

# Actuation and Power Electronics

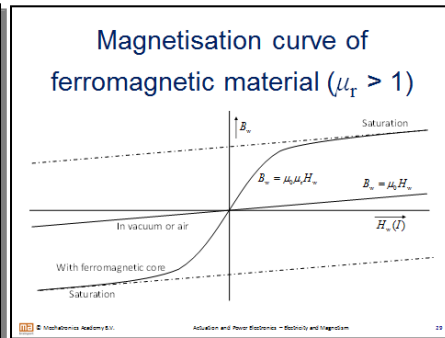
## Lorentz actuator

$F = f(B, I)$

A near perfect current to force converter, generating a force almost without introducing any mechanical coupling

I.e.:  
 - zero stiffness  
 - contactless  
 - no hysteresis

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## Balancing with two variable reluctance actuators

$F = F_2 - F_1$

$F = \frac{n^2 A \mu_0}{4} \left( \frac{I_1^2}{l_{e1}} - \frac{I_2^2}{l_{e2}} \right)$

In the mid-position:  $l_{e1} = l_{e2} = l_e$

With:  $I_1 = I_e + \Delta I$  and  $I_2 = I_e - \Delta I$  we get:

$F = \frac{n^2 A \mu_0}{4} \left( \frac{(I_e + \Delta I)^2}{l_e} - \frac{(I_e - \Delta I)^2}{l_e} \right) = \frac{n^2 A \mu_0}{4} \left( \frac{4 I_e \Delta I}{l_e} \right)$

$\frac{F}{\Delta I} = \frac{I_e n^2 A \mu_0}{l_e}$

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## Low or high output impedance of an Amplifier

- Low impedance:
  - When damping is necessary
  - Loudspeakers
  - Feedforward control (no feedback)
- High impedance
  - When the current/force has to be independent of the

Equivalent Actuator Impedance

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## PWM or switched mode power conversion

- A switch does not dissipate energy
- Switches can only create squarewave signals (on/off)
- Low pass filtering gives the average value (Fourier).
- L(C) filtering is non dissipating

$Z_1 = j\omega L$   
 $Z_2 = \frac{1}{j\omega C}$

• L can be actuator self inductance

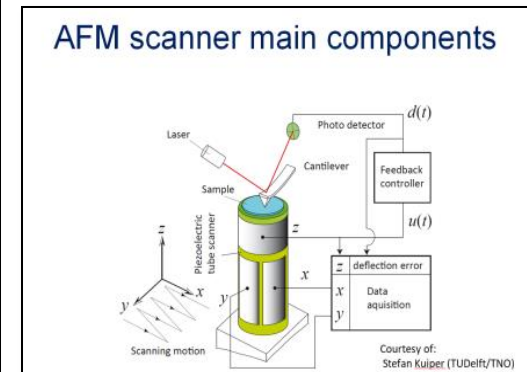
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## Geometries

- Several moving-magnet planar motor topologies have been manufactured and studied

HPPA (TU/e)      EPM (Philips)      COPAM (TU/e)

