Universidad Zaragoza 1542

ecc24 EUROPEAN CONTROL CONFERENCE

Faster Run-To-Run Feedforward Control of Electromechanical Switching Devices: A Sensitivity-Based Approach

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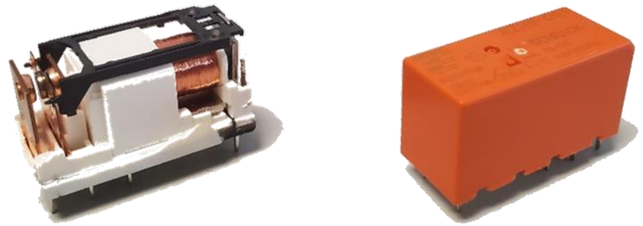
Outline

1. Introduction
2. System Dynamics
3. Run-to-Run Feedforward Control
4. Faster Run-to-Run Feedforward Control
5. Conclusions

Electromechanical switching devices

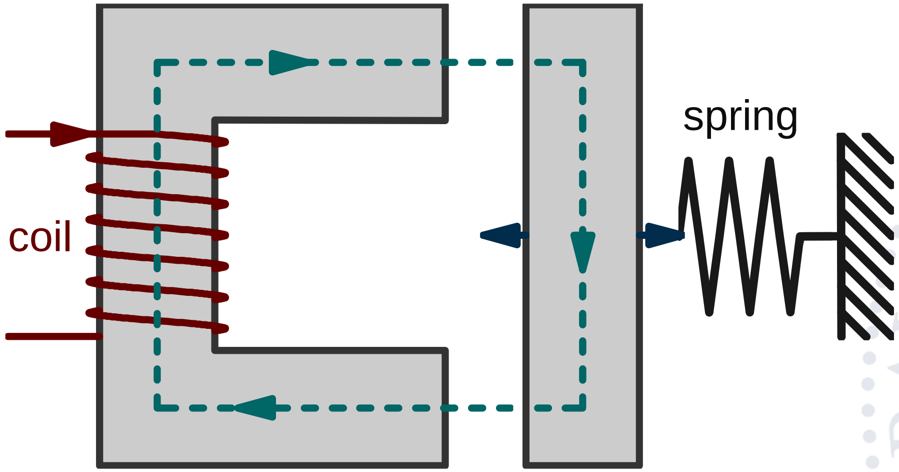
Collaboration with industry partner

Electromagnetic relays



Solenoid valves

Operating principle: small reluctance actuator

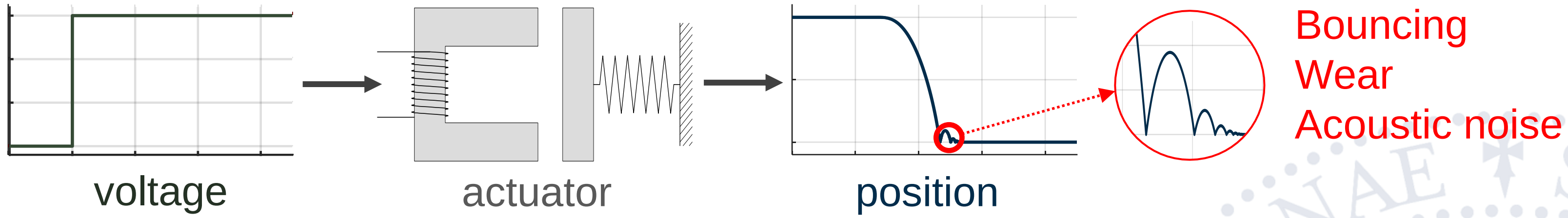


Motivation

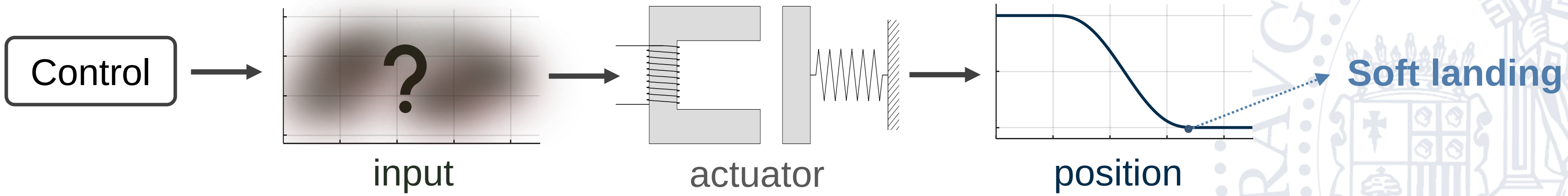
Advantages

Small size, low cost, high efficiency

Drawbacks



Research goal



Soft landing control

Difficulties

- Nonlinear dynamics
- Short displacement (~ 1 mm)
- Fast motion (~ 1 ms)
- No affordable position sensors

