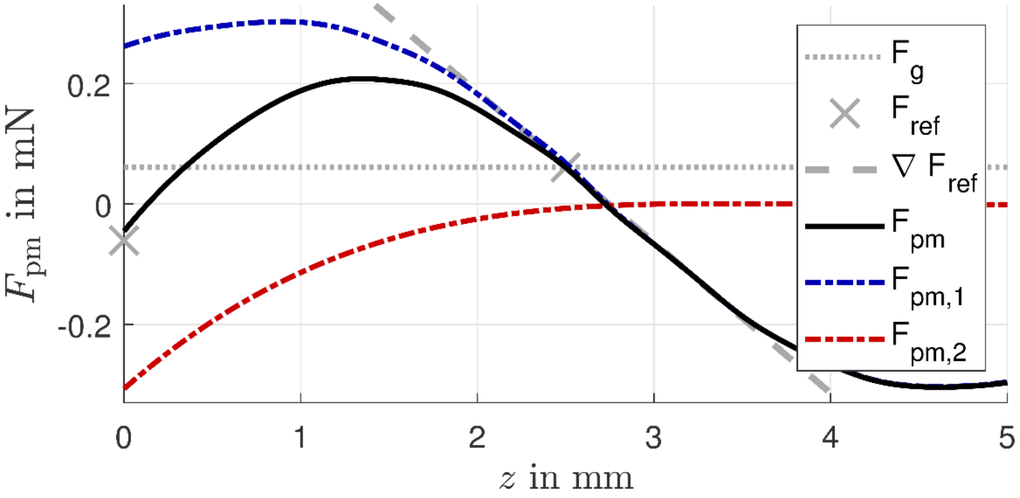


Simulation Results

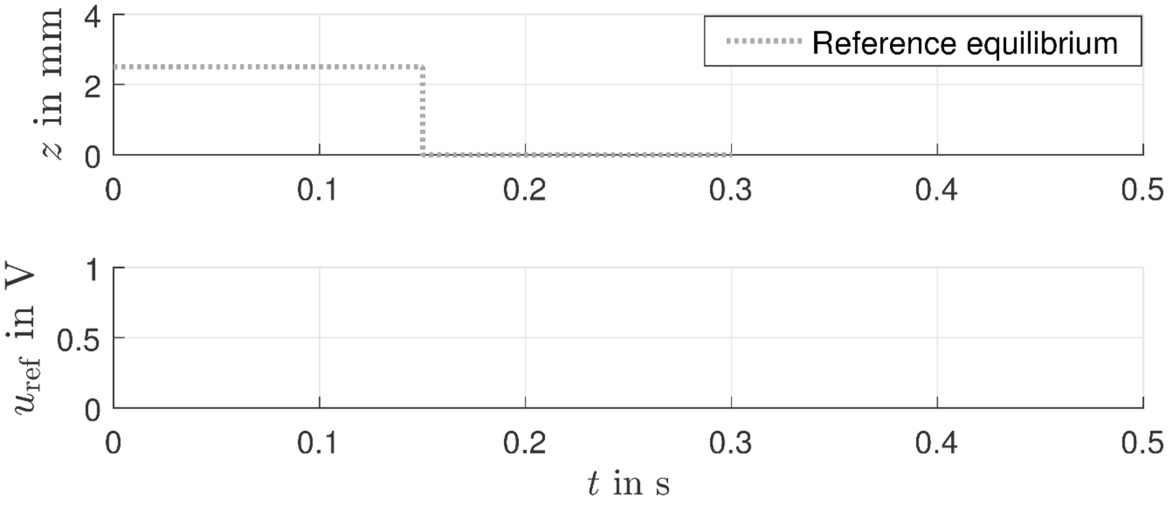
Co-Design

Superimposed magnetic field

- Close to reference gradient and forces
- Results in robust equilibria
- Both permanent magnets are relevant