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## Piezoelectric principle

Above the Curie temperature  
 Below the Curie temperature

Ion charge displacement by deformation

Used both for actuation and sensing

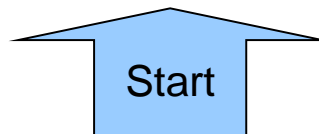
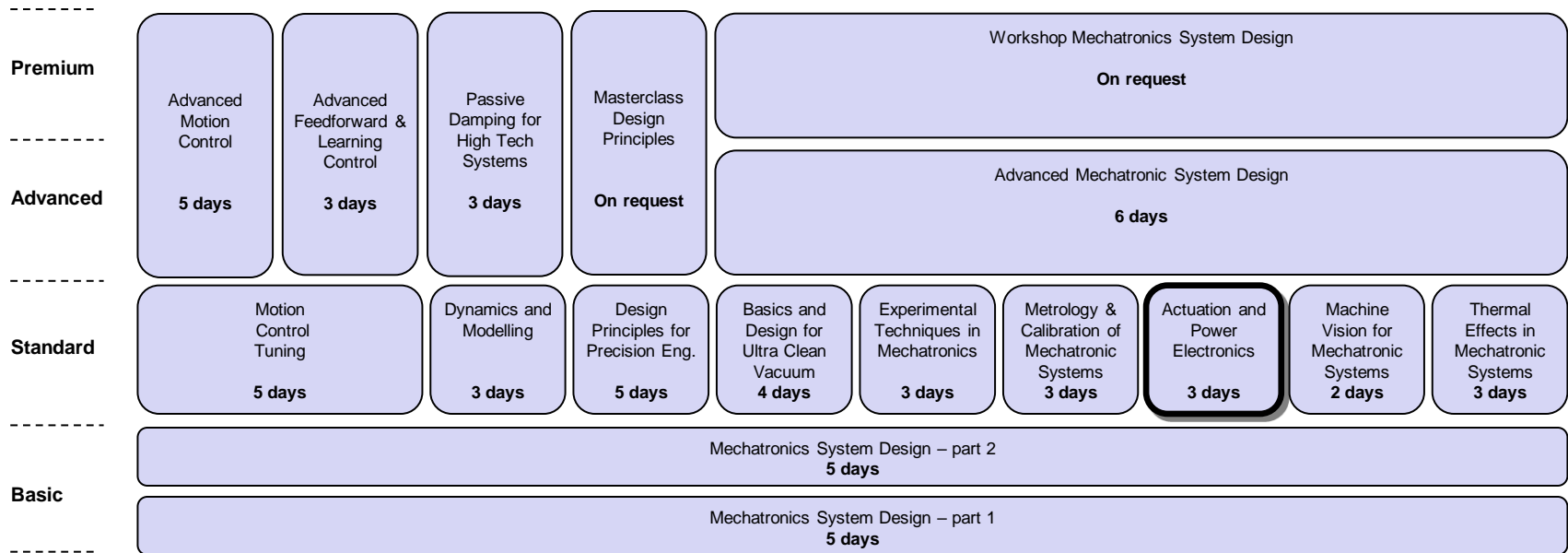
Force → Displacement → Voltage      Voltage → Displacement → Force

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# Contents

- Mechatronics Training Curriculum
- Details of Course *Actuation and Power Electronics*

# Mechatronics Training Curriculum



Relevant partner trainings:  
 Applied Optics, Electronics for non-electrical engineers, System Architecture, Soft skills for technology professionals, ...

[www.mechatronics-academy.nl](http://www.mechatronics-academy.nl)

# Mechatronics Academy

- In the past, many trainings were developed within Philips to train own staff, but the training center CTT stopped.
- **Mechatronics Academy B.V.** has been setup to provide continuity of the existing trainings and develop new trainings in the field of precision mechatronics. It is founded and run by:
  - Prof. Maarten Steinbuch
  - Prof. Jan van Eijk
  - Dr. Adrian Rankers
- We cooperate in the **High Tech Institute** consortium that provides sales, marketing and back office functions.

# Actuation and Power Electronics

# Course Director(s) / Trainers

## Teachers

- ir. Jeroen van Duivenbode (ASML & TU/e Fellow)
- Dr.ir. Bart Gysen (ProDrive & TU/e)
- Dr.ir. Coen Custers (TU/e)

## Course Director(s)

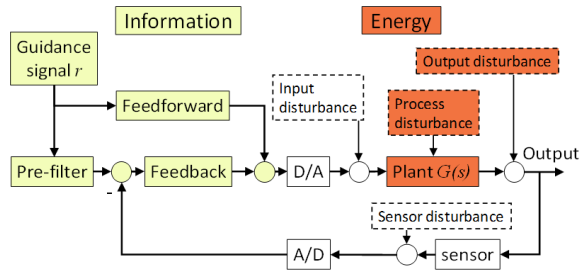
- ir. Jeroen van Duivenbode (ASML & TU/e Fellow)
- Dr.ir Adrian Rankers (Mechatronics Academy)