Approaches in the literature

- Backstepping control
- Sliding-mode control
- Extremum-seeking control
- (…)
- Open-loop control → No position sensors
- Iterative techniques → Exploit repetitive operation

Outline

State-space model

State z position
$\dot{z}$ velocity
λ flux linkage

Input u coil voltage

Differential equations

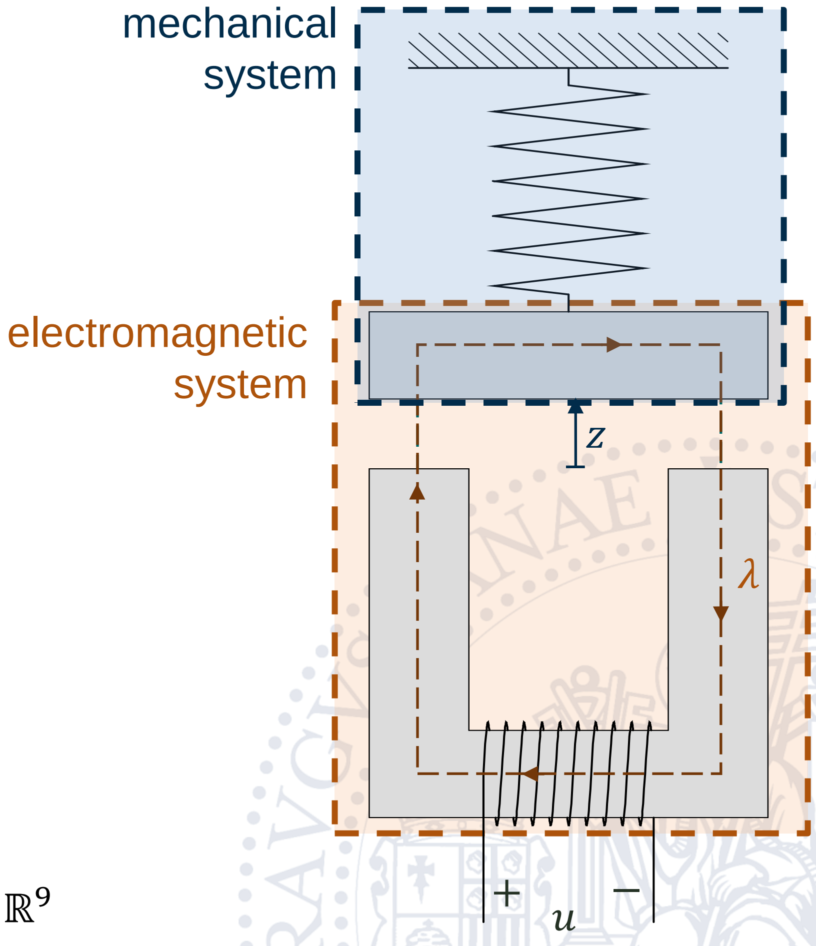
$$m\,\ddot{z} = F_{\text{magnetic}}(z,\lambda) - k_s(z - z_s)$$

$$\dot{\lambda} = -R\,\lambda\,\mathcal{R}\text{eluctance}(z,\lambda) + u$$

$$\mathcal{R}\text{eluctance}(z,\lambda) = \frac{\kappa_1}{1 - |\lambda|/\kappa_2} + \kappa_3 + \frac{\kappa_4\,z}{1 + \kappa_5\,z\log(\kappa_6/z)}$$

$$F_{\text{magnetic}}(z,\lambda) = -\frac{1}{2}\lambda^2\frac{\partial\mathcal{R}\text{eluctance}}{\partial z}(z)$$