Optimised trajectory



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Superimposed magnetic field

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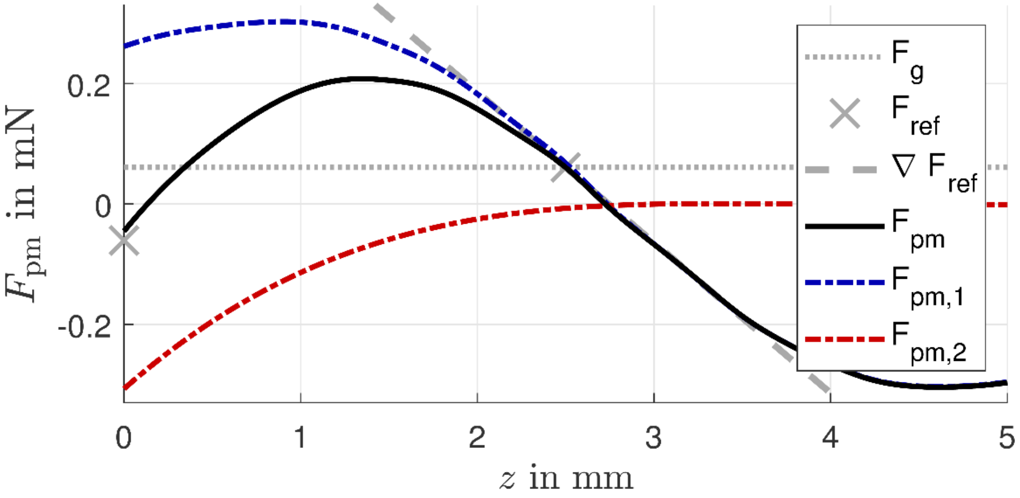
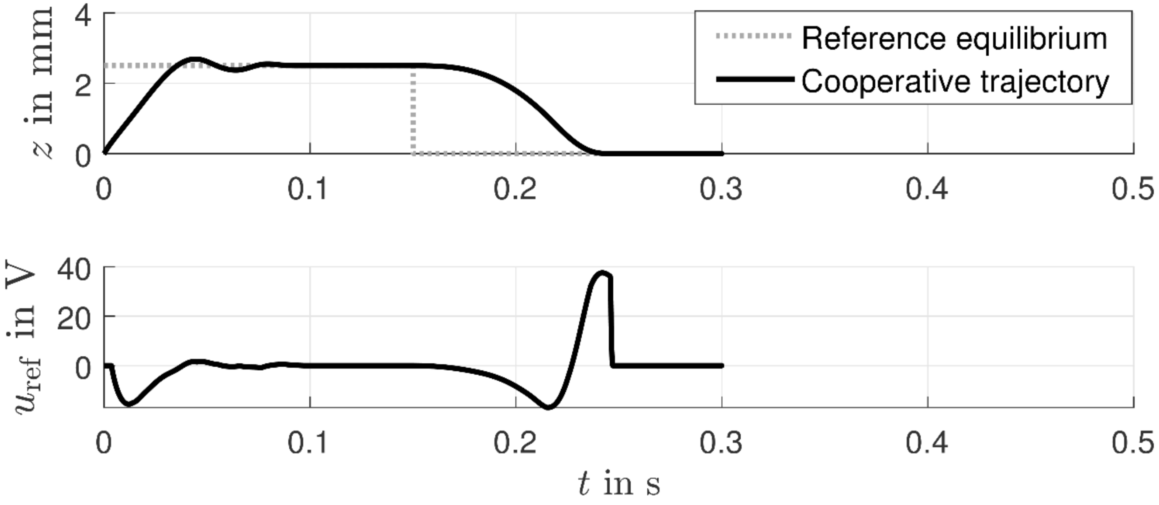
Optimised trajectory