# Program

Day	Time	Main Theme	Presenter	Keywords
1	9.00-10.30	1.1 Introduction	Jeroen van Duivenbode	Learning goals. The role of electromechanical drives in mechatronic positioning systems. Some application examples as preview
	11.00-15.00	1.2 “Working with” Electricity and Magnetism	Jeroen van Duivenbode	Maxwell Equations and Lorentz Force. Ohm’s and Hopkinson’s law: Electric and magnetic modeling with “circuits” consisting of sources, resistances/reluctances, permanent magnets and ferromagnetic parts.
	15.30-17.00	1.3 Actuators Part 1	Bart Gysen	A little recap of METRON 1,2. Basic terms and properties of electromotors and actuators, efficiency, thermal dissipation, performance figures of merit.
2	9.00-12:30	2.1 Actuators Part 2	Bart Gysen	Flux linkage vs Lorentz law. Force vs position dependency, current density, dynamic stiffness, damping, current control. Multi DOF actuation. Electrical properties, impact of actuator self-inductance. Amplifier - actuator matching, jerk and snap. Non-linear reluctance force, linearization by balancing and feedback. Flux control, permanent magnet biasing.
	13:30-17:00	2.2 Power Electronics	Jeroen van Duivenbode	Basics of power electronics. Linear and switching power conversion. Control of switching power amplifiers. Bidirectional energy flow between mechanics and electronics. Semiconductors: Switching diodes, power transistors and Mosfets. Design issues with current amplifiers. Current noise.
3	9:00-10:30	3.1 Piezo actuators	Bart Gysen	Basics of Piezoelectricity, Electromechanical properties, Limitations and drawbacks. Amplifier requirements. Applications
	11:00-12.30	3.2 Actuators Part 3: Application examples	Bart Gysen	Electronic commutation. Amplifier-actuator interaction with different drive electronics demonstrated on real hardware. Two stroke actuation. Magnetic Bearings.
	13:30-15:00	3.3 Lab Tour EPE	Coen Custers	Advanced research on actuators and power electronics
	15:00-16:30	3.4 Planar actuators	Coen Custers	6-DOF Planar actuation and commutation. Animations of magnetic flux and force.
	16.30-17.00	Wrap-up and closure		

# Day 1 (morning)

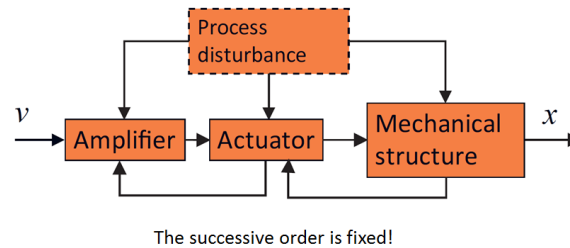
## Mechatronic Control Loop



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## The plant is the process that needs to be controlled.



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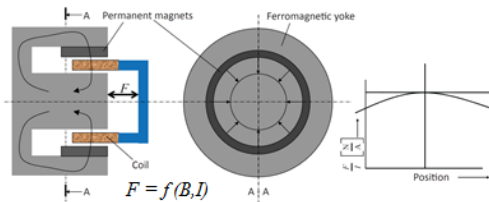
## The amplifier and actuator are one integrated system

- The performance of the actuator is determined by the amplifier:
  - Source impedance
  - Jerk limitation  $\frac{dF}{dt} \propto \frac{dI}{dT} \propto \text{Max power supply voltage}$
  - Power
- And vice-versa
  - Load impedance
  - Frequency response  $\rightarrow$  Stability

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## Lorentz actuator



A near perfect current to force converter, generating a force almost without introducing any mechanical coupling

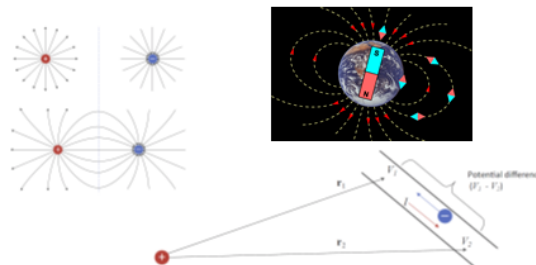
- I.e.:
- zero stiffness
  - contactless
  - no hysteresis

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## Electricity and Magnetism

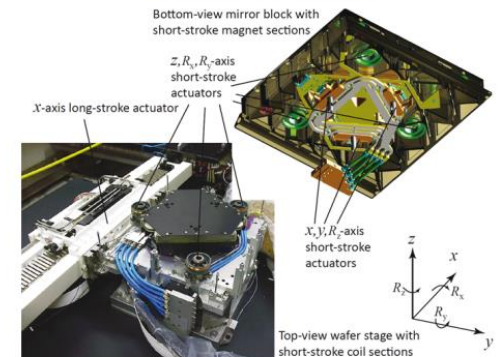
- Both are modelled with force fields
- Both models are abstract, not real!