Parameter vector $\theta = [k_s\ \ z_s\ \ m\ \ \kappa_1\ \ \kappa_2\ \ \kappa_3\ \ \kappa_4\ \ \kappa_5\ \ \kappa_6] \in \mathbb{R}^9$



Differential flatness

The position z is a flat output

$$z \xrightarrow{\frac{\mathrm{d}}{\mathrm{d}t}} \dot{z} \xrightarrow{\frac{\mathrm{d}}{\mathrm{d}t}} \ddot{z} \xrightarrow{\frac{\mathrm{d}}{\mathrm{d}t}} \dddot{z}$$

$$\left.\begin{aligned} m\,\ddot{z} &= F_{\mathrm{magnetic}}(z,\lambda) - k_s(z - z_s) \\ F_{\mathrm{magnetic}}(z,\lambda) &= -\frac{1}{2}\lambda^2 \frac{\partial \mathcal{R}\mathrm{eluctance}}{\partial z}(z) \end{aligned}\right\} \longrightarrow \lambda = f_\lambda(z,\ddot{z},\theta) = \sqrt{\frac{-2(k_s(z-z_s) + m\,\ddot{z})}{\frac{\partial \mathcal{R}\mathrm{eluctance}}{\partial z}}}$$

$$\dot{\lambda} = -R\,\lambda\,\mathcal{R}\mathrm{eluctance}(z,\lambda) + u \longrightarrow \boxed{u = f_u(z,\dot{z},\ddot{z},\dddot{z},\theta)}$$

Useful for feedforward control

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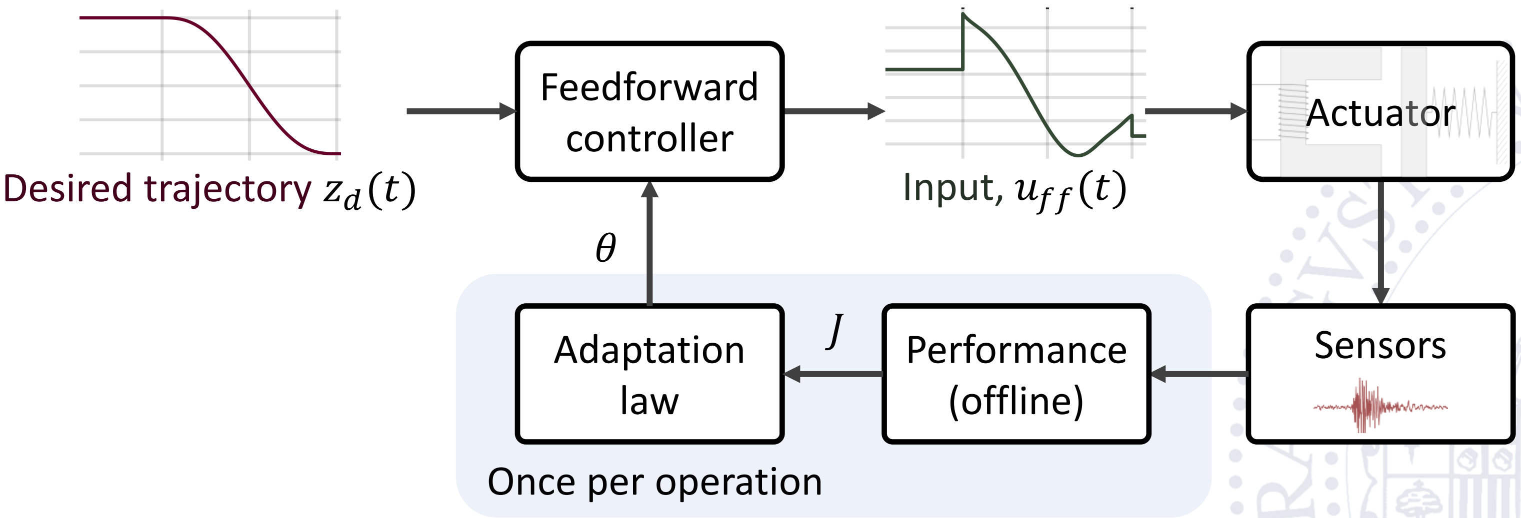
Run-to-Run Feedforward Control

E. Moya-Lasheras, E. Ramirez-Laboreo, E. Serrano-Seco, "Run-to-Run Adaptive Nonlinear Feedforward Control of Electromechanical Switching Devices", IFAC World Congress 2023, Yokohama, Japan.