- Fast transient motion with small overshoot
- Exploitation of the initial kick





Simulation Results

Co-Design

Superimposed magnetic field

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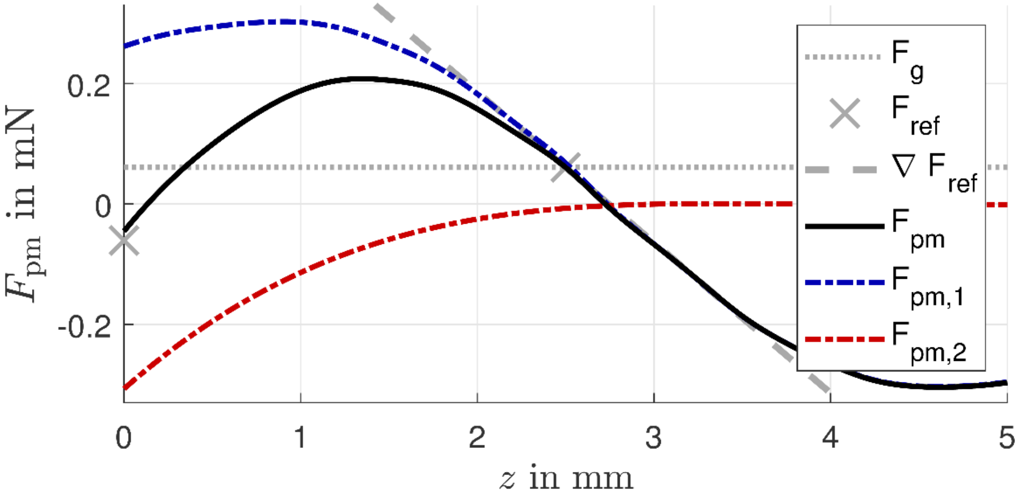
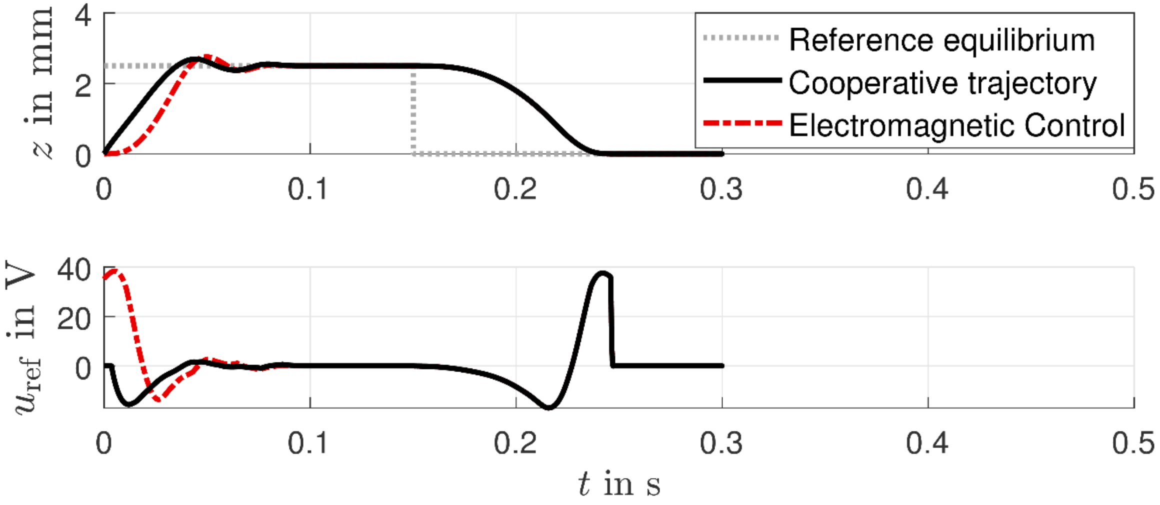
- Both permanent magnets are relevant

Optimised trajectory

- Fast transient motion with small overshoot
- Exploitation of the initial kick
- Improvement in comparison with electromagnet

