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Instituto Universitario de Investigación
en Ingeniería de Aragón
Universidad Zaragoza

PhD Thesis

Modeling and Control of Reluctance Actuators

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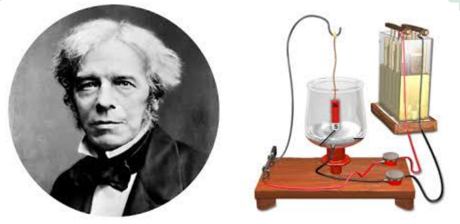
Zaragoza, Spain, October 18th 2019, 11:00

What is a reluctance actuator?

ELECTRIC MACHINES



DC Motor – Faraday, 1821

- DC motor
- Alternator
- AC motor
- Transformer
- Brushed machines
- Permanent magnet machines
- Reluctance machines
- Electrostatic machines

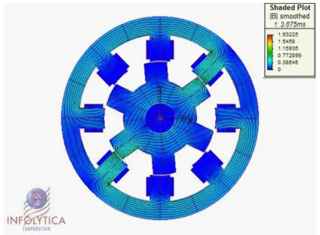
RELUCTANCE MACHINES

☐ High force density

☐ Good efficiency

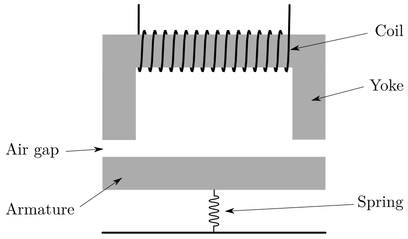
☐ Reduced cost

☐ Fault tolerance



- Stepper motor
- Synchronous reluctance motor
- Switched reluctance motor
- Linear reluctance actuators
- Single-coil reluctance actuators

(SINGLE-COIL) RELUCTANCE ACTUATORS



☐ Simple construction

☐ Compactness

Perfect solution for:

- Short-stroke actuators
- Switch-type devices

- Relays
- Solenoid valves

Why?

Collaboration agreement BSH Home Appliances Spain – Universidad de Zaragoza

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- Electronics
- Automatic control
- Mechanical engineering
- Materials
- Food technology
- …

There are electromechanical relays in…

and solenoid valves in…

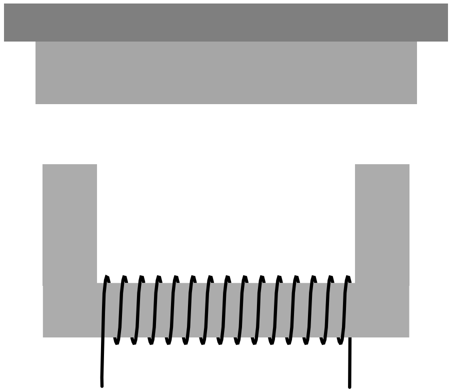
Gas cooktops,
ovens and stoves

…because they are **cheap**, **small** and **efficient**, but they have some **problems**

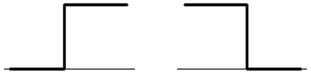
Why?

Switch-type devices are designed to switch between two states (open/close)

→ Reluctance actuator with position boundaries (~1mm, ~1ms)



No control (constant voltage)

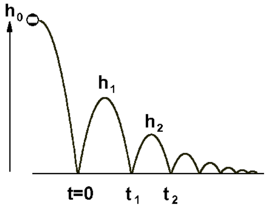


→ **Impacts**

→ **Bouncing**

→ **Acoustic noise**

→ **Wear**



In particular, in relays and valves…

- Electric arc, contact welding
- Larger (and random) switching times
- Premature failure
- Poor regulation

} Not present in more expensive actuators

What?

We want switch-type devices (relays and valves) which are…

…**small**, **efficient** and **cheap**…

…but also **silent**, **robust, fast** and **safe**

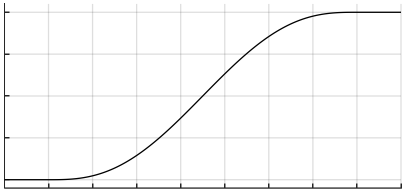
How?

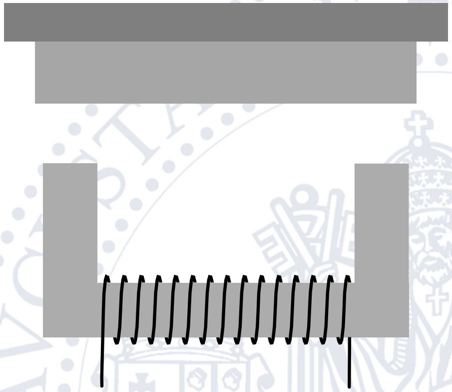
Control systems theory

In particular,

→ Soft-landing control policies

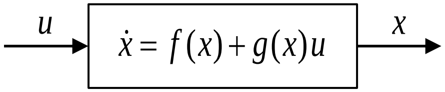
(Motion without impacts nor bounces)

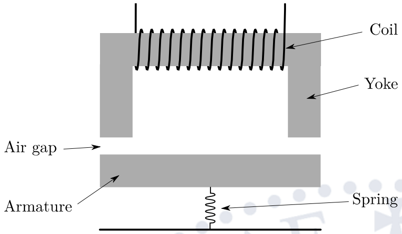


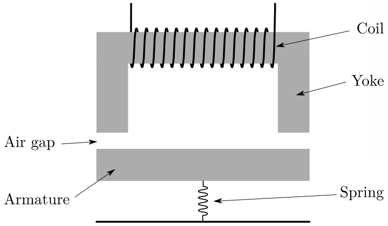


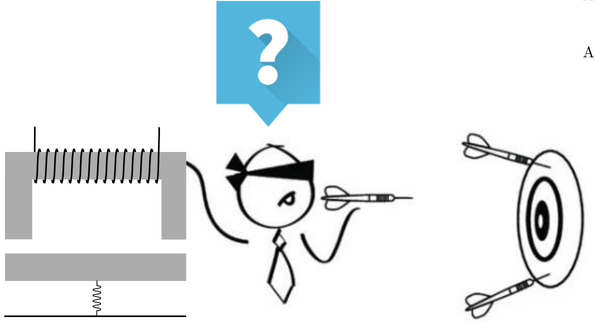
Thesis objectives

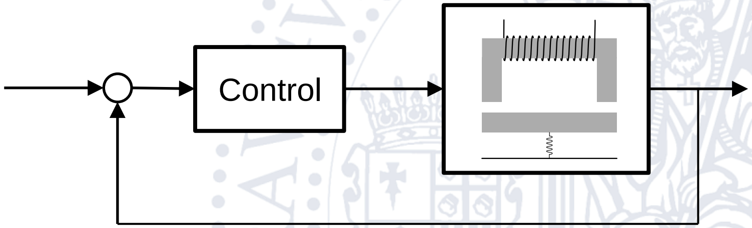
1) Design of control-oriented dynamical models for reluctance actuators
2) Evaluation of measurement techniques
3) Design and analysis of estimation algorithms
4) Design and validation of control algorithms







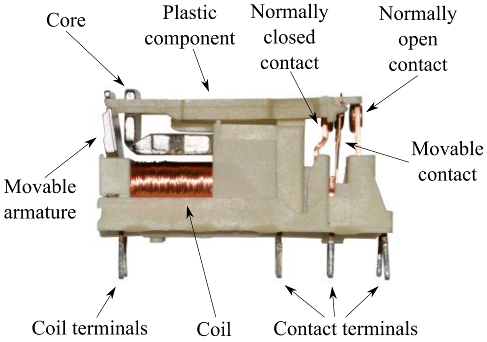


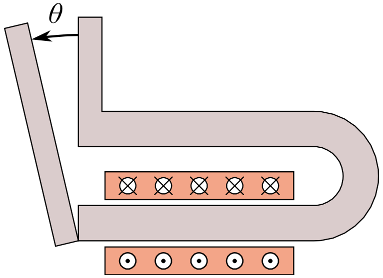


Devices under study

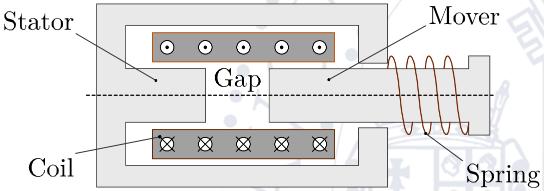
Switch-type devices used to illustrate the techniques presented in the thesis

Power relay





Solenoid valve



Outline

Introduction

Part I – Modeling and Experimentation

1. Electromagnetic Modeling
2. Dynamical Modeling of Reluctance Actuators
3. Measurement and Identification

Part II – Control and Estimation

4. Control
5. Estimation
6. Run-to-Run Control

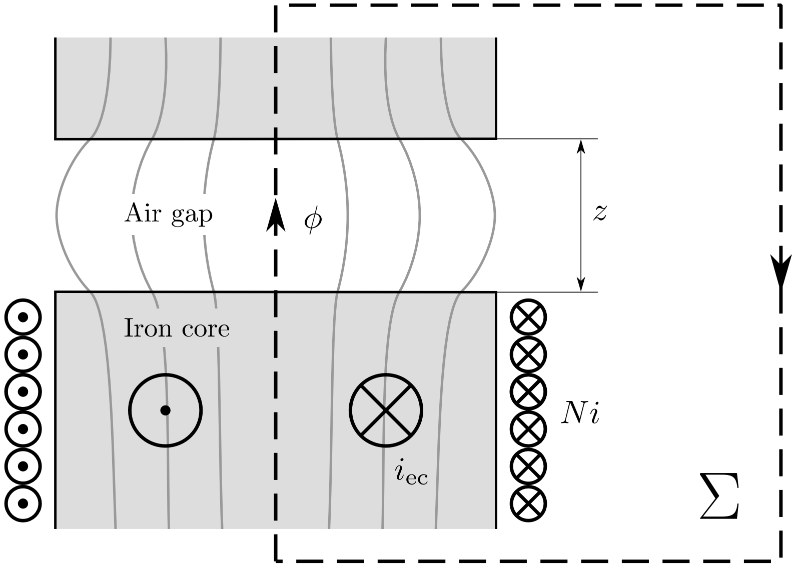
Conclusions

1. Electromagnetic Modeling

- Modeling fundamentals
- Electromagnetic phenomena
- Energy balance

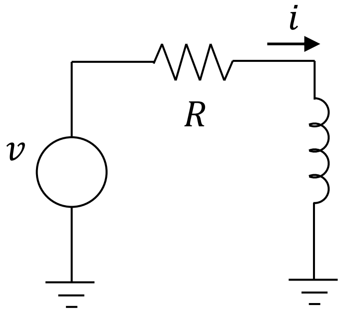
Modeling fundamentals

Reluctance actuator diagram



Goal → Find the dynamics of ϕ, i and i_{ec}

Coil electrical equation (Faraday's law)



Input

$$\boxed{v} = R\,i + N\,\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

$$\phi = \iint \mathbf{B}\cdot\mathrm{d}\mathbf{S}$$

Ampère's law

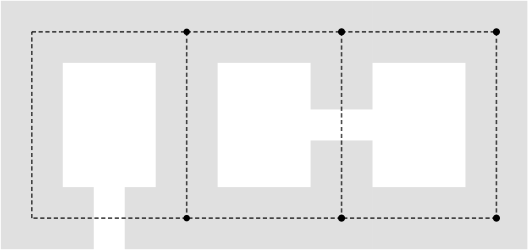
$$\int_{\partial\Sigma_{\mathrm{gap}}} \mathbf{H}\cdot\mathrm{d}\mathbf{l} + \int_{\partial\Sigma_{\mathrm{core}}} \mathbf{H}\cdot\mathrm{d}\mathbf{l} = N\,i + i_{\mathrm{ec}}$$

$$f(v, z, \phi, i)?$$

Modeling methodologies – Magnetic equivalent circuits (MEC)

Approximate method for magnetic systems:

- Flux confined within the main paths
- Magnetic fields are uniform in the cross section



$$\mathbf{H} = \frac{\mathbf{B}}{\mu} \implies \int H\,\mathrm{d}l = \phi\,\mathcal{R} \qquad \boxed{\mathcal{R} = \int \frac{\mathrm{d}l}{\mu\,A}} \left\{ \begin{array}{l} \text{Geometry} \\ \text{Materials} \\ \text{(Excitation)} \end{array} \right.$$

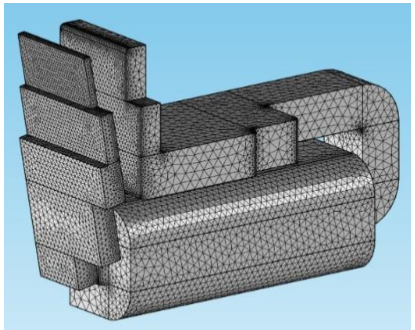
Reluctance

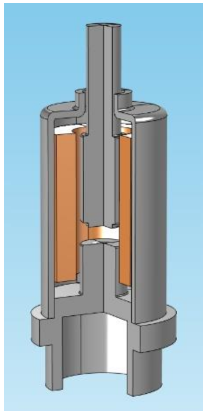
Reluctance actuators:

$$\int_{\partial\Sigma_{\mathrm{gap}}} \mathbf{H}\cdot\mathrm{d}\mathbf{l} + \int_{\partial\Sigma_{\mathrm{core}}} \mathbf{H}\cdot\mathrm{d}\mathbf{l} = N\,i + i_{\mathrm{ec}} \longrightarrow \boxed{\phi\left(\mathcal{R}_{\mathrm{gap}} + \mathcal{R}_{\mathrm{core}}\right) = N\,i + i_{\mathrm{ec}}}$$

$$\mathcal{R}_{\mathrm{gap}} = \int_{\partial\Sigma_{\mathrm{gap}}} \frac{\mathrm{d}l}{\mu_0\,A} \qquad \mathcal{R}_{\mathrm{core}} = \int_{\partial\Sigma_{\mathrm{core}}} \frac{\mathrm{d}l}{\mu\,A}$$

Modeling methodologies – Finite element method (FEM)



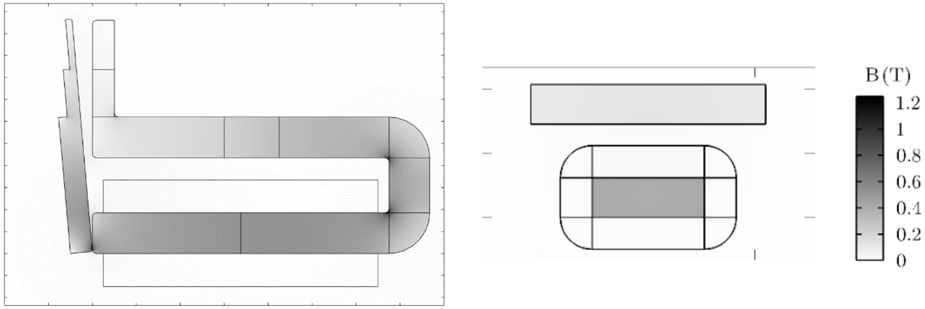


Numerical method:

- Detailed analysis
- Computationally expensive

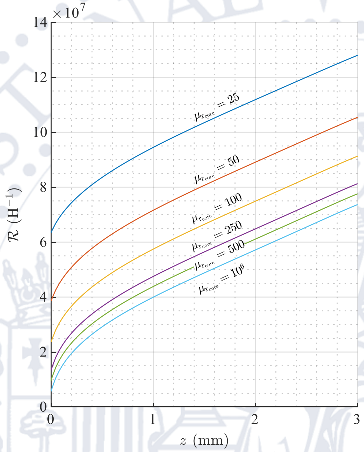
In this thesis:

1) Verify MEC assumptions (Field uniformity)

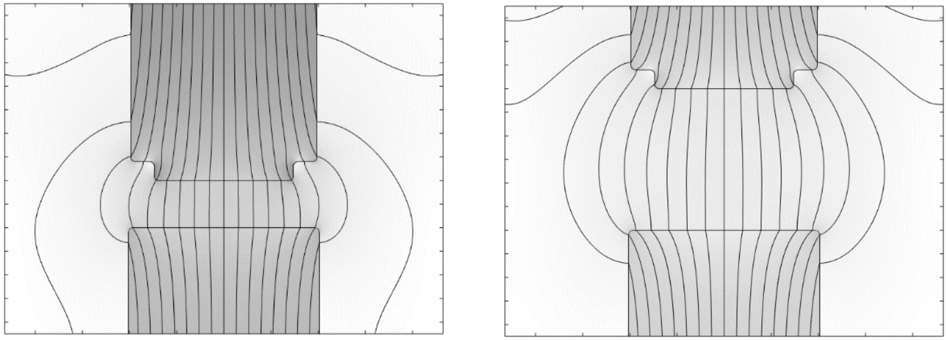


2) Compute the reluctance of the system

$$\mathcal{R} = Ni/\phi$$



Electromagnetic phenomena – Flux fringing



- Surroundings of air gaps
- Magnetic flux spreads out into the air
- Transmission into a low permeable material
- Affects the reluctance of the air gap

$$\mathcal{R}_{\text{gap}} = \int_{\partial\Sigma_{\text{gap}}} \frac{\mathrm{d}l}{\mu_0\, A}$$

Modeling approaches

1) Negligible

$$\mathcal{R}_{\text{gap}} \approx \frac{l_{\text{gap}}}{\mu_0\, A_{\text{core}}}$$

2) Analytic expressions

$$\mathcal{R}_{\text{gap}} = \frac{\dfrac{l_{\text{gap}}}{\mu_0\, A_{\text{core}}}}{1 + \dfrac{l_{\text{gap}}}{\sqrt{A_{\text{core}}}} \log\left(\dfrac{2\, l_{\text{w}}}{l_{\text{gap}}}\right)}$$