Combination of:

- Feedforward control
- Iterative control with offline measurements



Run-to-Run Adaptation Law

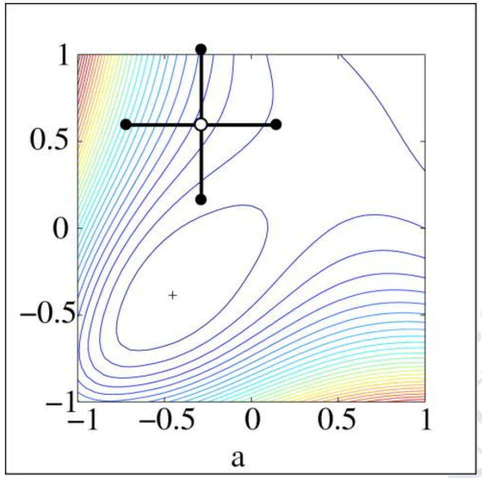
Based on optimization algorithms

Tradeoff: Complexity – Performance

E. Moya-Lasheras, E. Ramirez-Laboreo, E. Serrano-Seco, “Run-to-Run Adaptive Nonlinear Feedforward Control of Electromechanical Switching Devices”, IFAC World Congress 2023, Yokohama, Japan.

Pattern-search algorithm:

- Derivative free
- Computationally light
- Slow convergence (2 evaluations/coordinate)



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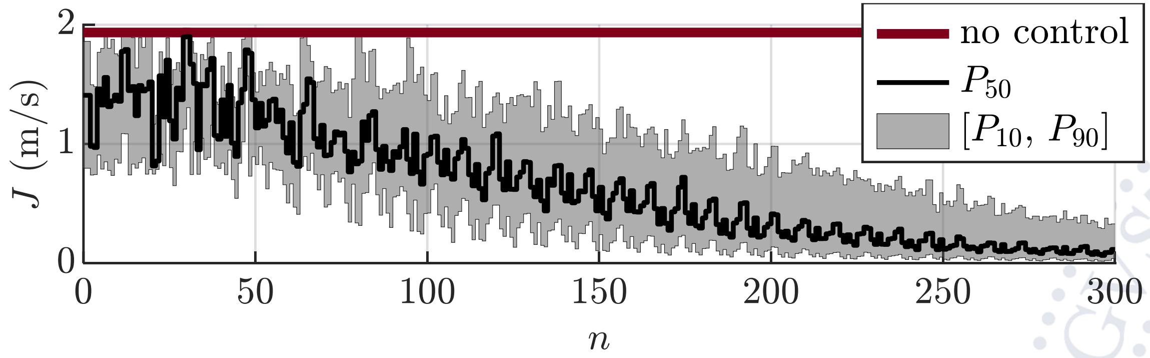
Simulation results

Monte Carlo analysis

$$10\,000\ \text{simulations} \times 300\ \frac{\text{operations}}{\text{simulation}}$$

Random initialization: $\theta_0 \sim \theta^* \pm\ 5\%$

Minimize $J = |\text{impact velocity}|$



Goal: improve performance without increasing complexity

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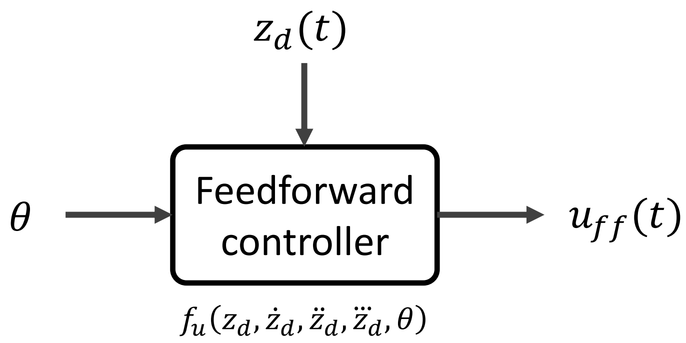
Faster Run-to-Run Feedforward Control