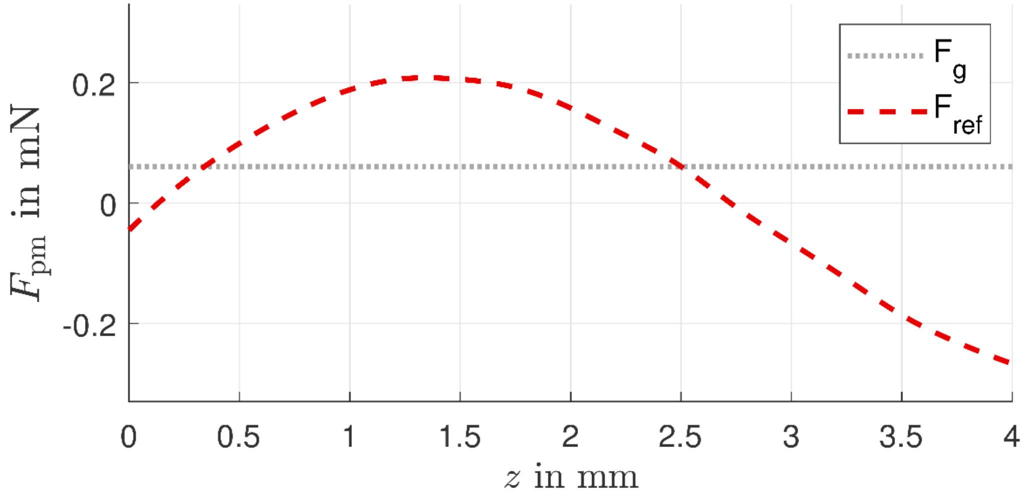


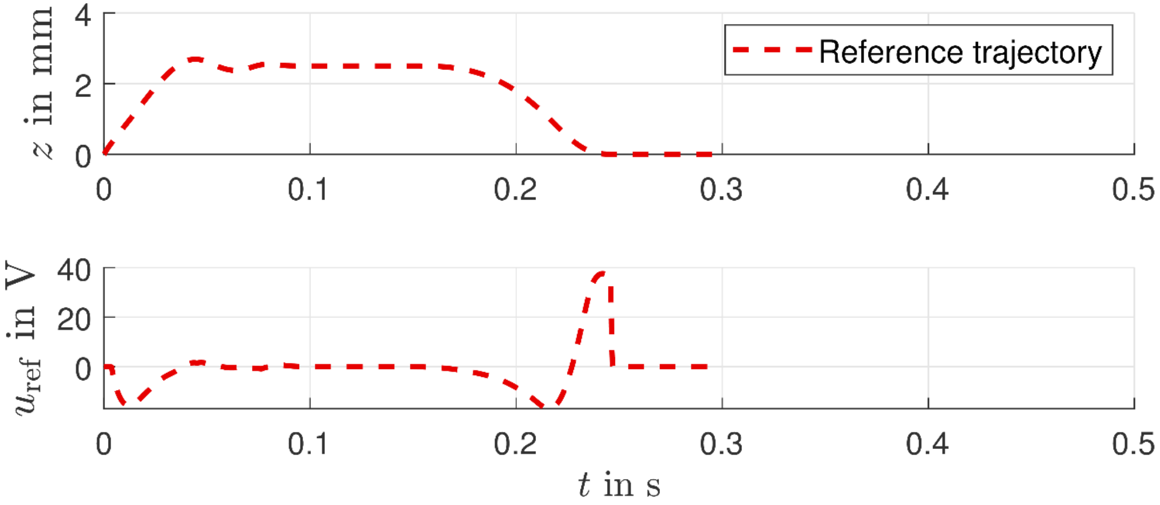


Simulation Results

Flatness-based Control

Evaluate controller under model mismatch





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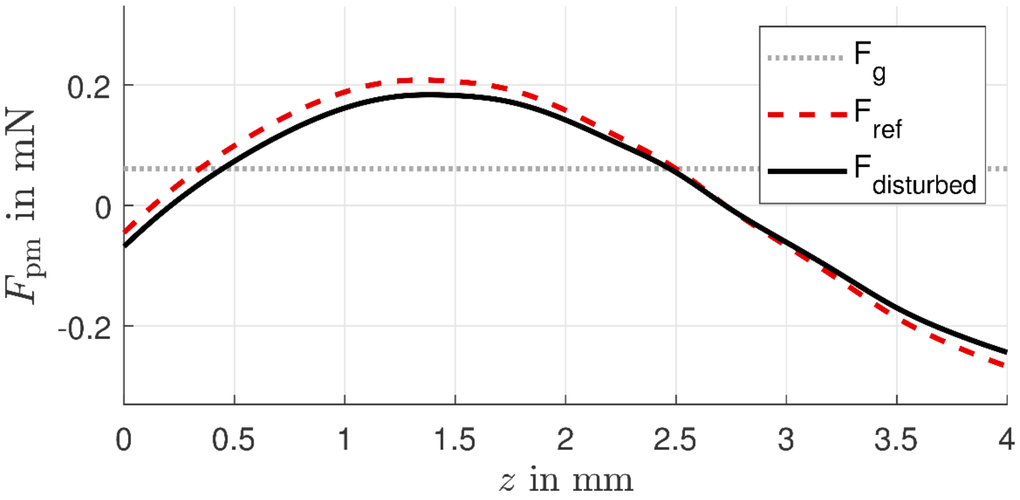