3) Finite Element Method

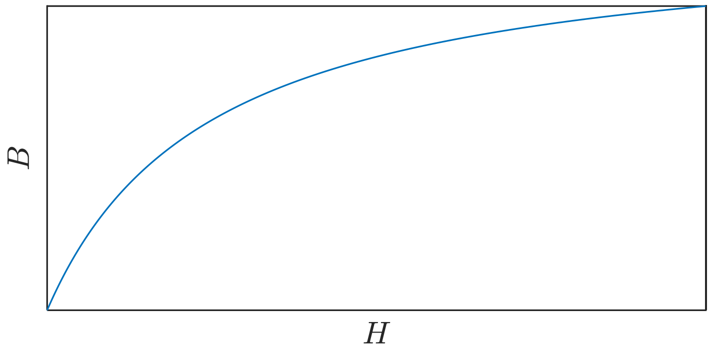
$$\mathcal{R}_{\text{gap}} = \mathcal{R}_{\text{gap}}(l_{\text{gap}})$$

Electromagnetic phenomena – Magnetic saturation

- Magnetic cores (ferromagnetic materials)
- Magnetization when an external field is applied
- Alignment of magnetic dipoles
- Affects the reluctance of the core (yoke + armature)

$$\mathcal{R}_{\text{core}} = \int_{\partial\Sigma_{\text{core}}} \frac{\mathrm{d}l}{\mu\, A}$$

μ_{core} is not constant



Modeling approaches

1) Negligible

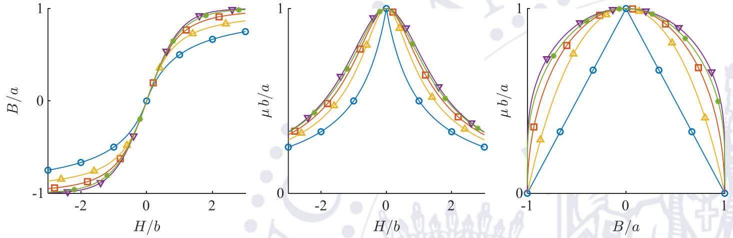
$\mu_{\text{core}} \approx$ constant

$$\mathcal{R}_{\text{core}} = \frac{1}{\mu_{\text{core}}} \int_{\partial\Sigma_{\text{core}}} \frac{\mathrm{d}l}{A}$$

2) Analytic expressions
(+ core discretization)

$$\mathcal{R}_{\text{core}} = \sum_j \frac{l_j}{\mu_{\text{core}}(B_j)\, A_j}$$

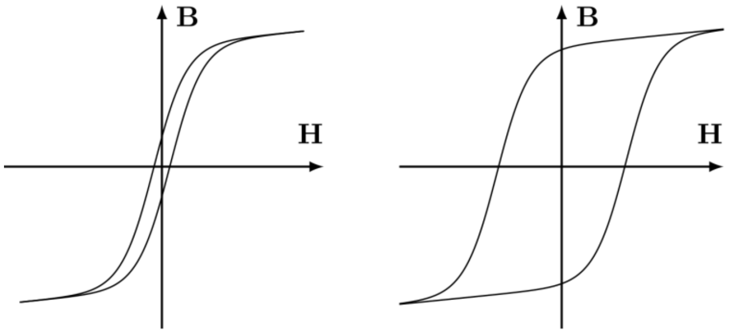
Frölich-Kennelly model →



B–H	$\mu(H)$	$\mu(B)$
$B = \frac{a\,H}{b+\lvert H\rvert}$	$\frac{a}{b+\lvert H\rvert}$	$\frac{a-\lvert B\rvert}{b}$

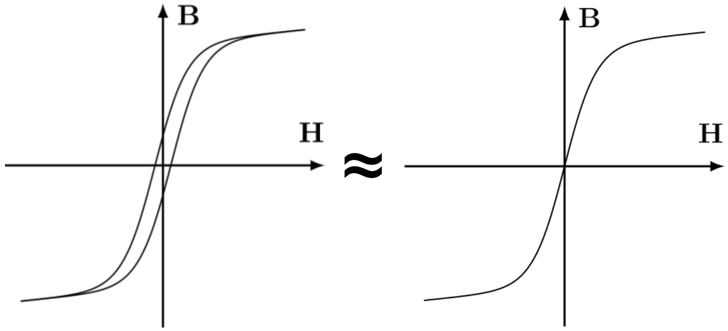
Electromagnetic phenomena – Magnetic hysteresis

- Magnetic cores (ferromagnetic materials)
- The alignment of magnetic dipoles is irreversible
- Hysteretic behavior between **B** and **H**
- Affects the magnetic behavior of the core (yoke + armature)

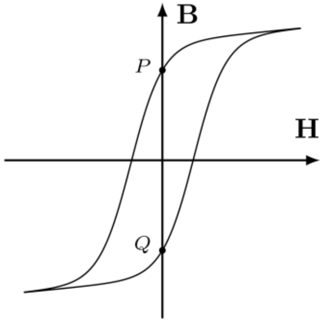


Modeling approaches

1) Negligible (Saturation model)



2) Hysteresis model **B** = *f* (**H**)



$$\xcancel{\begin{aligned}\phi\left(\mathcal{R}_{\mathrm{gap}}+\mathcal{R}_{\mathrm{core}}\right) &= N\,i + i_{\mathrm{ec}}\\ \mathcal{R}_{\mathrm{core}} &= \int_{\partial\Sigma_{\mathrm{core}}} \frac{\mathrm{d}l}{\mu\,A}\end{aligned}}$$

$$\boxed{\phi\,\mathcal{R}_{\mathrm{gap}} + \boxed{\int_{\partial\Sigma_{\mathrm{core}}} H\,\mathrm{d}l} = N\,i + i_{\mathrm{ec}}}$$

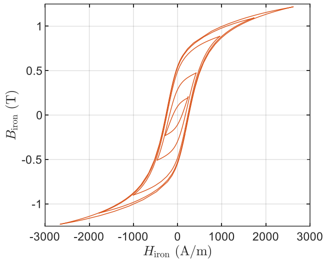
Electromagnetic phenomena – Magnetic hysteresis

Preisach model of hysteresis

Past maxima Past minima

Generalized Preisach model (GPM)

$$B = f_{\mathrm{GPM}}(H, \mathcal{A}, \mathcal{B}) = B_{\mathrm{Rev}}(H) + B_{\mathrm{Irr}}(H, \mathcal{A}, \mathcal{B})$$



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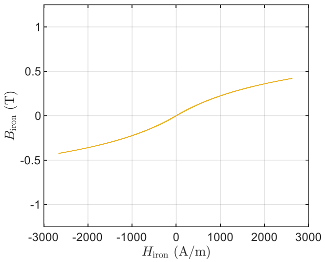
Reversible



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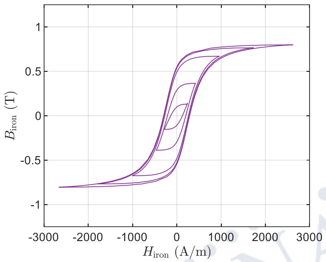
Irreversible



$$B_{\mathrm{Rev}}(H) = \int_0^H \mu'_{\mathrm{Rev}}(H)\,\mathrm{d}H$$

$$\mu'_{\mathrm{Rev}}(H) = \mu_0 + \mu_1\,\mathrm{e}^{-|H|/H_1} + \mu_2\,\mathrm{e}^{-|H|/H_2}$$

Classical Preisach Model

$$B_{\mathrm{Irr}}(H, \mathcal{A}, \mathcal{B})$$

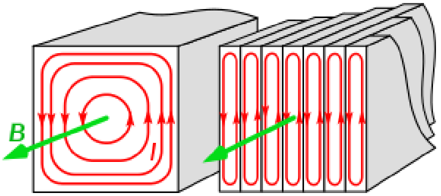
(Numerical integration)

Time derivative of the GPM:

$$\dot{B} = \big(\mu'_{\mathrm{Rev}}(H) + \mu'_{\mathrm{Irr}}(H, \mathcal{A}, \mathcal{B})\big)\dot{H} = \boxed{\mu'_{\mathrm{GPM}}(H, \mathcal{A}, \mathcal{B})}\,\dot{H}$$

Incremental permeability
(Analytic expression)

Electromagnetic phenomena – Eddy currents

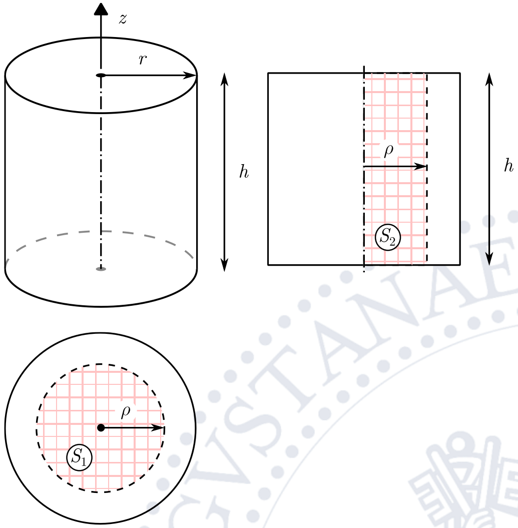


- Induced currents in conductive materials due to varying magnetic fields

Modeling approaches

1) Negligible $i_{\mathrm{ec}} = 0$

2) Analytic solution based on an infinite cylindrical core



$$\mathbf{B}(t,\rho) = B_z(t,\rho)\,\hat{\mathbf{z}} = \sum_{n=0}^{\infty}\left(b_n(t)\,\rho^n\right)\hat{\mathbf{z}}.$$

$$\mathbf{H} = \frac{\mathbf{B}}{\mu} \qquad \mathbf{J}_{\mathrm{f}} = \sigma\,\mathbf{E}$$

Ampère, Fourier

$$\sum_{m=0}^{\infty}\left(\frac{\left(\mu\sigma r^2/4\right)^m}{m!^2\,(m+1)}\,\frac{\mathrm{d}^m i_{\mathrm{ec}}}{\mathrm{d}t^m}\right) = -\frac{h\sigma}{4\pi}\sum_{m=0}^{\infty}\left(\frac{\left(\mu\sigma r^2/4\right)^m}{m!^2\,(m+1)^2}\,\frac{\mathrm{d}^{m+1}\phi}{\mathrm{d}t^{m+1}}\right)$$

First order approximation

$$i_{\mathrm{ec}} = -\frac{h\,\sigma}{4\pi}\,\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

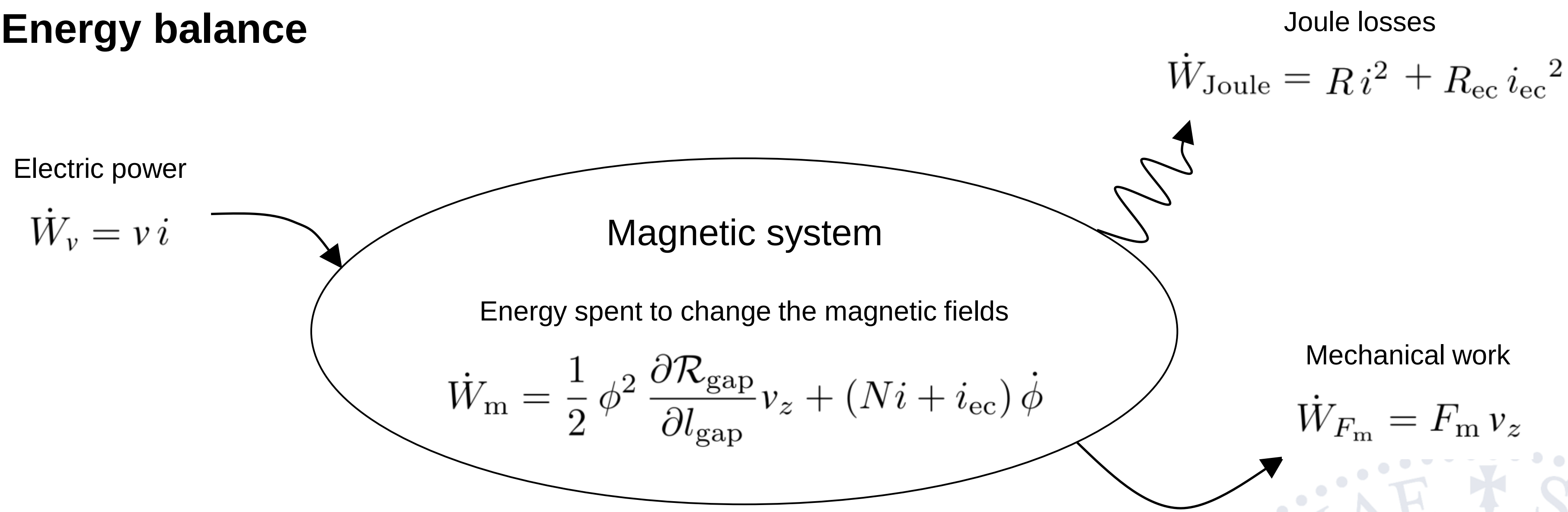
Generalization

$$i_{\mathrm{ec}} = -k_{\mathrm{geom}}\,\sigma_{\mathrm{core}}\,l_{\mathrm{core}}\,\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

Constant l_{core}

$$\boxed{i_{\mathrm{ec}} = -k_{\mathrm{ec}}\,\frac{\mathrm{d}\phi}{\mathrm{d}t}}$$

Energy balance



Joule losses

$$\dot{W}_{\mathrm{Joule}} = R\, i^2 + R_{\mathrm{ec}}\, {i_{\mathrm{ec}}}^2$$

Electric power

$$\dot{W}_{\mathrm{v}} = v\, i$$

Magnetic system

Energy spent to change the magnetic fields

$$\dot{W}_{\mathrm{m}} = \frac{1}{2}\,\phi^2\,\frac{\partial \mathcal{R}_{\mathrm{gap}}}{\partial l_{\mathrm{gap}}} v_z + (N i + i_{\mathrm{ec}})\,\dot{\phi}$$

Mechanical work

$$\dot{W}_{F_{\mathrm{m}}} = F_{\mathrm{m}}\, v_z$$

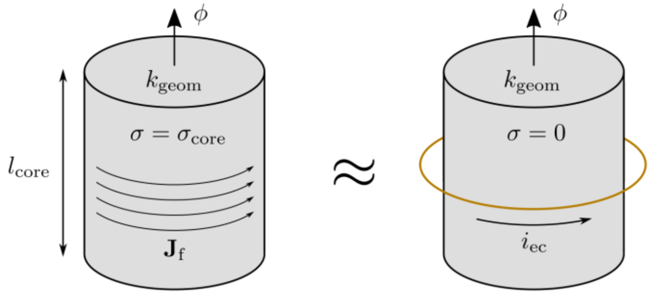
Two results:

Magnetic force

$$\boxed{F_{\mathrm{m}} = -\frac{1}{2}\,\phi^2\,\frac{\partial \mathcal{R}_{\mathrm{gap}}}{\partial l_{\mathrm{gap}}}}$$

Eddy-current resistance

$$\boxed{R_{\mathrm{ec}} = \frac{1}{k_{\mathrm{geom}}\,\sigma_{\mathrm{core}}\,l_{\mathrm{core}}}}$$



1. Electromagnetic Modeling

Contributions

- Detailed time-domain analysis of electromagnetic phenomena
- Time derivative of the Preisach model - Incremental permeability
- Analytic solution for induced currents in circular cores
- Energy balance

Publications

E. Ramirez-Laboreo, C. Sagues, and S. Llorente, “A new model of electromechanical relays for predicting the motion and electromagnetic dynamics”, in *IEEE Industry Applications Society Annual Meeting*, Addison, TX, Oct. 2015, pp. 1-8.

E. Ramirez-Laboreo, C. Sagues and S. Llorente, “A New Model of Electromechanical Relays for Predicting the Motion and Electromagnetic Dynamics”, *IEEE Transactions on Industry Applications*, vol. 52, no. 3, pp. 2545-2553, May/Jun. 2016.

E. Ramirez-Laboreo, E. Moya-Lasheras and C. Sagues, “Reluctance actuator characterization via FEM simulations and experimental tests”, *Mechatronics*, vol. 56, pp. 58-66, Dec. 2018.

E. Ramirez-Laboreo, M. G. L. Roes and C. Sagues, “Hybrid Dynamical Model for Reluctance Actuators Including Saturation, Hysteresis and Eddy Currents”, *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 3, pp. 1396-1406, Jun. 2019.