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## Short stroke



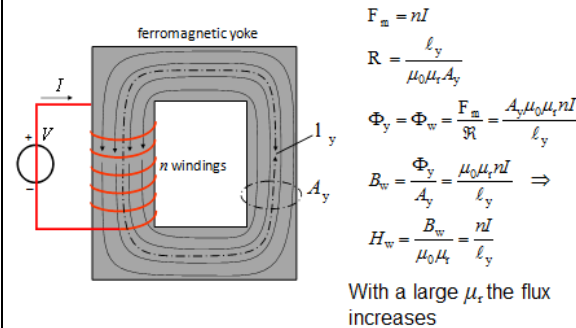
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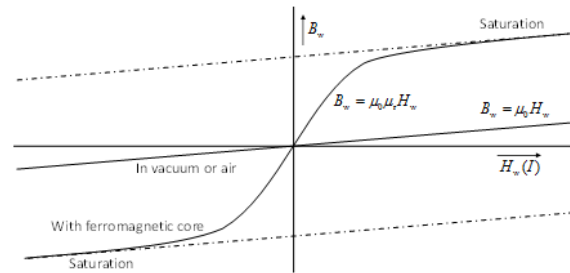


# Day 1 (afternoon)

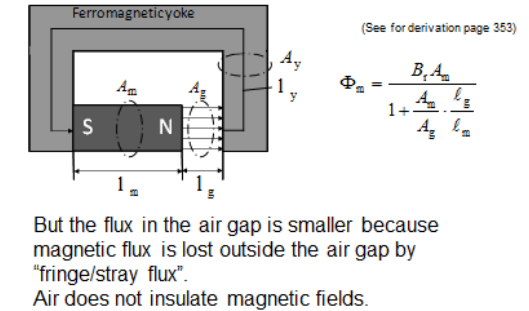
## Adding a ferromagnetic material reduces the reluctance



## Magnetisation curve of ferromagnetic material ( $\mu_r > 1$ )

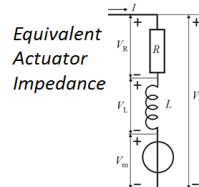


## Practical approximation for calculating a magnetic field in an airgap with a permanent magnet



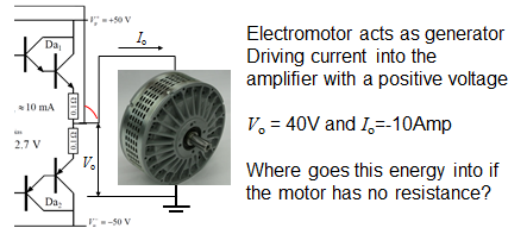
## Low or high output impedance of an Amplifier

- Low impedance:
  - When damping is necessary
    - Loudspeakers
    - Feedforward control (no feedback)



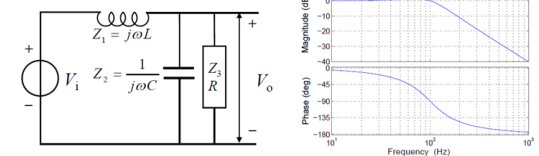
- High impedance
  - When the current/force has to be independent of the movement (Lorentz actuators).
  - When the current/force has to be independent of the self inductance (position control systems)

## And what if the load is an electric car that slows down?



## PWM or switched mode power conversion

- A switch does not dissipate energy
- Switches can only create squarewave signals (on/off)
- Low pass filtering gives the average value (Fourier).
- L(C) filtering is non dissipating



- L can be actuator self inductance

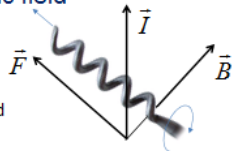
# Day 2 (morning)

Lorentz's law gives the force on a wire with current in a magnetic field

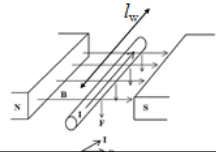
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad \text{with } q \cdot v = I$$

$$F = kI = BI \ell_w \sin \alpha$$

$\alpha$  = the angle between the current and the magnetic field  
 $\ell_w$  = length of the wire in the field  
 $k$  = force constant



"Corkscrew" or "righthand" rule due to cross product



## Power balance with dissipation

- Applied motor voltage  $V$ :  
 $V = V_m + R \cdot I$
- Power balance:  
 $P_{el} = V \cdot I = V_m \cdot I + R \cdot I^2$   
 $= k_t \omega \cdot I + P_{diss}$   
 $= T \cdot \omega + P_{diss}$   
 $P_{el} = P_{mach} + P_{diss}$
- Electrical power is converted into mechanical power and energy dissipation (heating up the motor) is next to mechanical torque usually the limiting factor and determines, together with suitable transmission the maximum mechanical energy extracted from an actuator or electromotor!
- Motor data on sheets often based on  $T_{ambient} = 25^\circ\text{C}$  !!