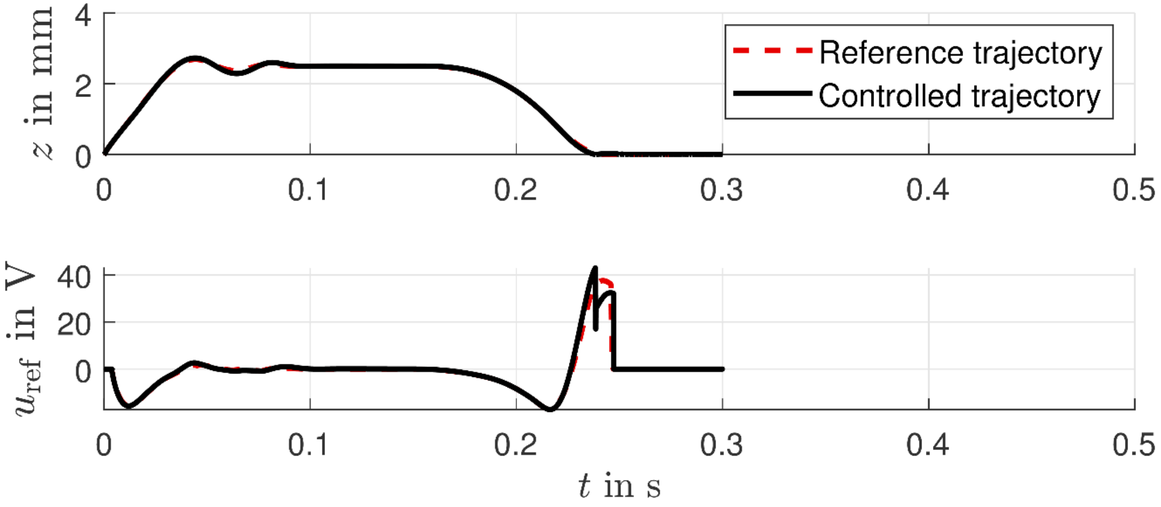
Evaluate controller under model mismatch

- Control the system under a different magnetic field than for trajectory generation





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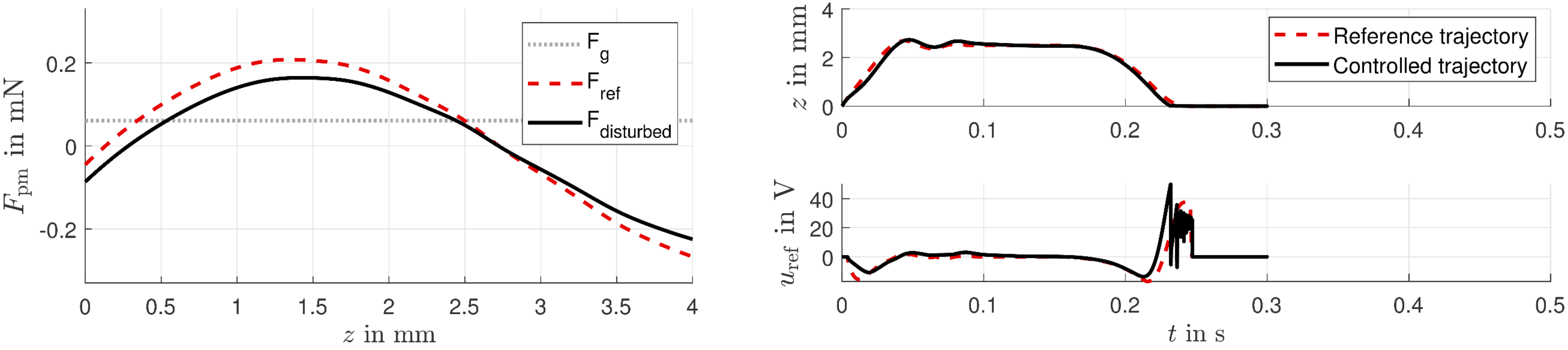