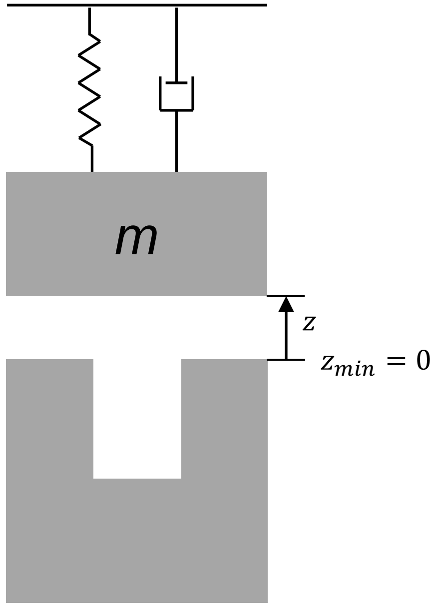
2. Dynamical Modeling of Reluctance Actuators

- Mechanical modeling
- Explicit dynamical models for reluctance actuators

Mechanical modeling

Most reluctance actuators have one-degree-of-freedom movements

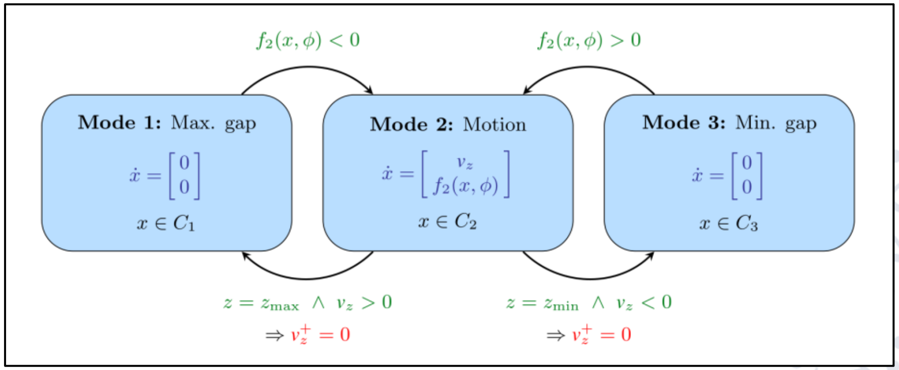
→ Mass-spring-damper system



Magnetic force *Elastic force* *Damping*

$$m\,\ddot{z} = F_{\mathrm{m}}(z,\phi) - k_{\mathrm{s}}\,(z - z_{\mathrm{s}}) - c\,\dot{z}$$

Position boundaries → Second order hybrid dynamics



$$f_2(x,\phi) = \frac{1}{m}\Big(F_{\mathrm{m}}(z,\phi) - k_{\mathrm{s}}\,(z - z_{\mathrm{s}}) - c\,v_z\Big)$$

Three dynamic modes:

- Motion / max./min. gap

State: $\chi = (x, q)$

- Continuous state
- Discrete state (dyn. mode)

Dynamical models

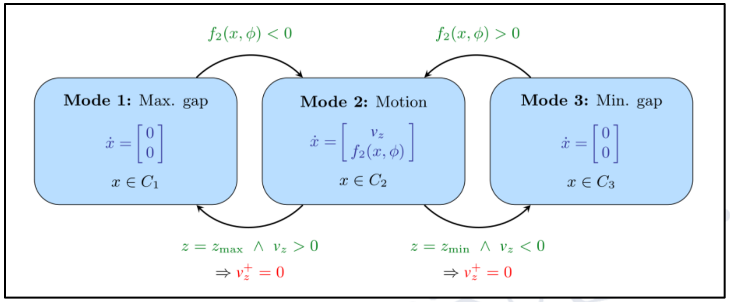
Electromagnetism

$$v = R\,i + N\,\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

$$\int_{\partial\Sigma_{\mathrm{gap}}} \mathbf{H}\cdot\mathrm{d}\mathbf{l} + \int_{\partial\Sigma_{\mathrm{core}}} \mathbf{H}\cdot\mathrm{d}\mathbf{l} = N\,i + i_{\mathrm{ec}}$$

Mechanics

$$m\,\ddot{z} = F_{\mathrm{m}}(z,\phi) - k_{\mathrm{s}}\,(z - z_{\mathrm{s}}) - c\,\dot{z}$$



Goal: Find explicit dynamical models of the form

$$\frac{\mathrm{d}x}{\mathrm{d}t} = f(x,v) \qquad x = \begin{bmatrix} z \\ v_z \\ \phi \end{bmatrix} \qquad \begin{aligned} i &= h_1(x,v) \\ i_{ec} &= h_2(x,v) \\ &\dots \end{aligned}$$

Dynamical models

Several possibilities (Electromagnetic phenomena, type of motion, bouncing)

Explicit solutions for:

- Rectilinear 1 DOF motion with purely inelastic collisions
- Five models depending on the electromagnetic phenomena considered

#	Model	Saturation	Flux fringing	Eddy currents	Hysteresis
0	B	x	x	x	x
1	S	✓	x	x	x
2	S+F	✓	✓	x	x
3	S+F+EC	✓	✓	✓	x
4	S+H+F+EC	✓	✓	✓	✓

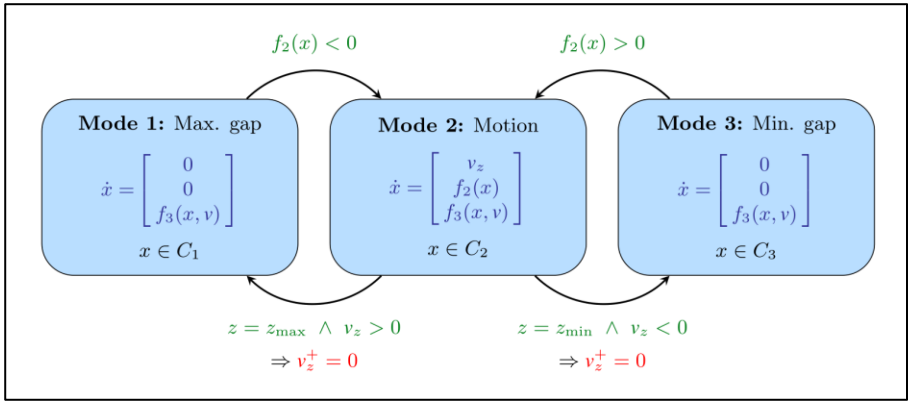
↓ + Complexity

Dynamical models without magnetic hysteresis (Models #0 to #3)

Common structure:

Continuous state: $x = \begin{bmatrix} z & v_z & \phi \end{bmatrix}^{\mathsf{T}}$

Dynamics:



$$\boxed{f_2(x)} = \frac{1}{m}\left(\boxed{F_{\mathrm{m}}(z, \phi)} - k_{\mathrm{s}}\,(z - z_{\mathrm{s}}) - c\, v_z\right)$$

$$\boxed{f_3(x, v)}$$

$$i = \boxed{h_1(x, v)}$$

$$i_{ec} = \boxed{h_2(x, v)}$$

Three dynamic modes:

- Motion / max. gap / min. gap

State:

$$\chi = (x, q)$$

- Continuous state
- Discrete state (dynamic mode)

Different expressions depending on:

- Saturation
- Flux fringing
- Eddy currents

2. Dynamical Modeling of Reluctance Actuators

NONLINEAR

Magnetic equation

B	$\dot{\phi} = \frac{v}{N} - \frac{R\,\phi}{N^2}\left(\mathcal{R}_0 + k_{\text{gap}}\, z\right)$
S	$\dot{\phi} = \frac{v}{N} - \frac{R\,\phi}{N^2}\left(\mathcal{R}_{\text{gap}0} + k_{\text{gap}}\, z + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)$
S+F	$\dot{\phi} = \frac{v}{N} - \frac{R\,\phi}{N^2}\left(\mathcal{R}_{\text{gap}}(z) + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)$
S+F+EC	$\dot{\phi} = \frac{\frac{v}{N} - \frac{R\,\phi}{N^2}\left(\mathcal{R}_{\text{gap}}(z) + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)}{1 + \frac{R\,k_{\text{ec}}}{N^2}}$

Motion equation

B	$\dot{v}_z = \frac{1}{m}\left(-\frac{1}{2}\, k_{\text{gap}}\, \phi^2 - k_{\text{s}}\,(z - z_{\text{s}}) - c\, v_z\right)$
S	$\dot{v}_z = \frac{1}{m}\left(-\frac{1}{2}\, k_{\text{gap}}\, \phi^2 - k_{\text{s}}\,(z - z_{\text{s}}) - c\, v_z\right)$
S+F	$\dot{v}_z = \frac{1}{m}\left(-\frac{1}{2}\, \phi^2\, \frac{\partial \mathcal{R}_{\text{gap}}(z)}{\partial z} - k_{\text{s}}\,(z - z_{\text{s}}) - c\, v_z\right)$
S+F+EC	$\dot{v}_z = \frac{1}{m}\left(-\frac{1}{2}\, \phi^2\, \frac{\partial \mathcal{R}_{\text{gap}}(z)}{\partial z} - k_{\text{s}}\,(z - z_{\text{s}}) - c\, v_z\right)$

Electric current

B	$i = \frac{\phi}{N}\left(\mathcal{R}_0 + k_{\text{gap}}\, z\right)$
S	$i = \frac{\phi}{N}\left(\mathcal{R}_{\text{gap}0} + k_{\text{gap}}\, z + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)$
S+F	$i = \frac{\phi}{N}\left(\mathcal{R}_{\text{gap}}(z) + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)$
S+F+EC	$i = \frac{\frac{\phi}{N}\left(\mathcal{R}_{\text{gap}}(z) + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)}{1 + \frac{R\,k_{\text{ec}}}{N^2}} + \frac{v}{R + \frac{N^2}{k_{\text{ec}}}}$

Equivalent eddy current

B	$i_{\text{ec}} = 0$
S	$i_{\text{ec}} = 0$
S+F	$i_{\text{ec}} = 0$
S+F+EC	$i_{\text{ec}} = -k_{\text{ec}}\, \frac{\frac{v}{N} - \frac{R\,\phi}{N^2}\left(\mathcal{R}_{\text{gap}}(z) + \frac{\mathcal{R}_{\text{core}0}}{1 - \lvert\phi\rvert/\phi_{\text{sat}}}\right)}{1 + \frac{R\,k_{\text{ec}}}{N^2}}$

Dynamical model including magnetic hysteresis (Model #4)

Model #4 includes the Preisach model of hysteresis

Continuous state:

$$\xcancel{x = [\; z \quad v_z \quad \phi \;]^{\mathsf{T}}}$$

$$x = [\; z \quad v_z \quad H_{\text{core}} \;]^{\mathsf{T}}$$

Inverse Preisach model (inefficient)

Dynamics:

$$\xcancel{\dot{\phi} = \left(\frac{v}{N} - \frac{R}{N^2}\left(\phi\,\mathcal{R}_{\text{gap}}(z) + f_{\text{GPM}}^{-1}(\phi/A_{\text{core}})\,l_{\text{core}}\right)\right)\left(1 + \frac{R\,k_{\text{ec}}}{N^2}\right)^{-1}}$$

Direct Preisach model (efficient)

$$\dot{H}_{\text{core}} = \frac{\dfrac{v}{N} - \dfrac{R}{N^2}\left(A_{\text{core}}\,f_{\text{GPM}}(H_{\text{core}})\,\mathcal{R}_{\text{gap}}(z) + H_{\text{core}}\,l_{\text{core}}\right)}{\left(1 + \dfrac{R\,k_{\text{ec}}}{N^2}\right) A_{\text{core}}\,\mu'_{\text{GPM}}(H_{\text{core}})}$$

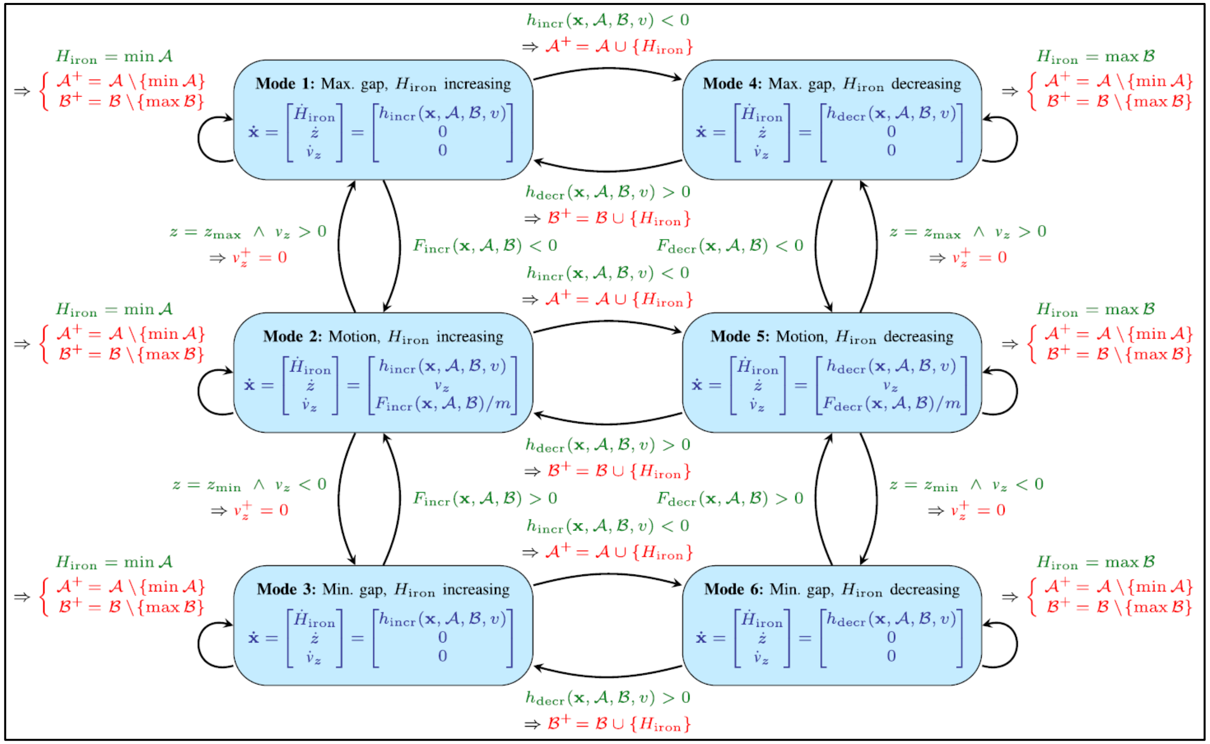
Incremental permeability (analytic expression)

$$\dot{v}_z = \frac{1}{m}\left(-\frac{1}{2}\,{A_{\text{core}}}^2\left(f_{\text{GPM}}(H_{\text{core}},\mathcal{A},\mathcal{B})\right)^2\frac{\partial\mathcal{R}_{\text{gap}}(z)}{\partial z} - k_{\text{s}}\,(z - z_{\text{s}}) - c\,v_z\right)$$

Dynamical model including magnetic hysteresis (Model #4)

The hysteresis model depends on the direction of H_{core} and the extrema sets $\mathcal{A}, \mathcal{B}$

Hybrid automaton:



Six dynamic modes:

- Motion / max. gap / min. gap
- *H* increasing / decreasing

State:

$$\chi = (x, q, \mathcal{A}, \mathcal{B})$$

- Continuous state
- Discrete state (dynamic mode)
- Extrema sets $\mathcal{A}, \mathcal{B}$

Contributions

- Model including saturation, hysteresis, eddy currents, flux fringing and the armature motion
- Efficient dynamical solution of the Preisach model of hysteresis
- New class of hybrid systems

Publications

E. Ramirez-Laboreo, C. Sagues, and S. Llorente, "A new model of electromechanical relays for predicting the motion and electromagnetic dynamics", in *IEEE Industry Applications Society Annual Meeting*, Addison, TX, Oct. 2015, pp. 1-8.

E. Ramirez-Laboreo, C. Sagues and S. Llorente, "A New Model of Electromechanical Relays for Predicting the Motion and Electromagnetic Dynamics", *IEEE Transactions on Industry Applications*, vol. 52, no. 3, pp. 2545-2553, May/Jun. 2016.

E. Ramirez-Laboreo, M. G. L. Roes and C. Sagues, "Hybrid Dynamical Model for Reluctance Actuators Including Saturation, Hysteresis and Eddy Currents", *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 3, pp. 1396-1406, Jun. 2019.

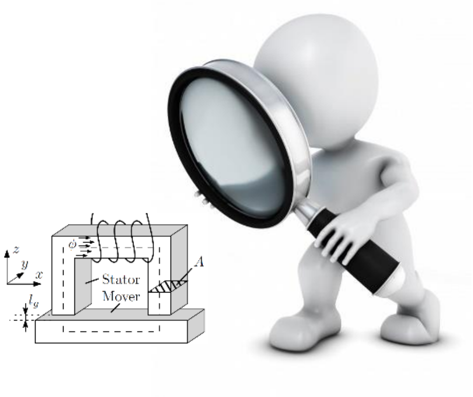
3. Measurement and Identification

- Position measurement
- Other measurements
- Model identification

Measurements in reluctance actuators

Purposes:

- Check modeling assumptions
- Parameter estimation
- Control / Estimation



Electromagnetic variables:

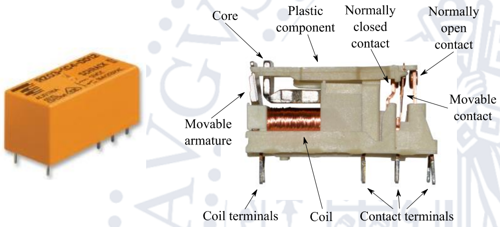
- Voltage and current → Direct measurements
- Magnetic flux → Estimation

Position:

- Specifications: 50 µm, 10 kHz
- No interference

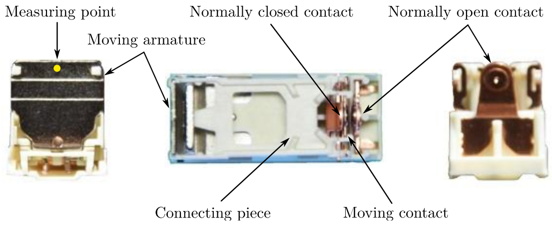
} Optical sensors

- Evaluation using the electromechanical relay



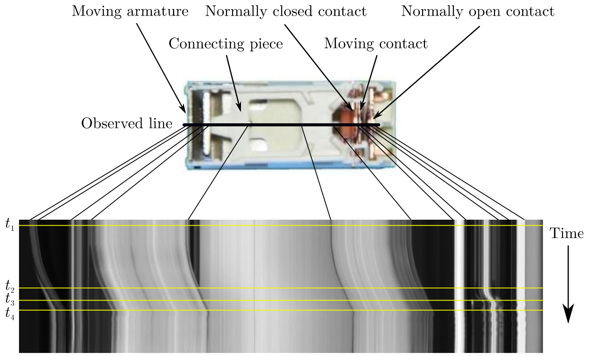
Position measurements

Laser sensor



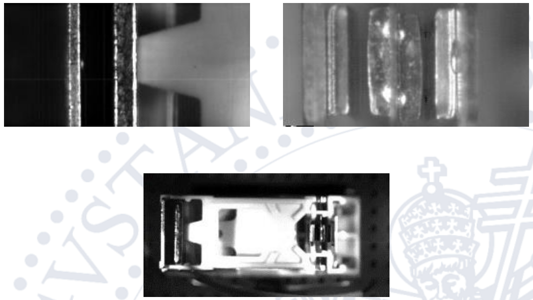
- Real-time measurement
- Captures bouncing
- Accessibility problems

Line scan camera



- Captures all components
- Requires (hard) processing
- Lighting limits performance

High speed camera



- Captures any component
- Requires processing
- Lighting limits performance

Other measurements

Drawbacks of position measurement techniques:

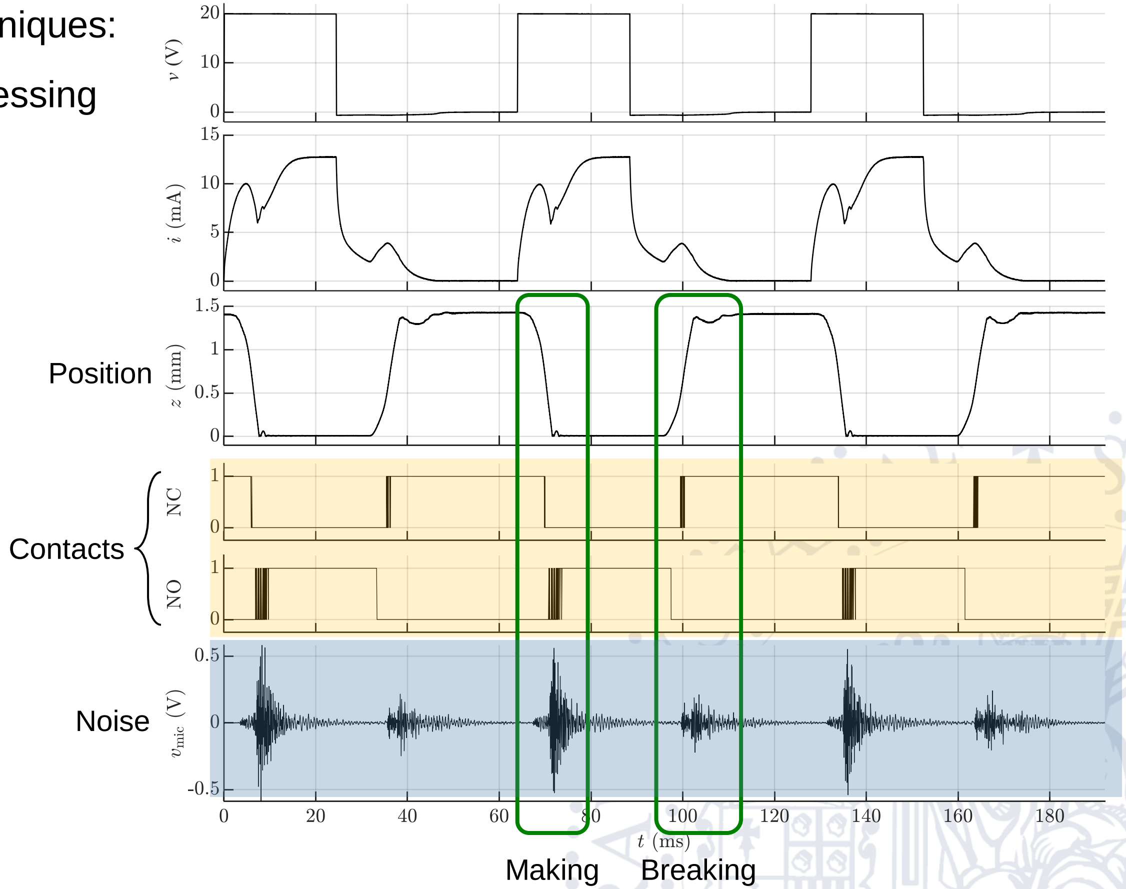
- Accessibility / lighting conditions / processing
- Requires disassembling the device

- <u>High cost</u> (x10,000-100,000 switches)

Alternative measurements?

Electrical contacts (only relays) / Noise:

- Easily obtainable
- Linked to the armature motion



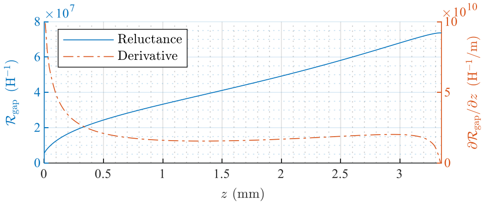
Identification

Identification procedure (Complete model):

Step 0

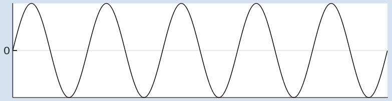
0a. Obtain geometry and electrical parameters

0b. Model air reluctance (FEM, Analytical)



Step 1 - Estimate hysteresis parameters

Experiments:
- Static position
- Bipolar, low freq. sinusoidal current



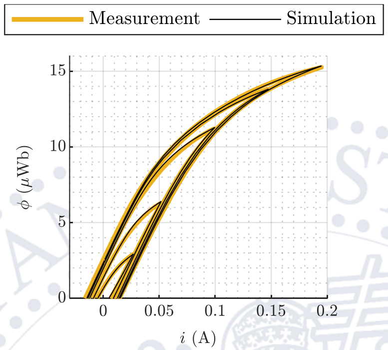
Model fitting:

1) Fit reversible GPM

$$\mu'_{\mathrm{Rev}}(H) = \mu_0 + \mu_1\,\mathrm{e}^{-|H|/H_1} + \mu_2\,\mathrm{e}^{-|H|/H_2}$$

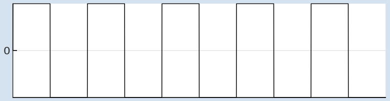
2) Fit irreversible GPM

$$B_{\mathrm{Irr}}(H, \mathcal{A}, \mathcal{B})$$



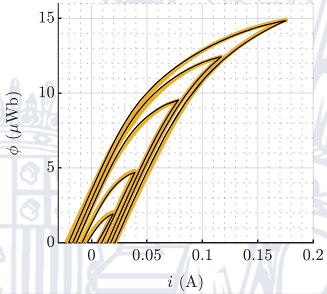
Step 2 - Estimate eddy-current parameter

Experiments:
- Static position
- Bipolar square voltage



Model fitting (Dynamical model):

$$J(k_{\mathrm{ec}}) = \sqrt{\frac{\int \left(i_{\mathrm{exp}}(t) - i_{\mathrm{sim}}(t)\right)^2 \mathrm{d}t}{\int \left(i_{\mathrm{exp}}(t)\right)^2 \mathrm{d}t} + \frac{\int \left(\phi_{\mathrm{exp}}(t) - \phi_{\mathrm{sim}}(t)\right)^2 \mathrm{d}t}{\int \left(\phi_{\mathrm{exp}}(t)\right)^2 \mathrm{d}t}}$$

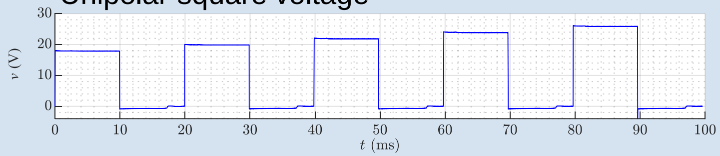


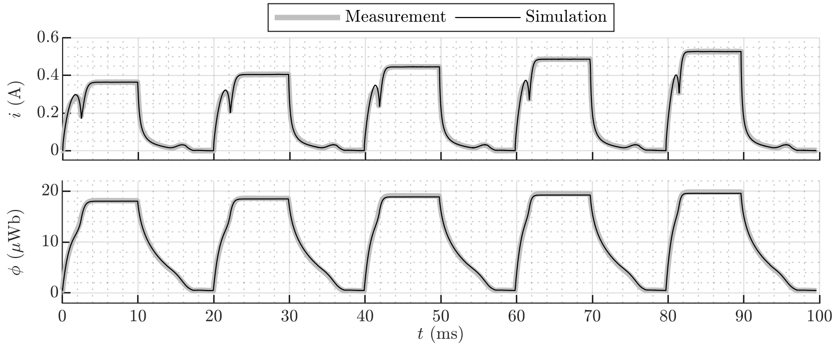
Identification

Step 3 - Validation

Experiments:

- Free motion
- Unipolar square voltage

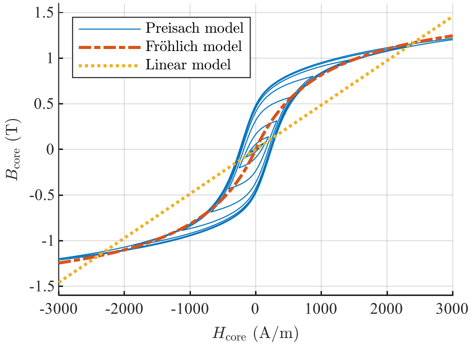




Similar identification procedures can be applied to all the models

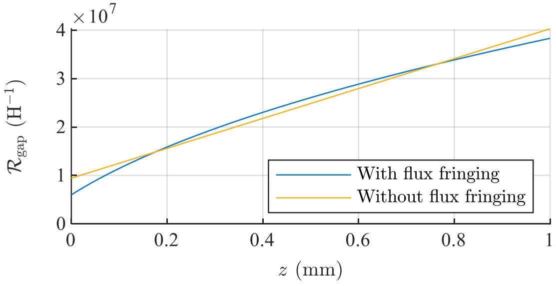
Core material

Linear / Saturation / Hysteresis



Air gap

Fringing / No Fringing



Eddy currents

$$k_{\text{ec}} \in \mathbb{R}^{>0}$$

$$k_{\text{ec}} = 0$$

Contributions

- Analysis of position measuring instruments
- Use of alternative measurements
- Parameter estimation procedure / Extension to simpler models

Publications

E. Ramirez-Laboreo, E. Moya-Lasheras and C. Sagues, “Reluctance actuator characterization via FEM simulations and experimental tests”, *Mechatronics*, vol. 56, pp. 58-66, Dec. 2018.

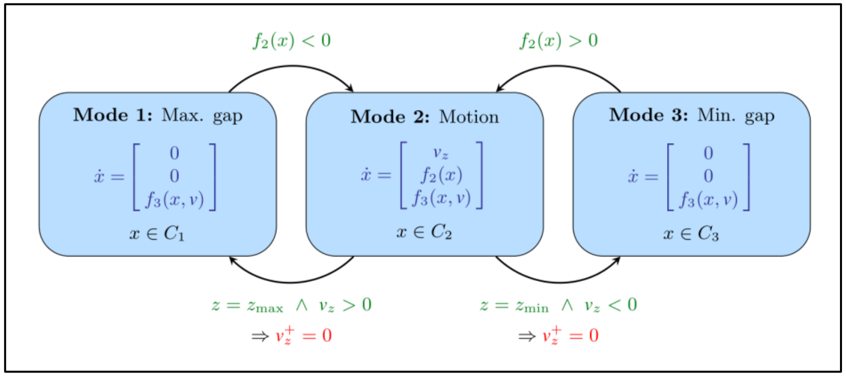
E. Ramirez-Laboreo, E. Moya-Lasheras and C. Sagues, “Real-Time Electromagnetic Estimation for Reluctance Actuators”, *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1952-1961, Mar. 2019.

E. Ramirez-Laboreo, M. G. L. Roes and C. Sagues, “Hybrid Dynamical Model for Reluctance Actuators Including Saturation, Hysteresis and Eddy Currents”, *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 3, pp. 1396-1406, Jun. 2019.

4. Control

- Control systems properties
- Feedback control
- Open-loop control

Control systems properties – Stability



For each dynamic mode q, equilibrium points satisfy

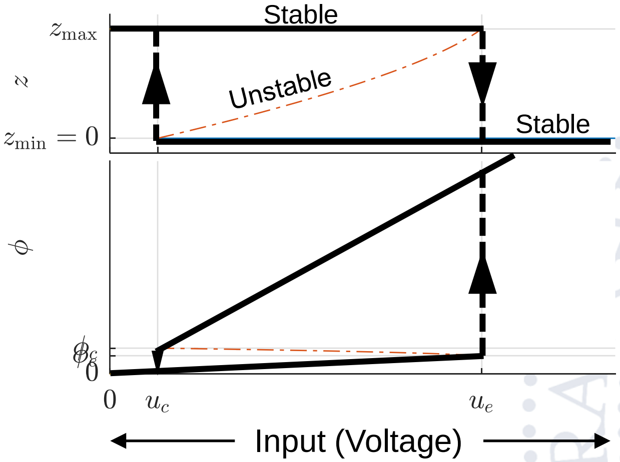
$$\underset{\substack{\uparrow \\ \text{Does not flow}}}{f_{\text{Mode } q}(x,u) = 0},\quad q \in Q,\ \overset{\substack{\text{Belongs to the domain} \\ \downarrow}}{x \in C_q},\ \underset{\substack{\uparrow \\ \text{Does not jump}}}{x \notin D_q}$$

The equilibrium points depend on the input

Coordinates for:

- Position
- Velocity (=0)
- Magnetic flux

Stability using Lyapunov’s indirect method



- Stable only at boundaries
- Hysteretic behavior

→ Switching conditions (analytic expressions)

Control systems properties – Controllability and observability

System

$$\dot{x} = A\,x + B\,u$$
$$y = C\,x$$

Controllability

$$\operatorname{rank}(\mathcal{C}) = n$$
$$\mathcal{C} = \begin{bmatrix} B & AB & A^2B & \cdots & A^{n-1}B \end{bmatrix}$$

Observability

$$\operatorname{rank}(\mathcal{O}) = n \qquad \mathcal{O} = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix}$$

$$\dot{x} = \varphi(x,u) = f(x) + g(x)u$$
$$y = h(x)$$

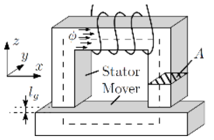
$$\exists k : \operatorname{rank}(\mathcal{C}_k(x)) = n$$
$$\mathcal{C}_k(x) = \left[g(x),\ \mathrm{ad}_f\, g(x),\ \ldots,\ \mathrm{ad}_f^{k-1} g(x) \right]$$

(Lie theory)

$$\exists k : \operatorname{rank}(\mathcal{O}_k(x)) = n \qquad \mathcal{O}_k(x) = \begin{bmatrix} \dfrac{\partial h}{\partial x} \\ \dfrac{\partial (\mathcal{L}_\varphi h)}{\partial x} \\ \vdots \\ \dfrac{\partial (\mathcal{L}_\varphi^{k-1} h)}{\partial x} \end{bmatrix}$$

(Lie theory)

Reluctance actuator



$$\dot{z} = f_1(x) = v_z\,,$$
$$\dot{v}_z = f_2(x) = \frac{1}{m}\left(-\frac{1}{2}\,k_{\mathrm{gap}}\,\phi^2 - k_{\mathrm{s}}\,(z - z_{\mathrm{s}}) - c\,v_z\right),$$
$$\dot{\phi} = f_3(x,u) = \frac{u}{N} - \frac{R}{N^2}\,\phi\,(\mathcal{R}_0 + k_{\mathrm{gap}}\,z)\,,$$

Completely controllable
(Controllable for all *x*)

Observable
(Observable for all *x*,
except for ϕ=0)

Feedback control

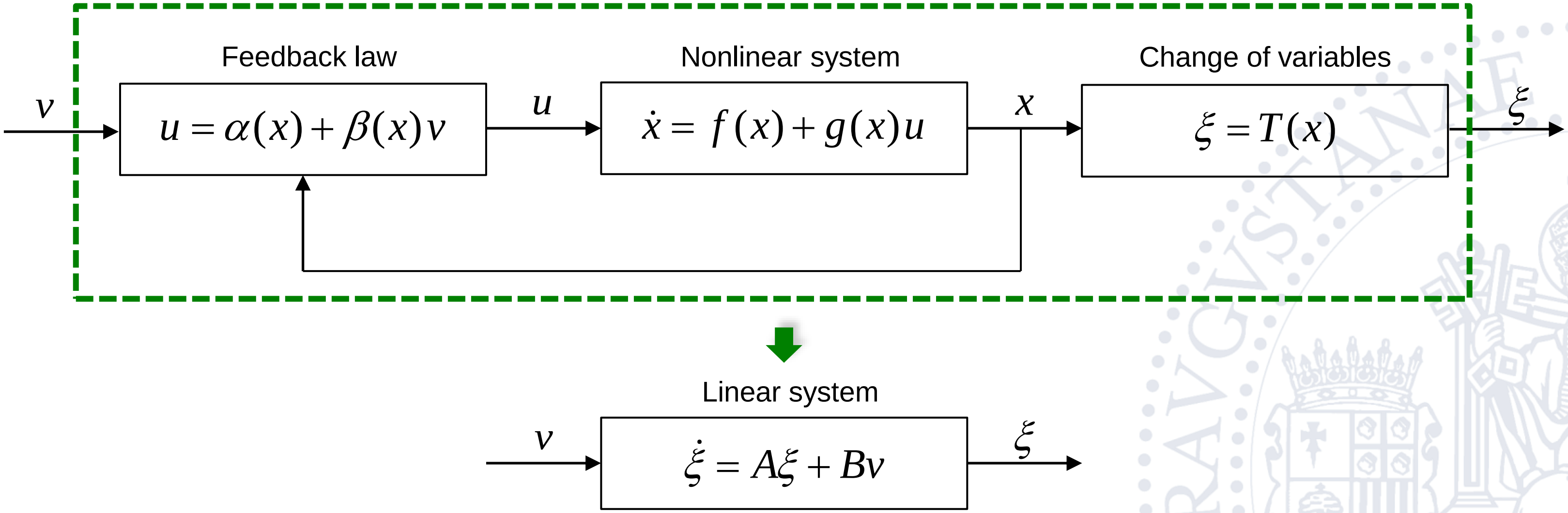
Soft-landing of reluctance actuators → Nonlinear position control of electromechanical system:

- Lyapunov-based methods (sliding mode control)
- Linearization, Gain scheduling

} ➡ State-of-the-art

- Feedback linearization ➡ Never applied to reluctance actuators

What is feedback linearization?



