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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Common problems

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

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- Mechanical limitations
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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
- Optimised cooperation

Problem formulation

- Coupling of design and control
- Contradictory goals
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- Coupling of design and control
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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

![Diagram](image.png)
System Description

Working Principle

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

![Diagram showing the working principle of the system with labeled parts: Glass tube, Magnetic proof mass, Piezoelectric staple actuator.]}
System Description

Working Principle

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

Working Principle

- Proof mass initially on the piezoactuator
- Initial acceleration (Kick) by piezoactuator
- Electromagnetic control (Catch) in upper position
- Stable levitation without input
System Description

Working Principle

- Proof mass initially on the piezoactuator
- 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)
System Description

Equations of Motion

- Electromagnet (current)
  \[ L \frac{di}{dt} = u_{in} - Ri \]

- Piezoactuator (deflection)

- Proof mass (vertical motion)
System Description

Equations of Motion

- Electromagnet
  
  \[
  L \frac{di}{dt} = u_{in} - Ri
  \]

- Piezoactuator
  
  \[
  M \ddot{d} = -Mg - c_A \dot{d} - k_A d - F_c(d, \dot{d}, z, \dot{z}) + \frac{F_{max}}{U_{max}} u_A
  \]

- Proof mass
  
  Vertical motion

Contact force \( F_c(d, \dot{d}, z, \dot{z}) \) adapted from [Specker2015]
System Description

Equations of Motion

- **Electromagnet (current)**
  \[
  L \frac{di}{dt} = u_{in} - Ri
  \]

- **Piezoactuator (deflection)**
  \[
  M \ddot{d} = -Mg - c_A \dot{d} - k_A d - F_c(d, \dot{d}, z, \dot{z}) + \frac{F_{\text{max}}}{U_{\text{max}}} u_A
  \]

- **Proof mass (vertical motion)**
  \[
  m \ddot{z} = -mg - F_r(\dot{z}) + F_c(d, \dot{d}, z, \dot{z}) + F_{\text{em}}(z, i) + \sum_j F_{\text{pm},j}(z)
  \]

Contact force \( F_c(d, \dot{d}, z, \dot{z}) \) adapted from [Specker2015]

Permanent magnetic force \( F_{\text{pm},j}(z) \sim B_p B_{\text{pm},j} \)

Electromagnetic force \( F_{\text{em}}(z) \sim B_p i \)
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Control Approach

Piezoactuator: Feedforward control

Input voltage spike for impulse-like acceleration with

$$u_A = \frac{u_p}{0.53} \left( \exp \left( \frac{-t}{\tau_2} \right) - \exp \left( \frac{-t}{\tau_1} \right) \right)$$

Electromagnet: Flatness-based control

**Assumption**: The proof mass remains below the solenoid centre

- System model is flat with respect to $z$
Control Approach

Piezoactuator: Feedforward control

Input voltage spike for impulse-like acceleration with

\[ u_A = \frac{u_p}{0.53}\left(\exp\left(-\frac{t}{\tau_2}\right) - \exp\left(-\frac{t}{\tau_1}\right)\right) \]

Electromagnet: Flatness-based control

**Assumption:** The proof mass remains below the solenoid centre

- System model is flat with respect to \( z \)
  - 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
Control Approach

Flatness-based Control

State transformation

\[ \mathbf{x} = [z, \dot{z}, i] \rightarrow \xi = [z, \dot{z}, \ddot{z}] \]
Control Approach

Flatness-based Control

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Control Approach

Reference trajectory generation

- Parameterise motion $z_{\text{ref}}$ by its third derivative
Control Approach

Reference trajectory generation

- Parameterise motion $z_{\text{ref}}$ by its third derivative
- Divide transient time $T_f$ into equal intervals
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Reference trajectory generation

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- Divide transient time $T_f$ into equal intervals
- Assign constant trajectory parameters $\ddot{z}_{\text{ref}} = u_i$, $t \in [T_i, T_{i+1}]$
Control Approach

Reference trajectory generation

- Parameterise motion $z_{ref}$ by its third derivative
- Divide transient time $T_f$ into equal intervals
- Assign constant trajectory parameters $\dddot{z}_{ref} = u_i, \ t \in [T_i, T_{i+1}]$
- Satisfy terminal state constraints up to second order
  - Achieve this with last three parameters