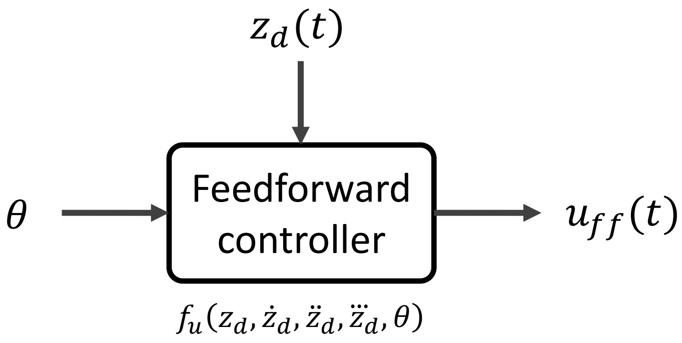
Idea: Reduce the search space (θ)



Assumptions:

- Relevant in u_{ff} implies relevant in J
- Desired trajectory does not change
- Search in the vicinity of θ^* (nominal value)

Sensitivity-based reduction



Sensitivity: $S(t,\theta) = \dfrac{\partial u_{ff}(t,\theta)}{\partial \theta}$

Method 1 (Integral-square sensitivity):

$$S_{IS}(\theta) = \int_{t_0}^{t_f} S(\tau,\theta)^2 \, \mathrm{d}\tau$$

Evaluate at θ^*: $S_{IS}(\theta^*)$

Reduce search space according to $S_{IS}(\theta^*)$

Method 2 (Fisher matrix):

$$\mathcal{F}(\theta) = \int_{t_0}^{t_f} S(\tau,\theta)^T \cdot S(\tau,\theta) \, \mathrm{d}\tau$$

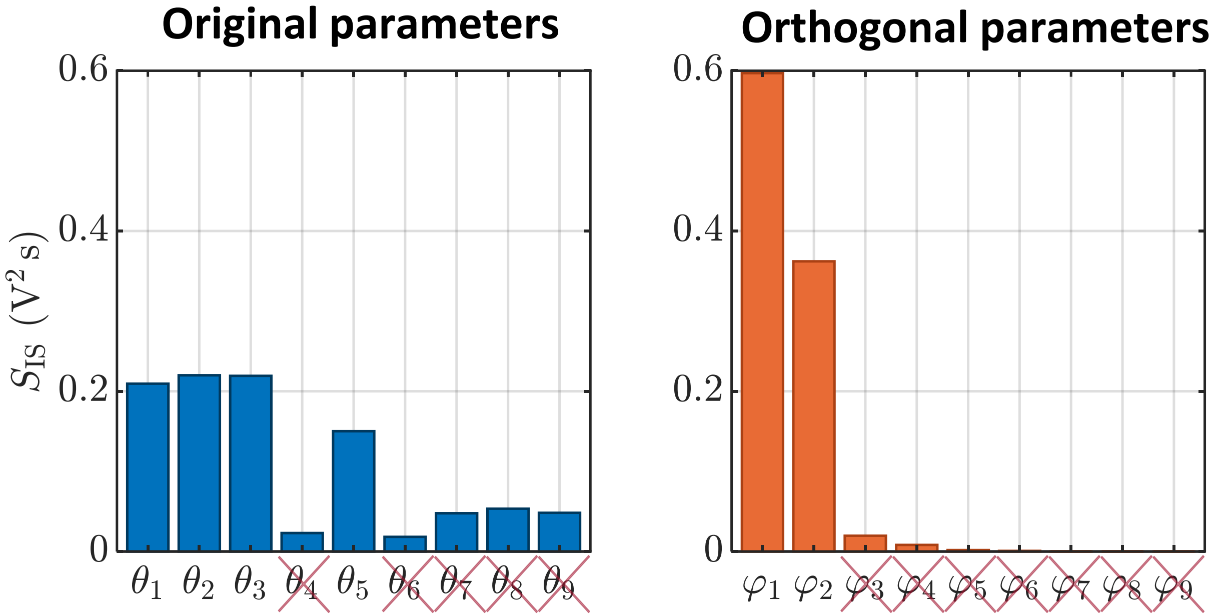
Evaluate at θ^*: $\mathcal{F}(\theta^*)$