Feedback law

$$u = \alpha(x) + \beta(x)v$$

Nonlinear system

$$\dot{x} = f(x) + g(x)u$$

Change of variables

$$\xi = T(x)$$

v u x ξ

Linear system

$$\dot{\xi} = A\xi + Bv$$

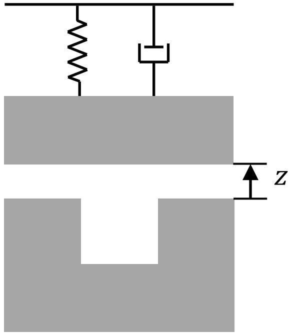
v ξ

Feedback control – Controller design

Step 1 – Feedback linearization

Model equations:

$$\boxed{\dot{x} = f(x) + g(x)u}$$



$$\begin{cases} \dot{z} = v_z, \\ \dot{v}_z = \dfrac{1}{m}\left(-\dfrac{1}{2}\,\phi^2\,\dfrac{\partial \mathcal{R}_{\text{gap}}(z)}{\partial z} - k_{\text{s}}\,(z - z_{\text{s}}) - c\,v_z\right), \\ \dot{\phi} = \left(\dfrac{u}{N} - \dfrac{R\,\phi\,\mathcal{R}(z,\phi)}{N^2}\right)\left(1 + \dfrac{R\,k_{\text{ec}}}{N^2}\right)^{-1}, \end{cases}$$

State: position, velocity, and flux

$$x = [\,z \;\; v_z \;\; \phi\,]^{\mathsf{T}}$$

Linearizing law (Khalil):

$$\boxed{u = \alpha(x) + \beta(x)v}$$

$$\alpha(x) = \frac{N c\,\phi}{2\,m} + \frac{R\,\phi\,\mathcal{R}(z,\phi)}{N\left(1 + \dfrac{R\,k_{\text{ec}}}{N^2}\right)} + \frac{N c\left(k_{\text{s}}\,(z - z_{\text{s}}) + c\,v_z\right)}{m\,\phi\,\mathcal{R}'_{\text{gap}}(z)} - \frac{N k_{\text{s}}\,v_z}{\phi\,\mathcal{R}'_{\text{gap}}(z)} - \frac{N v_z\,\phi\,\mathcal{R}''_{\text{gap}}(z)}{2\,\mathcal{R}'_{\text{gap}}(z)}$$

$$\beta(x) = -\frac{N m}{\phi\,\mathcal{R}'_{\text{gap}}(z)}$$

➡

$$\dot{\xi} = A\,\xi + B\,v$$

$$\begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \\ \dot{\xi}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v$$

State: position, velocity, and acceleration
(Triple integrator)

$$\boxed{\xi = T(x)}$$

$$\xi = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{bmatrix} = T(x) = \begin{bmatrix} z \\ v_z \\ \dfrac{1}{m}\left(-\dfrac{1}{2}\,\phi^2\,\mathcal{R}'_{\text{gap}}(z) - k_{\text{s}}\,(z - z_{\text{s}}) - c\,v_z\right) \end{bmatrix}$$

Feedback control – Controller design

Step 2 – Trajectory tracking controller design

Goal: $z(t) \to r(t)$ (Reference position)

$$\xi(t) \to \xi_{\mathrm{r}}(t) = \begin{array}{c|l} \left[\begin{array}{c} r(t) \\ \dot{r}(t) \\ \ddot{r}(t) \end{array}\right] & \begin{array}{l} \text{Position} \\ \text{Velocity} \\ \text{Acceleration} \end{array} \end{array}$$

Error: $\tilde{\xi}(t) = \xi_{\mathrm{r}}(t) - \xi(t)$

Error dynamics: $\dot{\tilde{\xi}} = A\tilde{\xi} - B\left(v - \frac{\mathrm{d}^3 r}{\mathrm{d}t^3}\right)$

Control law: $v = K\tilde{\xi} + \frac{\mathrm{d}^3 r}{\mathrm{d}t^3}$ ➡ $\dot{\tilde{\xi}} = \underbrace{(A - BK)}\tilde{\xi}$

Hurwitz → Exponential tracking

Complete control law:

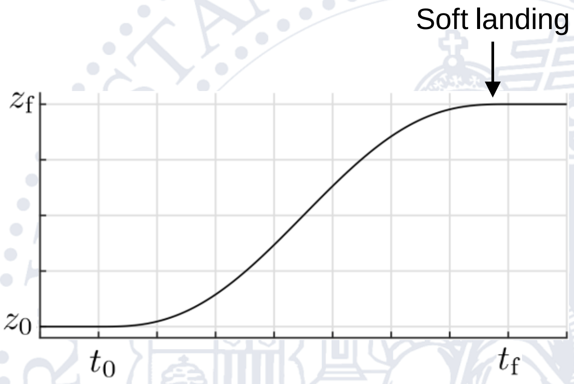
$$\boxed{u = \alpha(x) + \beta(x)\left(K\left(\xi_{\mathrm{r}} - T(x)\right) + \frac{\mathrm{d}^3 r}{\mathrm{d}t^3}\right)}$$

Step 3 – Path planning

Goal: Soft landing ➡ Polynomial trajectory: $r(t) = \begin{cases} z_0 & \text{if} \quad 0 \le t < t_0, \\ s(t) & \text{if} \quad t_0 \le t \le t_{\mathrm{f}}, \\ z_{\mathrm{f}} & \text{if} \quad t > t_{\mathrm{f}}, \end{cases}$

$$s(t_0) = z_0, \quad s(t_{\mathrm{f}}) = z_{\mathrm{f}}, \quad \dot{s}(t_0) = \dot{s}(t_{\mathrm{f}}) = \ddot{s}(t_0) = \ddot{s}(t_{\mathrm{f}}) = 0$$

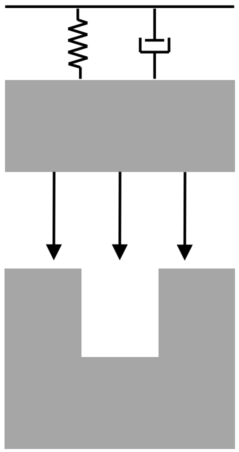
Initial/final position   Initial/final velocity and acceleration

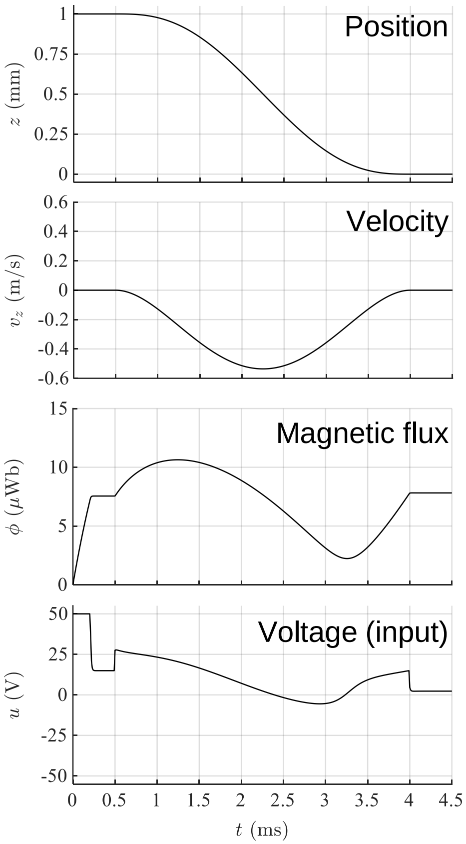


Feedback control – Simulation results

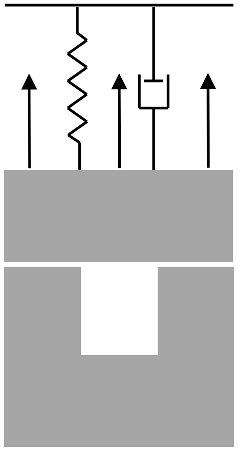
Perfect tracking
(continuous time)

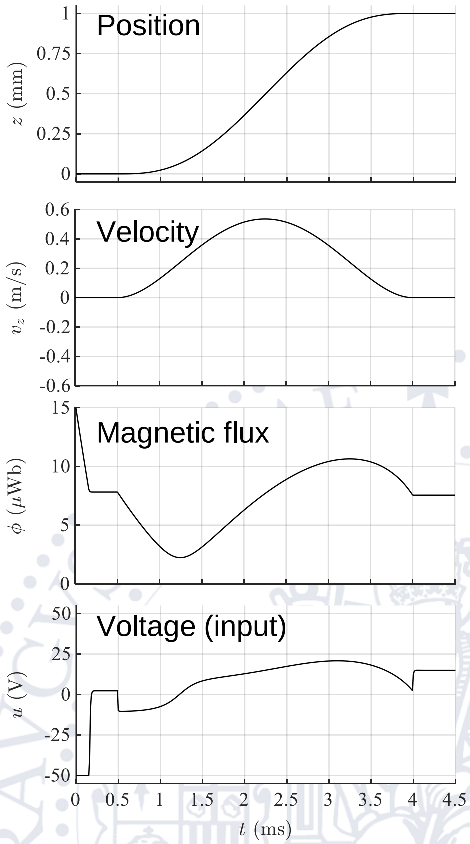
Closing operation





Opening operation





Open-loop control

Feedback control → Good performance but… it needs feedback

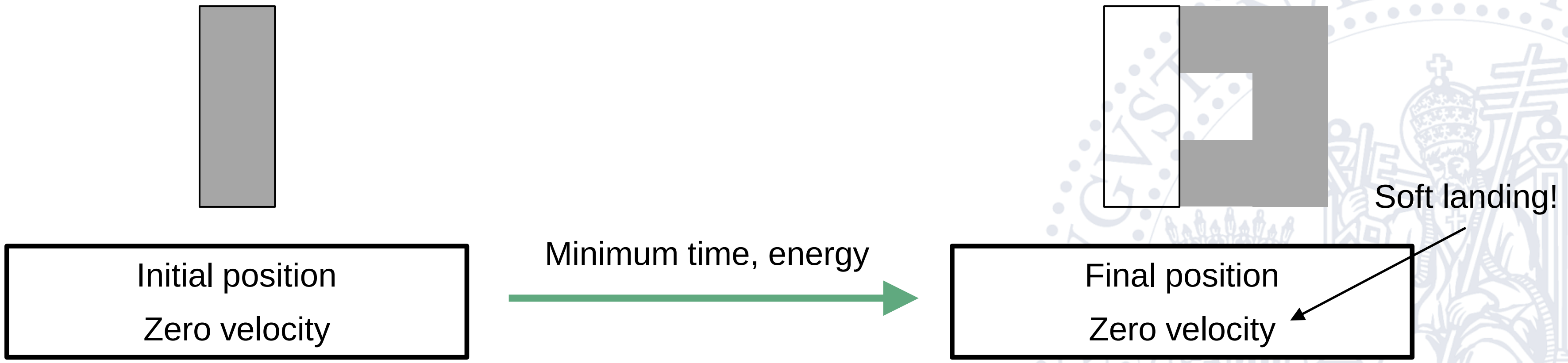
Switch-type actuators → No position measurements (accessibility, cost)

Practical, low-cost alternative?

↓

Optimal design of open-loop policies

Optimal control → Find the input (voltage) profiles that results in…



Initial position
Zero velocity

Minimum time, energy

Final position
Zero velocity

Soft landing!

Open-loop control – Optimal policy design

1) Problem formulation

Dynamic optimization problem

$$\min_{u(t)}.\ J = \int_{t_0}^{t_f} V\left(\mathbf{x}(t), u(t)\right) \mathrm{d}t$$

$$\begin{aligned} \text{s.t.}\quad & \dot{\mathbf{x}}(t) = \mathbf{f}\left(\mathbf{x}(t), u(t)\right) \\ & \alpha \leq u(t) \leq \beta \\ & \phi(t) \geq 0 \\ & \mathbf{x}(t_0) = \mathbf{x_0} = \begin{bmatrix} z_0 & 0 & \phi_0 \end{bmatrix}^\mathrm{T} \\ & \mathbf{x}(t_\mathrm{f}) = \mathbf{x_f} = \begin{bmatrix} z_\mathrm{f} & 0 & \phi_\mathrm{f} \end{bmatrix}^\mathrm{T} \\ & F_\mathrm{mag}(z_0, \phi_0) - k_\mathrm{s}(z_0 - z_\mathrm{s}) = 0 \\ & F_\mathrm{mag}(z_\mathrm{f}, \phi_\mathrm{f}) - k_\mathrm{s}(z_\mathrm{f} - z_\mathrm{s}) = 0 \end{aligned}$$

2) Solution method

Pontryagin method

Hamiltonian

$$\mathrm{H}\left(\mathbf{x}, \boldsymbol{\lambda}, u\right) = V\left(\mathbf{x}, u\right) + \boldsymbol{\lambda}^\mathrm{T} \mathbf{f}(\mathbf{x}, u),$$

Optimal input

$$u^* = \min_{u \in [\alpha, \beta]} \mathrm{H}\left(\mathbf{x}, \boldsymbol{\lambda}, u\right) \rightarrow \mathrm{H}^*\left(\mathbf{x}, \boldsymbol{\lambda}\right) = \mathrm{H}\left(\mathbf{x}, \boldsymbol{\lambda}, u^*\right)$$

Optimal trajectory

$$\begin{cases} \dot{\mathbf{x}}(t) = +\dfrac{\partial \mathrm{H}^*}{\partial \boldsymbol{\lambda}^*} \\ \dot{\boldsymbol{\lambda}}(t) = -\dfrac{\partial \mathrm{H}^*}{\partial \mathbf{x}} \end{cases}$$

$$\mathbf{x}(t_0) = \mathbf{x_0} = \begin{bmatrix} z_0 & 0 & \phi_0 \end{bmatrix}^\mathrm{T}$$

$$\mathbf{x}(t_\mathrm{f}) = \mathbf{x_f} = \begin{bmatrix} z_\mathrm{f} & 0 & \phi_\mathrm{f} \end{bmatrix}^\mathrm{T}$$

3) Numerical solutions

a) Time-optimal solution

$$V\left(\mathbf{x}, u\right) = 1$$

- Fastest possible movement

b) Energy-optimal solutions

$$V\left(\mathbf{x}, u\right) = u^2$$

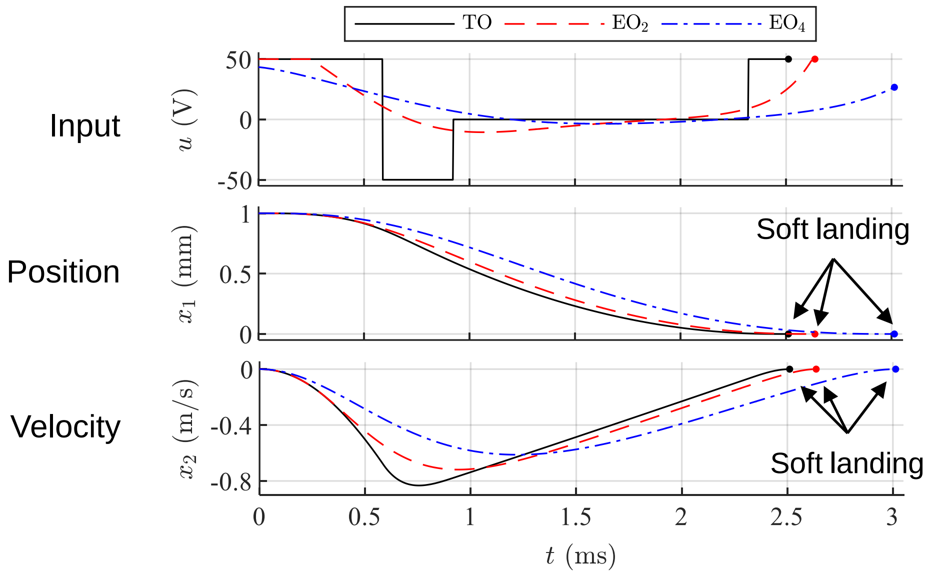
- Larger duration, but less energy consumption

Open-loop control – Simulation results

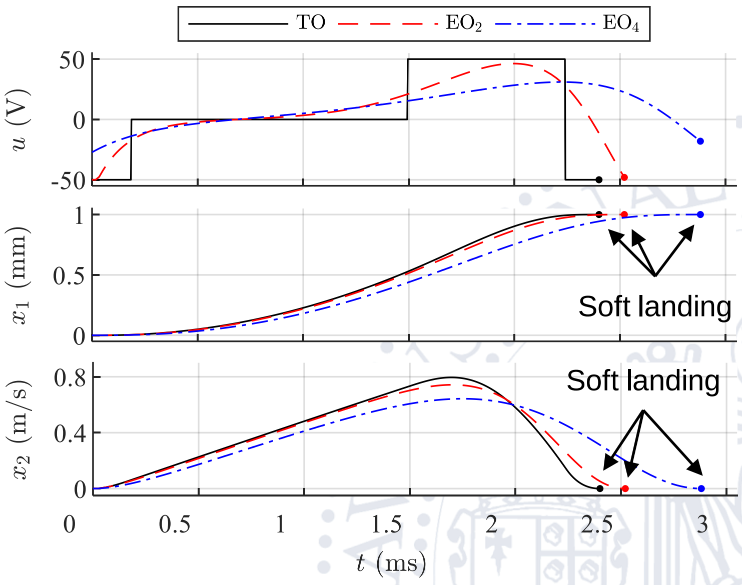
Nominal system

Results corresponding to the time-optimal solution and two energy-optimal policies

From z_{max} to z_{min}



From z_{min} to z_{max}



Open-loop control – Simulation results

Perturbed system

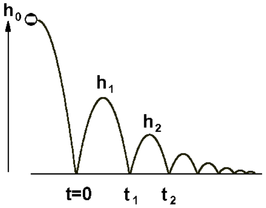
Monte Carlo analysis

Nominal parameter set $\mathbf{p}$ $\longrightarrow$ $\mathbf{p}_{\mathbf{pert}} \sim N\left(\mathbf{p}, \Sigma^2\right), \quad \Sigma = \mathrm{diag}\left(0.01\mathbf{p}\right)$

For any given simulation:

Equivalent impact velocity $\longrightarrow$

$$v_{\mathrm{eq}} = +\sqrt{\frac{m_{\mathrm{pert}}}{m}\sum_i \left(v_z(t_i)\right)^2}$$