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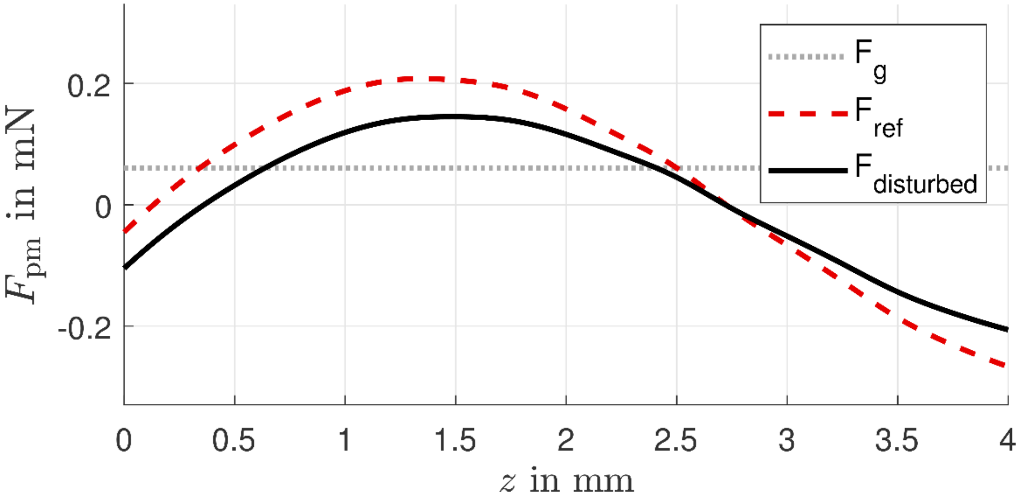
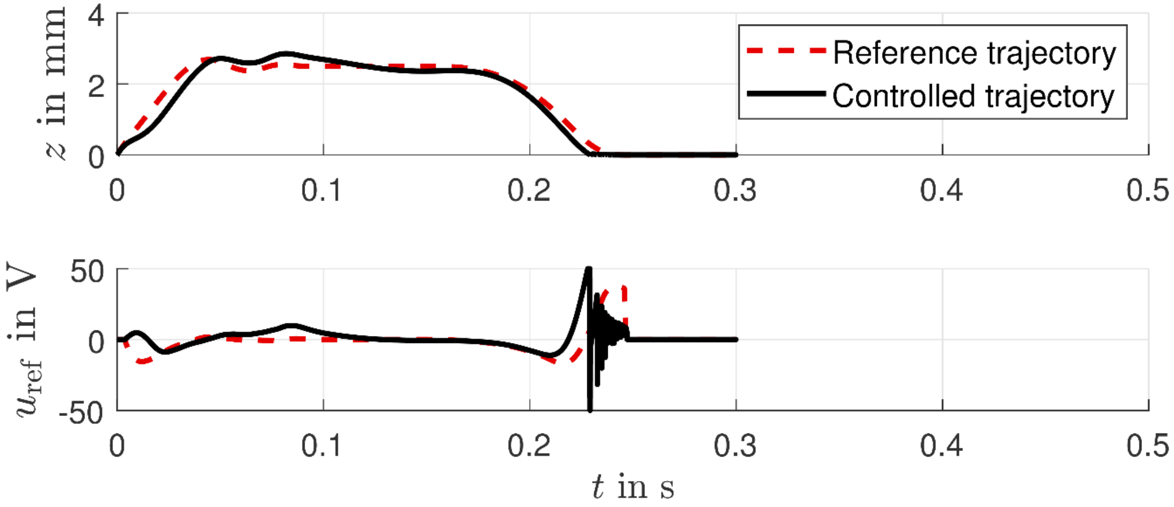
Evaluate controller under model mismatch

- Control the system under a different magnetic field than for trajectory generation
- The largest error is at the beginning (kick not optimised for this magnetic field, no control active)