Compute eigendecomposition: $\mathcal{F}(\theta^*) = V \, \Lambda \, V^T$

$$\varphi = V^T \theta \iff \theta = V\varphi$$

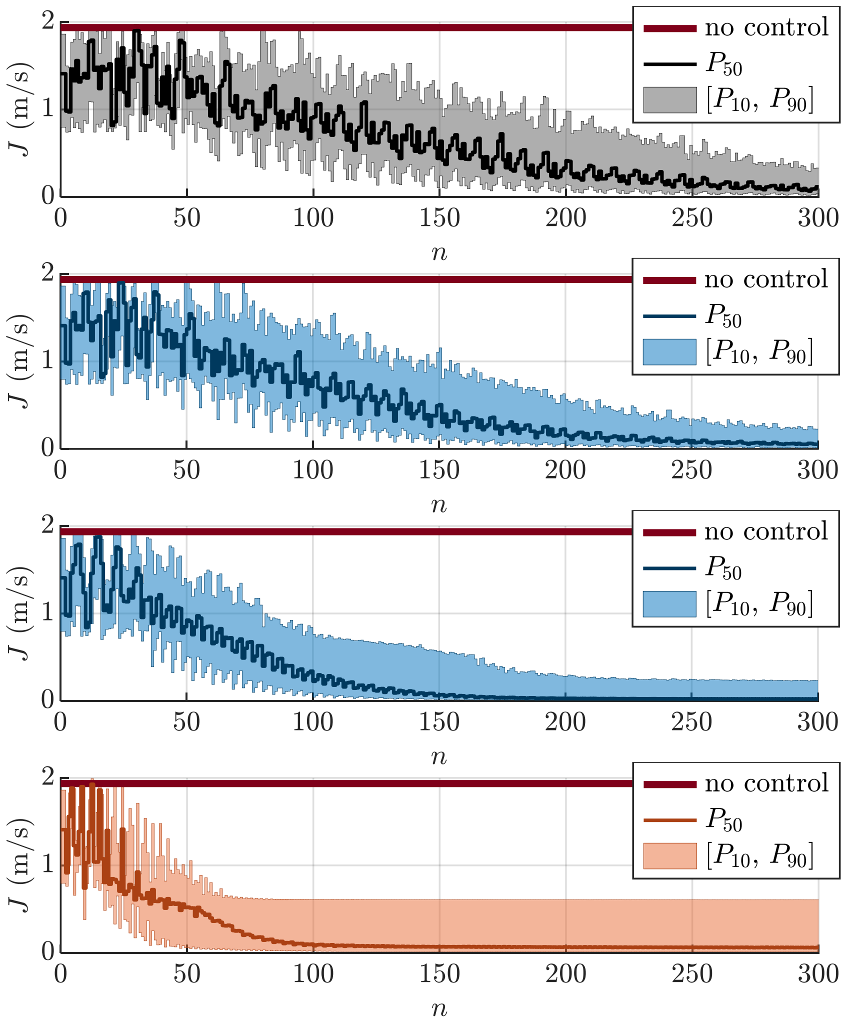
Modify search space according to V and Λ

Sensitivity analysis



Parametrization	Reduction order (r)	Free parameters	Fixed parameters
Original	7	$\theta_1, \theta_2, \theta_3, \theta_5, \theta_7, \theta_8, \theta_9$	θ_4, θ_6
Original	4	$\theta_1, \theta_2, \theta_3, \theta_5$	$\theta_4, \theta_6, \theta_7, \theta_8, \theta_9$
Orthogonal	2	φ_1, φ_2	$\varphi_3 \cdots \varphi_9$

Simulation results



Evaluations to reach a median of $J = 1$ m/s:

No reduction:

$$n \approx 100\ (p_{50})$$

Original parameters, $r = 7$

$$n \approx 75\ (p_{50})$$

Original parameters, $r = 4$

$$n \approx 50\ (p_{50})$$

Orthogonal parameters, $r = 2$

$$n \approx 25\ (p_{50})$$

Outline

Conclusions

- R2R FF Control: low-cost approach to control electromechanical devices
- Adaptation law: Tradeoff between complexity and performance
- Parameter reduction improves convergence with no additional complexity

  About 50%-75% less evaluations
- Optimal method and reduction order depend on the system

Future work

- (…)
- Experiments

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