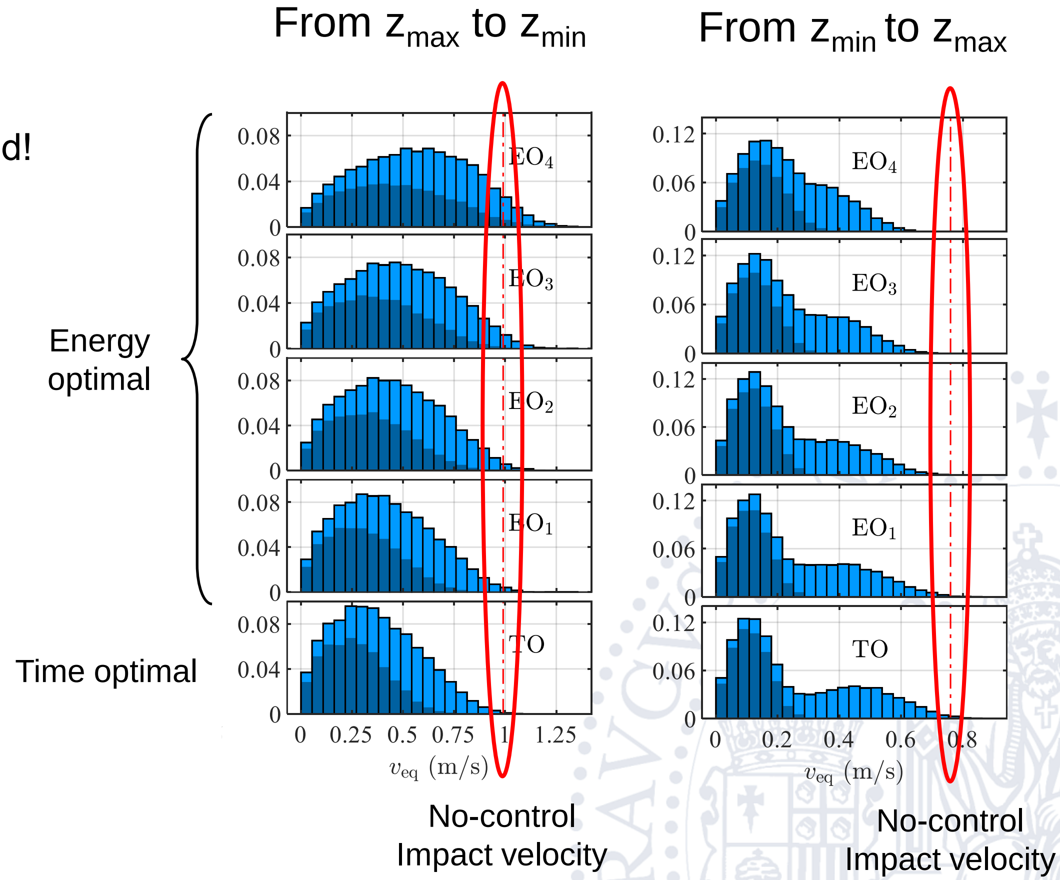
Takes into account the bouncing phenomenon (if there are bounces)

Open-loop control – Simulation results

Analysis of impact velocities

Soft-landing is not always achieved…

…but impact velocities are greatly reduced!



Contributions

- Stability, controllability and observability analysis – Explanation of switching behavior
- Application of feedback linearization to reluctance actuators
- Robustness analysis of optimal soft-landing open-loop policies

Publications

E. Ramirez-Laboreo, E. Moya-Lasheras and C. Sagues, “Optimal Open-Loop Control Policies for a Class of Nonlinear Actuators”, in *2019 European Control Conference (ECC)*, Napoli, Italia, Jun. 2019.

E. Moya-Lasheras, **E. Ramirez-Laboreo** and C. Sagues, “Probability-Based Control Design for Soft Landing of Short-Stroke Actuators”, *IEEE Transactions on Control Systems Technology*, in press, 2019.

5. Estimation

- Electromagnetic estimation
- Position estimation

Electromagnetic estimation

Estimation of electromagnetic variables on reluctance actuators

Voltage and current can be easily measured

Magnetic flux / Flux linkage $\lambda = N\phi$

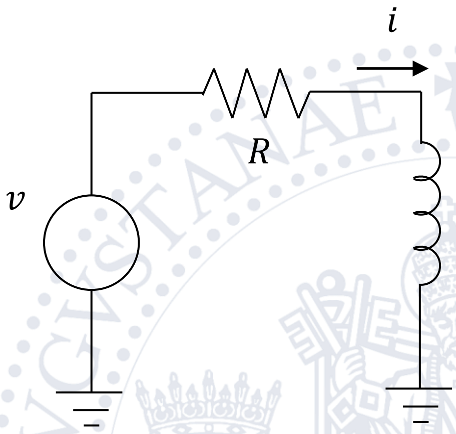
- Parameter estimation / System identification
- Force prediction

$$F_\mathrm{m} = -\frac{1}{2}\,\phi^2\,\frac{\partial \mathcal{R}_\mathrm{gap}}{\partial l_\mathrm{gap}}$$

$$\boxed{v = R\,i + N\,\frac{\mathrm{d}\phi}{\mathrm{d}t}}$$

Coil resistance R

- Great variations with temperature → Temperature sensor
- Fault detection



Inductance/Reluctance $L = N^2/\mathcal{R}$

- Depends on the armature position → Position estimation

$$\mathcal{R} = \int \frac{\mathrm{d}l}{\mu\,A}$$

Electromagnetic estimation – SEMERA Algorithm

Stochastic Electromagnetic Estimation for Reluctance Actuators

Based on Kalman filtering theory

Observation model

Based on the electrical equation of an inductor

$$v(t) = R(t)\, i(t) + \frac{\mathrm{d}\lambda(t)}{\mathrm{d}t}$$

$$\bar{y}_k = H_k\, x_k + v_k$$

Observation $\bar{y}_k = \bar{v}_k,$

Obs. matrix $H_k = \left[\begin{array}{ccc} \bar{i}_k & \bar{i}_k/\Delta & -\bar{i}_{k-1}/\Delta \end{array}\right],$

State $x_k = \left[\begin{array}{ccc} R_k & L_k & L_{k-1} \end{array}\right]^{\mathsf{T}},$

Obs. noise $v_k = \tilde{v}_k - \tilde{i}_k\,(R_k + L_k/\Delta) + \tilde{i}_{k-1}\, L_{k-1}/\Delta.$

Process model

- Constant resistance
- Constant variation of L

$$\hat{R}_{k+1/k} = \hat{R}_{k/k}$$
$$\hat{L}_{k+1/k} = \hat{L}_{k/k} + \left(\hat{L}_{k/k} - \hat{L}_{k-1/k}\right)$$

$$x_{k+1} = F\, x_k + G\, w_k$$

$$F = \left[\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 2 & -1 \\ 0 & 1 & 0 \end{array}\right] \qquad G w_k = \left[\begin{array}{c} \dot{R}_k\, \Delta \\ \ddot{L}_k\, \Delta^2 \\ 0 \end{array}\right]$$

Electromagnetic estimation – SEMERA Algorithm

In addition…

Observability analysis

- Explains the selection of state variables
- Not observable for constant variation of i ($i_{k+j} = i_k + jd \quad j \in \mathbb{N} \quad d \in \mathbb{R}$)

Convergence analysis

- Excitation conditions $0 < \beta_1 I \leq W_{O[k,\,k+n]} \leq \beta_2 I$

Expert rule

- The observation matrix depends on current measurements $H_k = [\ \bar{i}_k \quad \bar{i}_k/\Delta \quad -\bar{i}_{k-1}/\Delta\ ]$
- When $\bar{i}_k$ is close to zero, the signal-to-noise ratio is very poor…

…but we know that the actuator returns to the original position → $\hat{L}_k = \mu_{L_0}$

Electromagnetic estimation – Integral observer

Computationally-inexpensive observer

Electric equation

$$v(t) = R(t)\,i(t) + \frac{\mathrm{d}\lambda(t)}{\mathrm{d}t}$$

Electric equation (integral form)

$$\lambda(t) = \lambda(t_0) + \int_{t_0}^{t} \big(v(\tau) - R(\tau)\,i(\tau)\big)\,\mathrm{d}\tau$$

Discretization

$$\lambda_k = \lambda_0 + \Delta \sum_{j=1}^{k} \left(v_j - R_j\,i_j\right)$$

Approximation

Measurements

$$\hat{\lambda}_k = \lambda_0 + \Delta \left(\sum_{j=1}^{k} \bar{v}_j - \hat{R} \sum_{j=1}^{k} \bar{i}_j \right)$$

Estimated resistance

How to update the value of $\hat{R}$? → Switch-type actuators operate periodically

$$\hat{\lambda}_n = \hat{\lambda}_{n+m} \quad \Rightarrow \quad \hat{R} = \sum_{j=n+1}^{n+m} \bar{v}_j \left(\sum_{j=n+1}^{n+m} \bar{i}_j \right)^{-1}$$

At the reset events, $\hat{R}$ is recalculated and the integrals are reset

Electromagnetic estimation – Results

Simulation

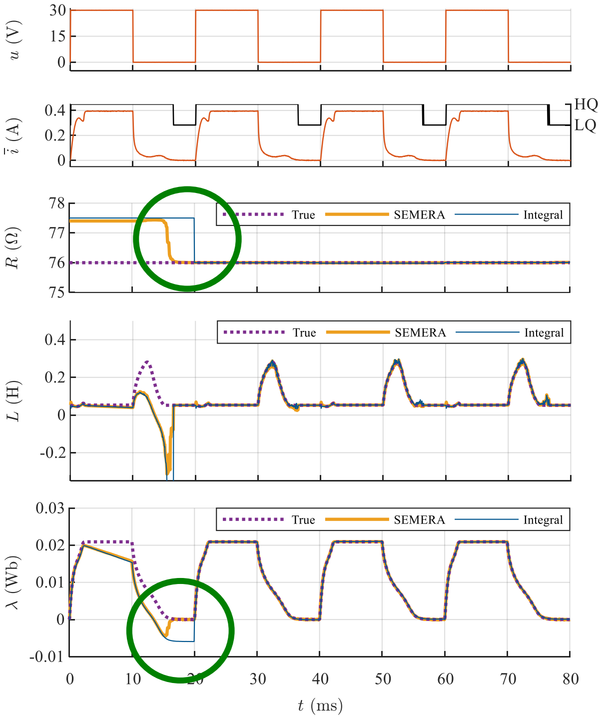
Voltage

Current

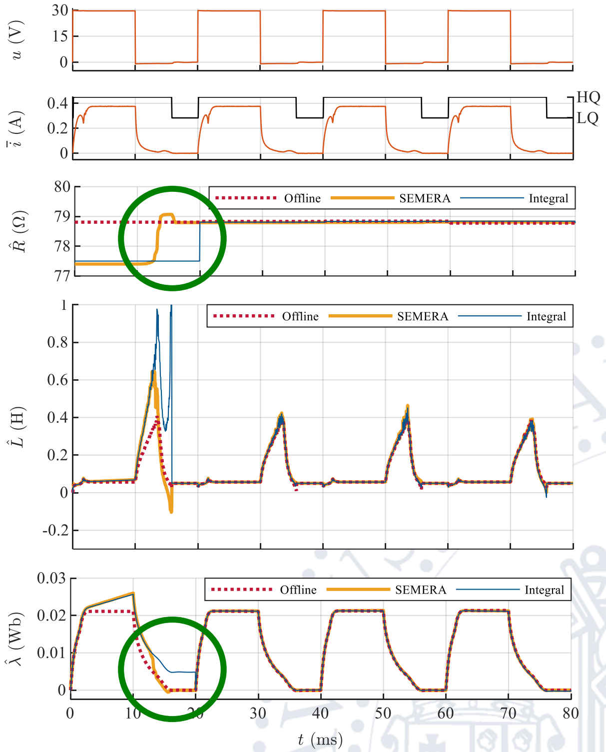
Resistance

Inductance

Magnetic flux



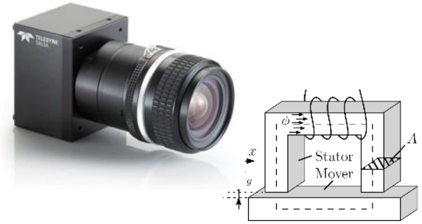
Experiments



The SEMERA algorithm converges faster

Position estimation

Position measurements in switch-type actuators are not viable (cost, accessibility, processing)



How to perform feedback control? → Position estimation

In the literature:

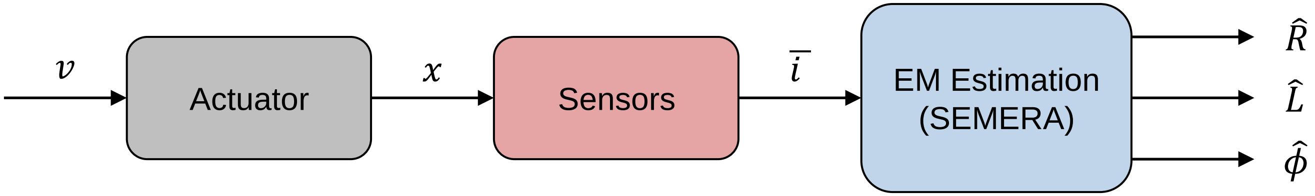
- Inductance method (Inductance estimation + Inductance-position model)
- Sliding-mode observers (Models without hysteresis)

In this thesis:

- Evaluate the inductance-based estimation method
- Analyze the effects of magnetic hysteresis
- Compare different estimation approaches

Position estimation – Estimation approaches

Current situation:



Actuator

Sensors

EM Estimation (SEMERA)

Actuator model (no hyst.)

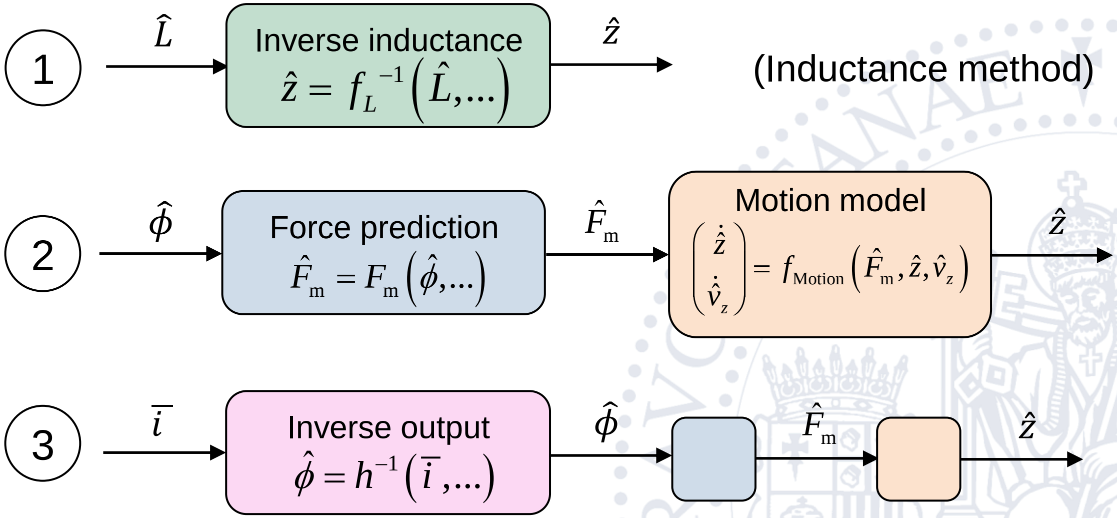
$$L = f_L\left(z,\ldots\right)$$

$$F_\mathrm{m} = F_\mathrm{m}\left(\phi,\ldots\right)$$

$$\begin{pmatrix} \dot{z} \\ \dot{v}_z \end{pmatrix} = f_\mathrm{Motion}\left(F_\mathrm{m}, z, v_z\right)$$

$$i = h\left(\phi,\ldots\right)$$

Estimation approaches:



Inverse inductance $\hat{z} = f_L^{-1}\left(\hat{L},\ldots\right)$

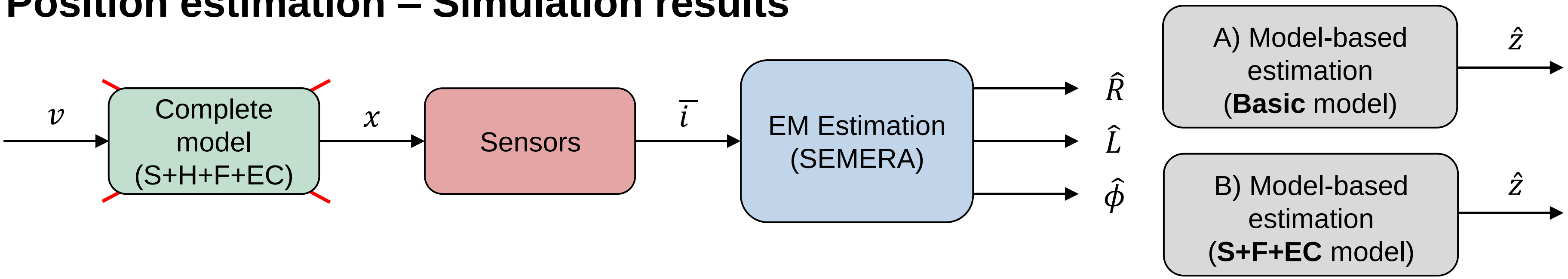
(Inductance method)

Force prediction $\hat{F}_\mathrm{m} = F_\mathrm{m}\left(\hat{\phi},\ldots\right)$

Motion model $\begin{pmatrix} \dot{\hat{z}} \\ \dot{\hat{v}}_z \end{pmatrix} = f_\mathrm{Motion}\left(\hat{F}_\mathrm{m}, \hat{z}, \hat{v}_z\right)$

Inverse output $\hat{\phi} = h^{-1}\left(\bar{i},\ldots\right)$

Position estimation – Simulation results



v

Complete model (S+H+F+EC)

x

Sensors

$\bar{i}$

EM Estimation (SEMERA)

$\hat{R}$

$\hat{L}$

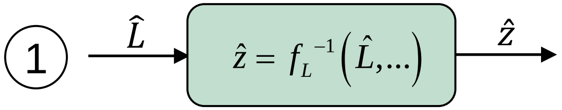
$\hat{\phi}$

A) Model-based estimation (**Basic** model)

$\hat{z}$

B) Model-based estimation (**S+F+EC** model)