![Graph showing trajectory and acceleration](image)
Control Approach

Overall Procedure

- Start at lower position

\[ t = T_0 \]
Control Approach

Overall Procedure

- Start at lower position
- Kick proof mass upwards (Piezo)

\[ t = T_0 \]
\[ T_0 < t \leq T_1 \]
Control Approach

Overall Procedure

- Start at lower position
- Kick proof mass upwards (Piezo)
- Controlled catch in upper position (Electromagnet)

\[
\begin{align*}
t &= T_0 \\
T_0 &< t \leq T_1 \\
T_1 &< t \leq T_2
\end{align*}
\]
Control Approach

Overall Procedure

- Start at lower position
- Kick proof mass upwards (Piezo)
- Controlled catch in upper position (Electromagnet)
- Hold proof mass without input (Permanent magnets)

\[ t = T_0 \]
\[ T_0 < t \leq T_1 \]
\[ T_1 < t \leq T_2 \]
\[ T_2 < t \leq T_3 \]
Control Approach

Overall Procedure

- Start at lower position
- Kick proof mass upwards (Piezo)
- Controlled catch in upper position (Electromagnet)
- Hold proof mass without input (Permanent magnets)
- Controlled motion downwards (Electromagnet)

\[
\begin{align*}
t &= T_0 \\
T_0 &< t \leq T_1 \\
T_1 &< t \leq T_2 \\
T_2 &< t \leq T_3 \\
T_3 &< t \leq T_4
\end{align*}
\]
Control Approach

Overall Procedure

- Start at lower position
  \[ t = T_0 \]
- Kick proof mass upwards (Piezo)
  \[ T_0 < t \leq T_1 \]
- Controlled catch in upper position (Electromagnet)
  \[ T_1 < t \leq T_2 \]
- Hold proof mass without input (Permanent magnets)
  \[ T_2 < t \leq T_3 \]
- Controlled motion downwards (Electromagnet)
  \[ T_3 < t \leq T_4 \]
- Hold proof mass without input (Permanent magnets and Piezo)
  \[ T_4 < t \]
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Co-Design

Simultaneous Design and Controller Optimisation

Controller objective: $\min_{p_t} J_t$
- Short transient times
- Low input effort
- Small overshoot

Design objective: $\min_{p_d} J_d$
- Stable equilibrium positions
- Robustness
Co-Design

Simultaneous Design and Controller Optimisation

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Contradictory goals

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**Co-Design**

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Design objective: \( \min_{p_d} J_d \)
- Stable equilibrium positions
- Robustness

Optimal trade-off by minimising a common cost function
\[
\min_{p_d,p_t} w_d J_d + w_t J_t
\]
Co-Design

Simultaneous Design and Controller Optimisation

Controller objective: \( \min_{p_t} J_t \)

- Short transient times
- Low input effort
- Small overshoot

\[
J_t = \sum w_1 (z_{eq} - z)^2 + w_2 z^2 + w_3 i^2 + w_4 u^2
\]

Design objective: \( \min_{p_d} J_d \)

- Stable equilibrium positions
- Robustness

\[
J_d = (F_{pm}(0) - F_{ref})^2 + (F_{pm}(z_{eq}) - F_g)^2 + (\nabla F_{pm}(z_{eq}) - \nabla F_{ref})^2
\]

Optimal trade-off by minimising a common cost function

\[
\min_{p_d, p_t} w_d J_d + w_t J_t
\]
Co-Design

Optimisation Variables

Design parameters $p_d$
- Remanence values $B_p, B_{pm,j}$
- Permanent magnet centres $z_{pm,j}$
- Solenoid centre $z_{em}$

Control parameters $p_t$
- Piezo voltage spike $u_p$
- Controller switch on time $T_{kick}$
- Trajectory parameters $u_i$
- Transient time $T_t$

Stability and robustness
Controlability and efficiency
Cooperation
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

Optimised trajectory
Simulation Results

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- Both permanent magnets are relevant

Optimised trajectory
Simulation Results

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Optimised trajectory
- Fast transient motion with small overshoot
- Exploitation of the initial kick
Simulation Results

Co-Design

Superimposed magnetic field
- Close to reference gradient and forces
- Results in robust equilibria
- 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
Simulation Results

Flatness-based Control

Evaluate controller under model mismatch

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

![Graphs showing simulation results](image-url)
Simulation Results

Flatness-based Control

Evaluate controller under model mismatch

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

- 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
Thank you for your attention!


Specker, T, Buchholz, M., Dietmayer, K. *Dynamical Modeling of Constraints with Friction in Mechanical Systems*. 8th Vienna International Conference on Mathematical Modelling, Vienna, Austria, 2015, pp. 514-519