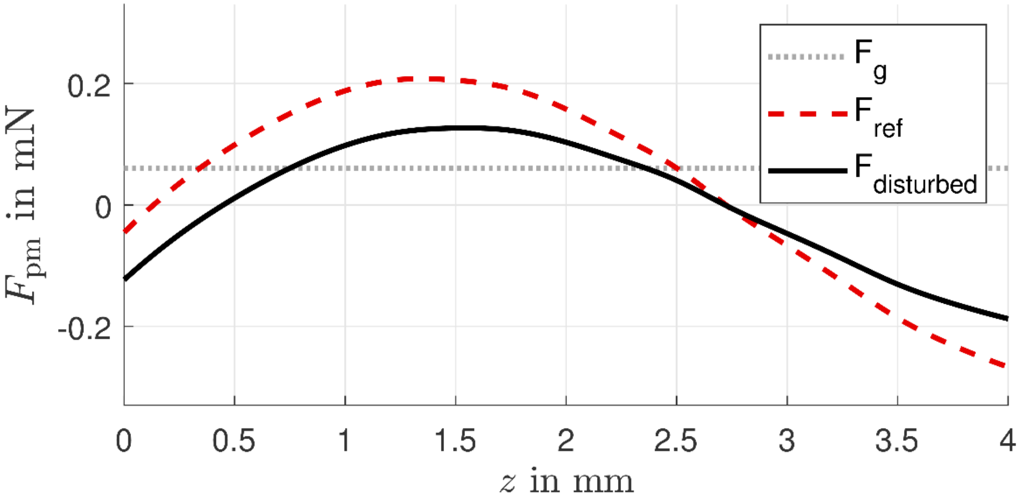


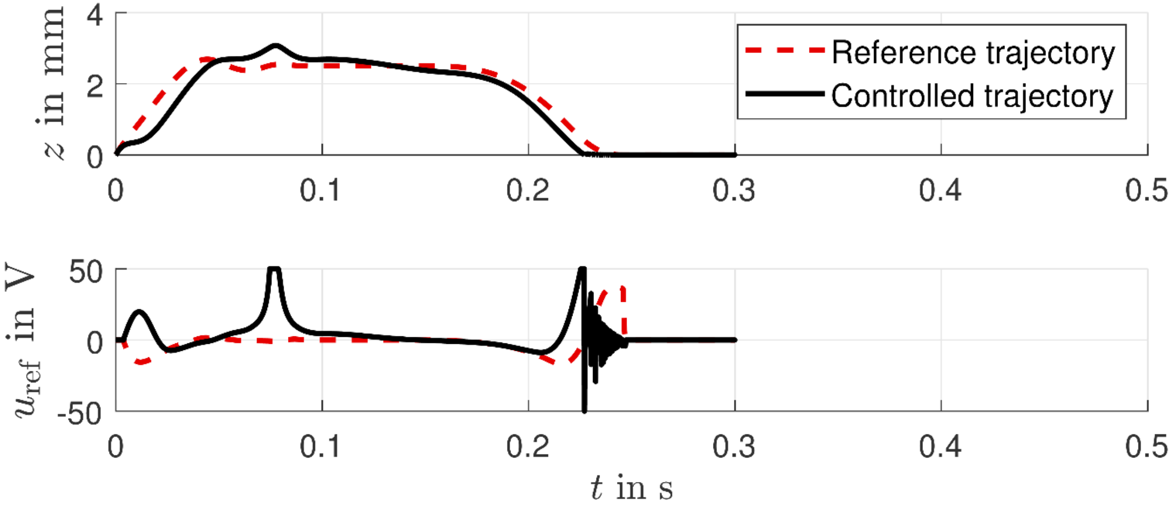
Simulation Results

Flatness-based Control

Evaluate controller under model mismatch

- Control the system under a different magnetic field than for trajectory generation
- The largest error is at the beginning (kick not optimised for this magnetic field, no control active)
- Control even possible under large mismatches, but limited in vicinity of solenoid centre





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Summary and Outlook

Summary

- Novel cooperative microactuator concept
- Bistability by superposition of permanent magnets
- Co-design for optimizing cooperative microactuators
- Nonlinear control under model mismatch

Outlook

- Multistability by using more permanent magnets
- Additional solenoids for increased effectiveness
- Implement sensing coils and included the positioning into the co-design
- Model verification with real data

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