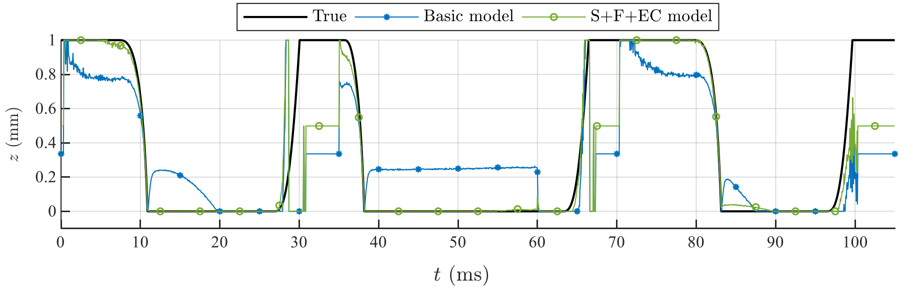
$\hat{z}$



① $\hat{L}$

$$\hat{z} = f_L^{-1}\left(\hat{L},\ldots\right)$$

$\hat{z}$



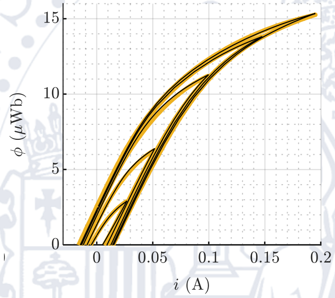
Basic model RMSE: 0.322 mm

S+F+EC model RMSE: 0.234 mm

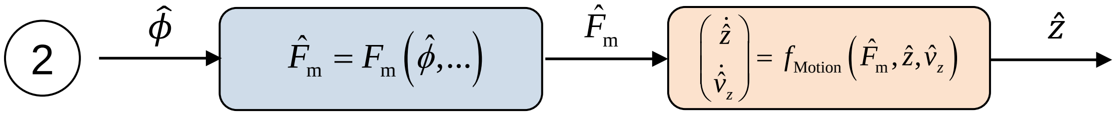
- Estimations are not consistent

→ Hysteresis leads to infinite values of the apparent inductance

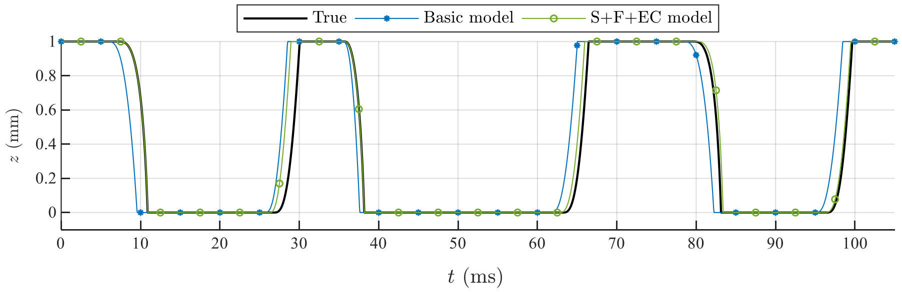
$$L = \frac{N\phi}{i}$$



Position estimation – Simulation results

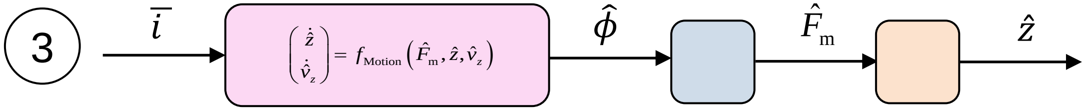


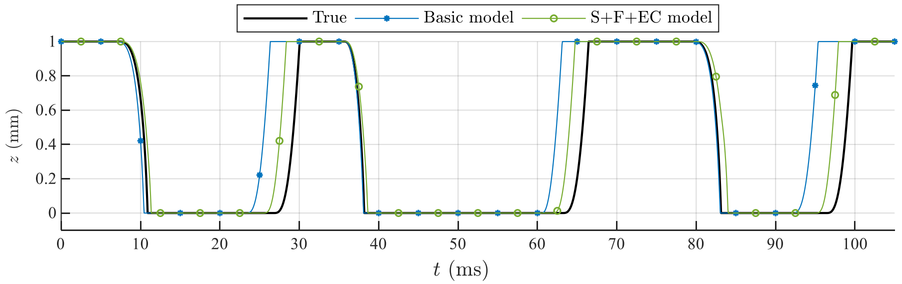
BEST POLICY



Basic model RMSE: 0.190 mm
S+F+EC model RMSE: 0.078 mm

- Estimations are consistent
- Precision is not high enough for control





Basic model RMSE: 0.297 mm
S+F+EC model RMSE: 0.177 mm

- Estimations are consistent
- Results are worse than using ②

Contributions

- Real-time estimation of resistance, inductance and flux → No need of additional sensors
- Influence of hysteresis on position estimation algorithms → Do not use inductance-based methods

Publications / Patents

E. Moya-Lasheras, C. Sagues, **E. Ramirez-Laboreo**, and S. Llorente, “Nonlinear Bounded State Estimation for Sensorless Control of an Electromagnetic Device”, in *56th IEEE Conference on Decision and Control*, Melbourne, Australia, Dec. 2017.

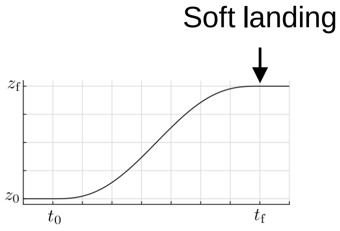
E. Ramirez-Laboreo, E. Moya-Lasheras and C. Sagues, “Real-Time Electromagnetic Estimation for Reluctance Actuators”, *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1952-1961, Mar. 2019.

S. Llorente Gil, C. Sagues Blazquiz, **E. Ramirez Laboreo**, E. Moya Lasheras, “Domestic Appliance Device”, international patent application WO 2019/106488 (A1).

6. Run-to-Run Control

- Introduction
- Controller design
- Experimental results

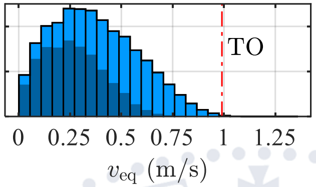
In previous chapters…



<u>Feedback control:</u> Good performance, but it needs feedback

→ Position measurements are not viable

→ Estimations are (still) not accurate enough



<u>Open-loop control:</u> Practical and cost effective solution to reduce impact velocities…

…but soft landing only in a few cases

<u>Measurement:</u> Noise measurements (and electrical contacts) contain useful information

<u>Estimation (Integral observer):</u> Estimation benefits from the repetitive operation of switch-type devices

How to <u>improve the robustness</u> of open-loop policies?

How to <u>use</u> noise (and electrical contacts) <u>measurements</u>?

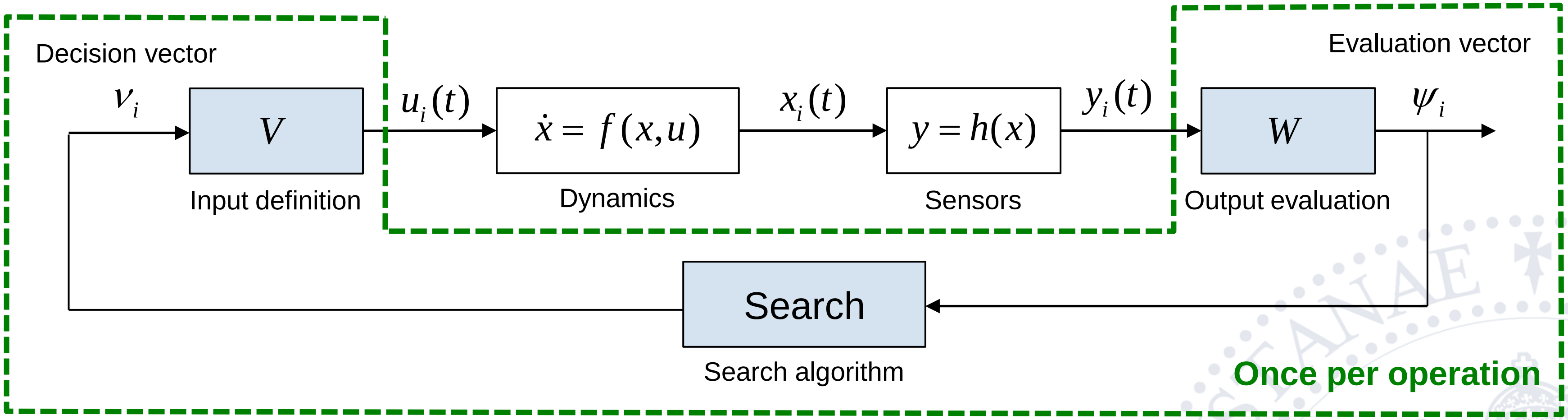
How to exploit the <u>repetitive operating mode</u> of relays and valves?

→ Run-to-Run control

What is (implicit) Run-to-Run control?

Control method for repetitive processes with offline information

Basic idea: Transform the dynamic system into a black box and use an optimization/search algorithm

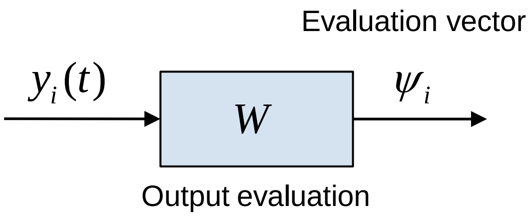


R2R control on switch-type actuators

Two alternating processes (making and breaking) → Two R2R algorithms

Controller design – Output evaluation

Evaluation of a given operation by means of a finite set of evaluation variables

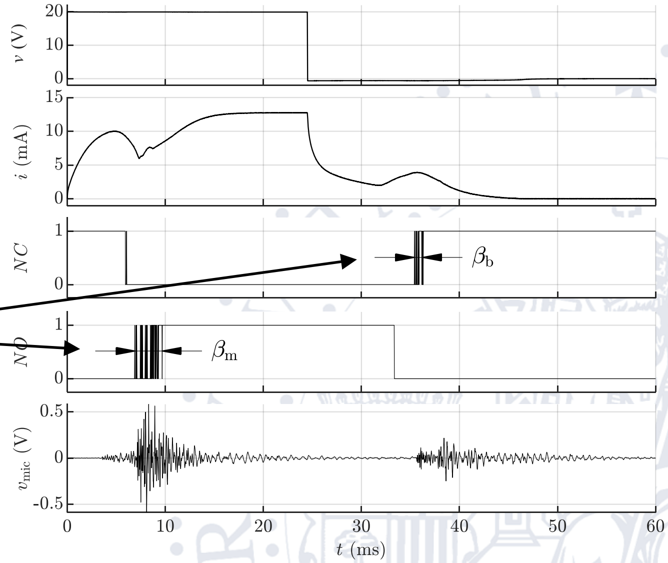


Evaluation vector

$y_i(t)$ → W → ψ_i

Output evaluation

Proposal for switch-type reluctance actuators



→ Noise level (microphone signal)

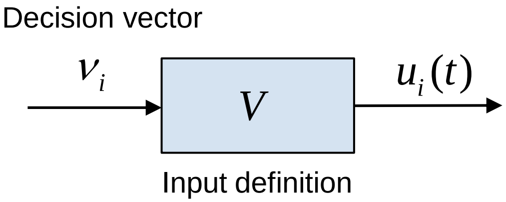
$$\rho_m = \int_{t_{0m}}^{t_{m,total}+\Delta} {v_{mic}}^2 \, dt, \qquad \rho_b = \int_{t_{0b}}^{t_{b,total}+\Delta} {v_{mic}}^2 \, dt,$$

→ Bounce duration (electrical contacts, only in relays)

$$\psi_m = [\ \rho_m \quad \beta_m\ ]^T \qquad \psi_b = [\ \rho_b \quad \beta_b\ ]^T$$

Controller design – Input definition

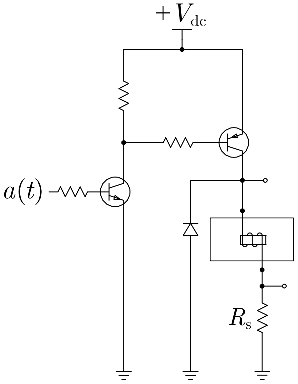
Definition of the input profile in terms of a finite set of decision variables

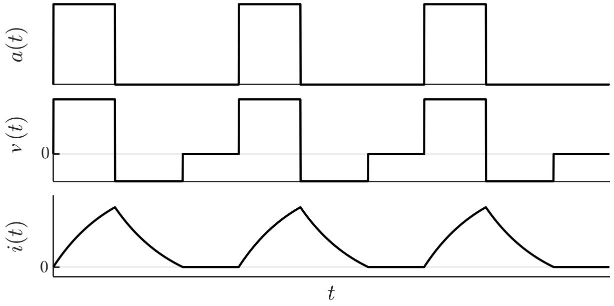

Decision vector

ν_i → V → $u_i(t)$

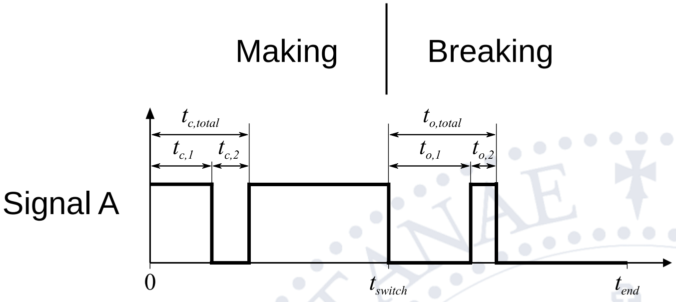
Input definition

Proposal for switch-type reluctance actuators

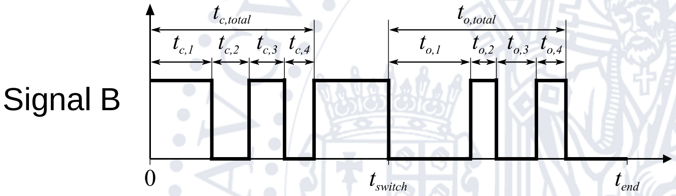




Same profiles than the time-optimal policy!



$\nu_{\mathrm{m}} = \left[\begin{array}{cc} \tau_{\mathrm{m}1} & \tau_{\mathrm{m}2} \end{array}\right]^{\mathsf{T}}$ $\nu_{\mathrm{b}} = \left[\begin{array}{cc} \tau_{\mathrm{b}1} & \tau_{\mathrm{b}2} \end{array}\right]^{\mathsf{T}}$

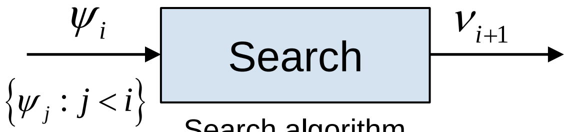


$\nu_{\mathrm{m}} = \left[\begin{array}{cccc} \tau_{\mathrm{m}1} & \tau_{\mathrm{m}2} & \tau_{\mathrm{m}3} & \tau_{\mathrm{m}4} \end{array}\right]^{\mathsf{T}},$ $\nu_{\mathrm{b}} = \left[\begin{array}{cccc} \tau_{\mathrm{b}1} & \tau_{\mathrm{b}2} & \tau_{\mathrm{b}3} & \tau_{\mathrm{b}4} \end{array}\right]^{\mathsf{T}}$

Controller design – Search algorithm

Looks for the new decision variables using the evaluation variables

Similar to an optimization algorithm, but it runs endlessly



Search algorithm

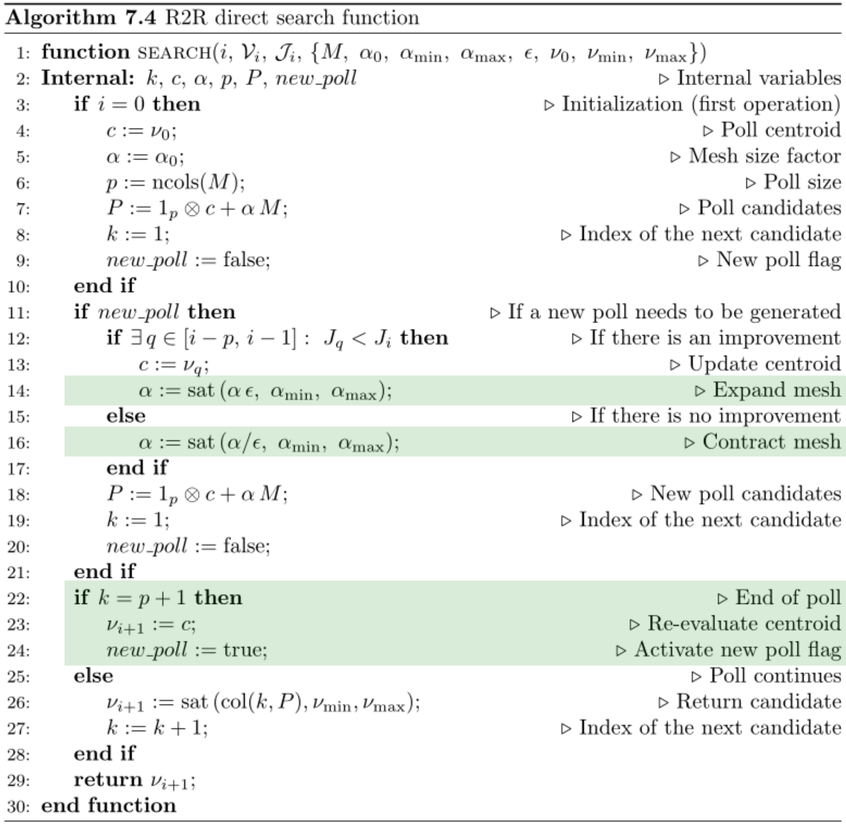
Cost function is nonconvex, non-smooth, and stochastic

→ Avoid gradient-based algorithms

Proposal: Pattern search R2R algorithm

Modifications for R2R control:

- Reevaluation of pattern centroid
- Saturation of the mesh size

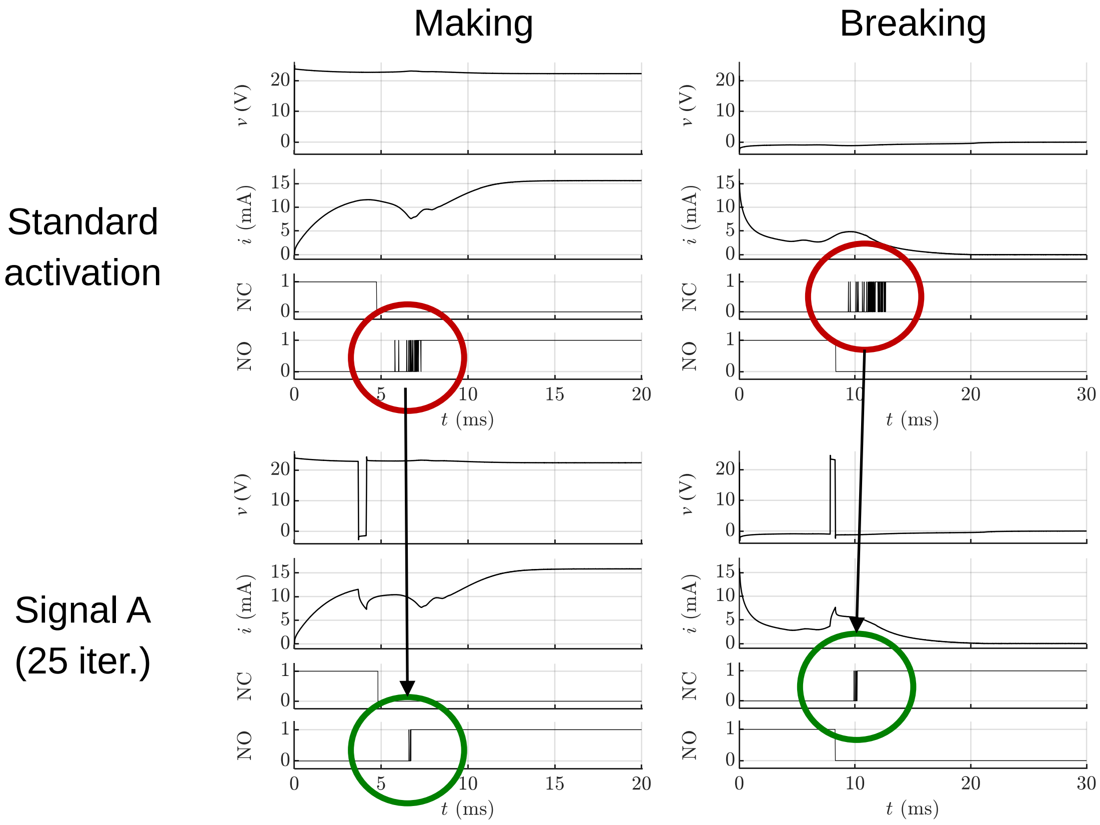


Algorithm 7.4 R2R direct search function

```
function SEARCH($i$, $\mathcal{V}_i$, $\mathcal{J}_i$, $\{M,\ \alpha_0,\ \alpha_{\min},\ \alpha_{\max},\ \epsilon,\ \nu_0,\ \nu_{\min},\ \nu_{\max}\}$)
Internal: $k$, $c$, $\alpha$, $p$, $P$, $new\_poll$                    ▷ Internal variables
    if $i = 0$ then                                                ▷ Initialization (first operation)
        $c := \nu_0$;                                              ▷ Poll centroid
        $\alpha := \alpha_0$;                                      ▷ Mesh size factor
        $p :=$ ncols($M$);                                         ▷ Poll size
        $P := 1_p \otimes c + \alpha M$;                           ▷ Poll candidates
        $k := 1$;                                                  ▷ Index of the next candidate
        $new\_poll :=$ false;                                      ▷ New poll flag
    end if
    if $new\_poll$ then                                            ▷ If a new poll needs to be generated
        if $\exists q \in [i-p,\ i-1] :\ J_q < J_i$ then           ▷ If there is an improvement
            $c := \nu_q$;                                          ▷ Update centroid
            $\alpha :=$ sat $(\alpha\,\epsilon,\ \alpha_{\min},\ \alpha_{\max})$;   ▷ Expand mesh
        else                                                       ▷ If there is no improvement
            $\alpha :=$ sat $(\alpha/\epsilon,\ \alpha_{\min},\ \alpha_{\max})$;    ▷ Contract mesh
        end if
        $P := 1_p \otimes c + \alpha M$;                           ▷ New poll candidates
        $k := 1$;                                                  ▷ Index of the next candidate
        $new\_poll :=$ false;
    end if
    if $k = p + 1$ then                                            ▷ End of poll
        $\nu_{i+1} := c$;                                          ▷ Re-evaluate centroid
        $new\_poll :=$ true;                                       ▷ Activate new poll flag
    else                                                           ▷ Poll continues
        $\nu_{i+1} :=$ sat $(\mathrm{col}(k, P), \nu_{\min}, \nu_{\max})$;   ▷ Return candidate
        $k := k + 1$;                                              ▷ Index of the next candidate
    end if
    return $\nu_{i+1}$;
end function
```

Experimental results

Bounce reduction in electromechanical relay → The R2R algorithm minimizes the bounce duration



	Configuration 1	
	Making	**Breaking**
	β_m (ms)	β_b (ms)
Square signal	1.791	3.228
Type A signal*	0.144	0.324
Reduction	*91.96%*	*89.97%*

Contact bounce is greatly reduced

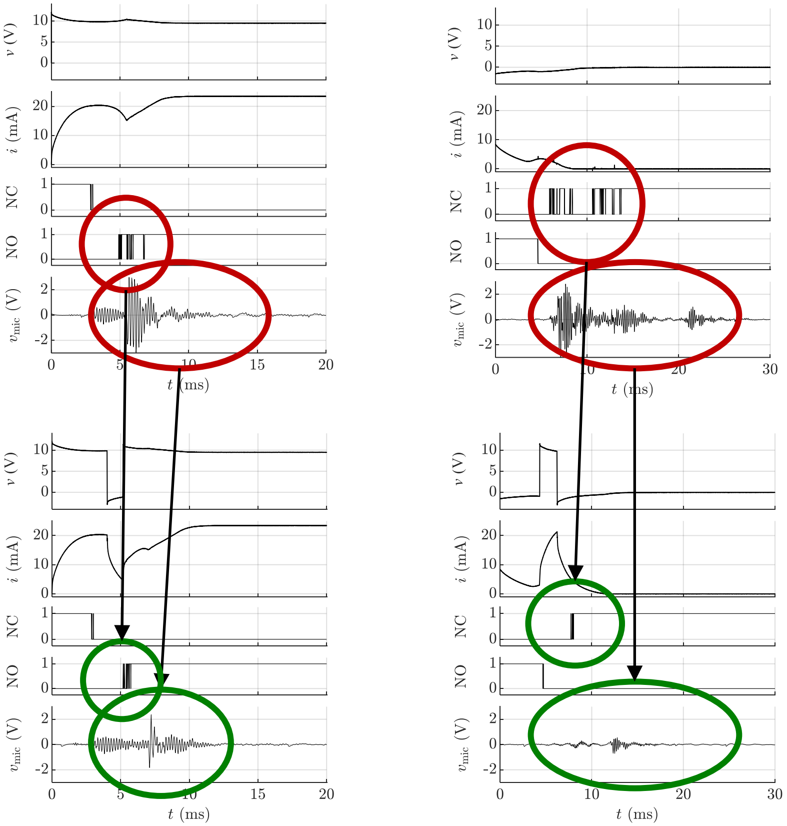
Experimental results

Noise reduction in electromechanical relay → The R2R algorithm minimizes

$$\begin{cases} \rho_{\mathrm{b}} = \displaystyle\int_{t_{0\mathrm{b}}}^{t_{\mathrm{b,total}}+\Delta} {v_{\mathrm{mic}}}^2 \, \mathrm{d}t, \\ \rho_{\mathrm{m}} = \displaystyle\int_{t_{0\mathrm{m}}}^{t_{\mathrm{m,total}}+\Delta} {v_{\mathrm{mic}}}^2 \, \mathrm{d}t, \end{cases}$$

Standard activation

Signal A (25 iter.)



The R2R algorithm reduces the noise…

…but also contact bounce!

→ Application to solenoid valves (No electrical contacts available)

Contributions

- Adaptation of Run-to-Run control to switch-type reluctance actuators
- Practical advice on inputs, outputs and search algorithm
- State-of-the-art bounce-reduction algorithm for electromechanical relays

Publications / Patents

E. Ramirez-Laboreo, C. Sagues and S. Llorente, “A New Run-to-Run Approach for Reducing Contact Bounce in Electromagnetic Switches”, *IEEE Transactions on Industrial Electronics*, vol. 64, no. 1, pp. 535-543, Jan. 2017.

E. Moya-Lasheras, **E. Ramirez-Laboreo** and C. Sagues, “A novel algorithm based on Bayesian optimization for run-to-run control of short-stroke reluctance actuators”, in *2019 European Control Conference (ECC)*, Napoli, Italia, Jun. 2019.

D. Anton Falcon, S. Llorente Gil, D. Puyal Puente, **E. Ramirez Laboreo** and C. Sagues, “A home appliance device and a method for operating a home appliance device”, international patent application WO 2017/163114 (A1).

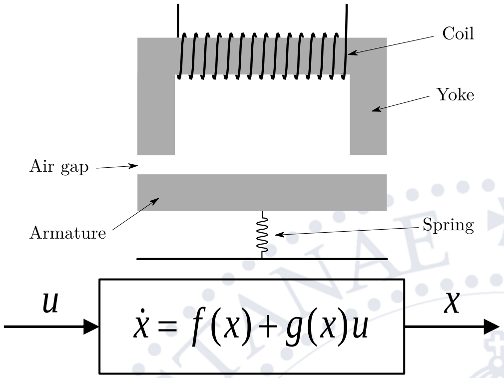
Conclusions

Conclusions

Focus on modeling and control of switch-type devices…

…but most of the findings are valid for any reluctance actuator

Dynamical modeling



$$\dot{x} = f(x) + g(x)u$$

Electromagnetic modeling approaches

- MEC → Fast transient simulations
- FEM → Useful for some particular aspects

Limited range of motion → Hybrid dynamics

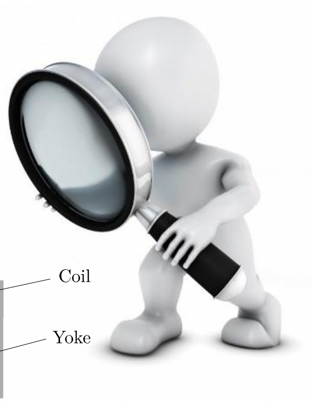
Electromagnetic phenomena → Tradeoff Precision - Computational requirements

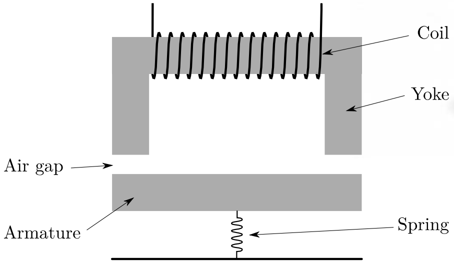
- Complete model → Fast offline simulations (analysis, control/estimation design/validation)
- S+F+EC model → Fast online calculations (still not valid for position estimation)

Measurement

Position measurements

- Switch type devices are usually encapsulated
  - → Measurements are impractical
- Restrictive specifications (Fast and accurate)
  - → Measurements are expensive
- Lack of flexibility

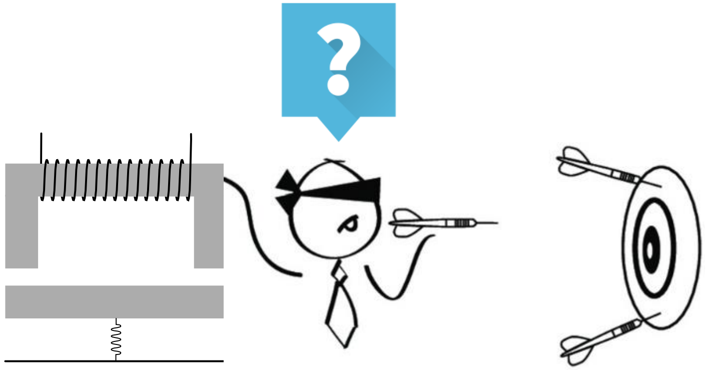




Alternative measurements (Noise and electrical contacts)

- Easily obtainable
- Simple but powerful information

Estimation



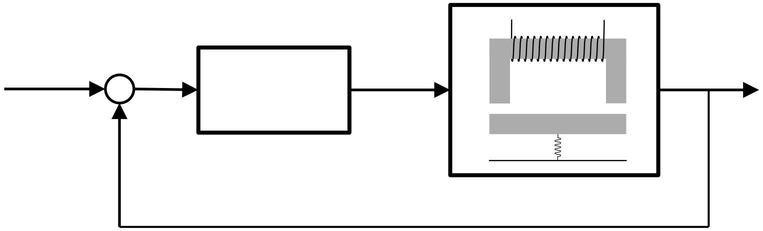
Electromagnetic estimation

- Algorithms using only voltage and current measurements
  - → No need for additional sensors
- Magnetic flux → Identification, Force prediction
- Resistance and inductance → Further uses

Position estimation

- Inductance method should not be used if hysteresis is present
- Best policy: Flux estimation + Force prediction + Motion model
- However… Still not accurate enough for position control

Control



Control properties

- Stability → Switching conditions
- Observable and controllable

Classical control

- Feedback linearization → Almost perfect tracking, but requires feedback
- Open-loop optimal control → Practical low-cost alternative

Run-to-Run control

- Benefits from the repetitive operating mode of switch-type actuators
- Easy implementation and good results
- Further improvements

International high-impact journals

[1] **E. Ramirez-Laboreo**, C. Sagues and S. Llorente, “A New Model of Electromechanical Relays for Predicting the Motion and Electromagnetic Dynamics”, *IEEE Transactions on Industry Applications*, vol. 52, no. 3, pp. 2545-2553, May/Jun. 2016.

[2] **E. Ramirez-Laboreo**, C. Sagues and S. Llorente, “A New Run-to-Run Approach for Reducing Contact Bounce in Electromagnetic Switches”, *IEEE Transactions on Industrial Electronics*, vol. 64, no. 1, pp. 535-543, Jan. 2017.

[3] **E. Ramirez-Laboreo**, E. Moya-Lasheras and C. Sagues, “Reluctance actuator characterization via FEM simulations and experimental tests”, *Mechatronics*, vol. 56, pp. 58-66, Dec. 2018.

[4] **E. Ramirez-Laboreo**, E. Moya-Lasheras and C. Sagues, “Real-Time Electromagnetic Estimation for Reluctance Actuators”, *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1952-1961, Mar. 2019.

[5] **E. Ramirez-Laboreo**, M. G. L. Roes and C. Sagues, “Hybrid Dynamical Model for Reluctance Actuators Including Saturation, Hysteresis and Eddy Currents”, *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 3, pp. 1396-1406, Jun. 2019.

[6] E. Moya-Lasheras, **E. Ramirez-Laboreo** and C. Sagues, “Probability-Based Control Design for Soft Landing of Short-Stroke Actuators”, *IEEE Transactions on Control Systems Technology*, in press, 2019.

International peer-reviewed conferences

[1] **E. Ramirez-Laboreo**, C. Sagues, and S. Llorente, “A new model of electromechanical relays for predicting the motion and electromagnetic dynamics”, in *IEEE Industry Applications Society Annual Meeting*, Addison, TX, Oct. 2015, pp. 1-8.

[2] E. Moya-Lasheras, C. Sagues, **E. Ramirez-Laboreo**, and S. Llorente, “Nonlinear Bounded State Estimation for Sensorless Control of an Electromagnetic Device”, in *56th IEEE Conference on Decision and Control*, Melbourne, Australia, Dec. 2017.

[3] E. Moya-Lasheras, **E. Ramirez-Laboreo** and C. Sagues, “A novel algorithm based on Bayesian optimization for run-to-run control of short-stroke reluctance actuators”, in *2019 European Control Conference (ECC)*, Napoli, Italia, Jun. 2019.

[4] **E. Ramirez-Laboreo**, E. Moya-Lasheras and C. Sagues, “Optimal Open-Loop Control Policies for a Class of Nonlinear Actuators”, in *2019 European Control Conference (ECC)*, Napoli, Italia, Jun. 2019.

International patent applications

[1] D. Anton Falcon, S. Llorente Gil, D. Puyal Puente, **E. Ramirez Laboreo** and C. Sagues, “A home appliance device and a method for operating a home appliance device”, international patent application WO 2017/163114 (A1).

[2] S. Llorente Gil , E. Moya Lasheras, **E. Ramirez Laboreo**, C. Sagues Blazquiz, “Domestic Appliance Device”, international patent application WO 2019/106488 (A1).

Conclusions

Students supervision

[1] J. Anzola Trevijano, “Técnicas de sensorización para caracterización y control de dispositivos electromecánicos”, Bachelor’s thesis, Universidad de Zaragoza, 2015.

[2] S. Nogueras Ona, “Modelado, análisis y control de electroválvula de seguridad de encimera de gas”, Bachelor’s thesis, Universidad de Zaragoza, 2016.

[3] C. Campos Martínez, “Técnicas de optimización Run-to-Run para dispositivos electromecánicos”, Master’s thesis, Universidad de Zaragoza, 2016.

[4] A. Guillén Asensio, “Análisis del movimiento de un relé electromecánico en conmutación”, Bachelor’s thesis, Universidad de Zaragoza, 2017.

Three-month research stay

E. Ramirez-Laboreo, M. G. L. Roes and C. Sagues, “Hybrid Dynamical Model for Reluctance Actuators Including Saturation, Hysteresis and Eddy Currents”, *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 3, pp. 1396-1406, Jun. 2019.

Departamento de
Informática e Ingeniería
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PhD Thesis

Modeling and Control of Reluctance Actuators

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Zaragoza, Spain, October 18th 2019, 11:00