Electrical energy Mechanical energy

## Some data are less important for servo

Motor Data (provisional)

Values at nominal voltage	
1 Nominal voltage	V 24
2 No load speed	rpm 5780
3 No load current	mA 225
4 Nominal speed	rpm 5540
5 Nominal torque (max. continuous torque)	mNm 354
6 Nominal current (max. continuous current)	A 9.15
7 Stall torque	mNm 8420
8 Starting current	A 212
9 Max. efficiency	% 94
Characteristics	
10 Terminal resistance	$\Omega$ 0.113
11 Terminal inductance	mH 0.0937
12 Torque constant	mNm / A 39.6
13 Speed constant	rpm / V 241
14 Speed / torque gradient	rpm / mNm 0.687
15 Mechanical time constant	ms 4.20
16 Rotor inertia	gcm <sup>2</sup> 584

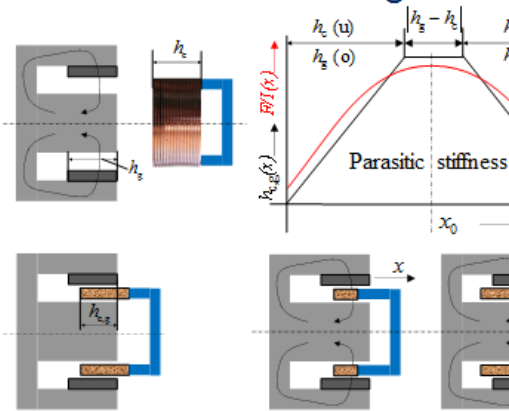
Friction  
 Highest efficiency working point  
 If used with switch = Stall current @24V  
 1/S.  
 Must be matched with load by transmission

Characteristic motor data

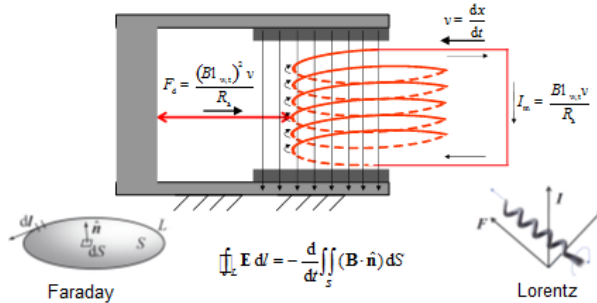
- What is nominal?  
 - Servo applications have a varying speed and torque demand.

nominal < maximum!

## Limited Range!

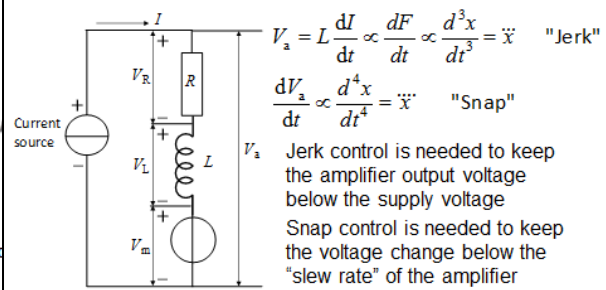


## Damping force direction



Movement of coil to the left  $\rightarrow$  increase of flux in negative  $\hat{n}$  direction  
 $\rightarrow$  E field in direction of  $d\vec{l} \rightarrow$  electrons (neg charges) in opposite direction  
 $\rightarrow$  Current in direction of  $d\vec{l} \rightarrow$  Lorentz force opposite to  $v$

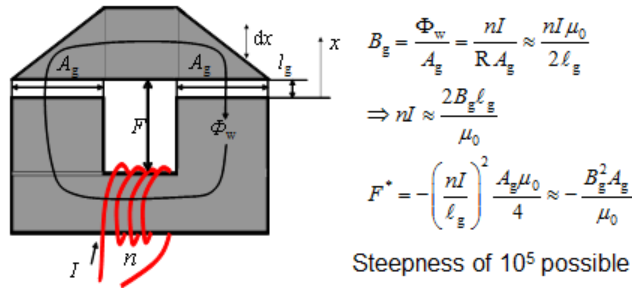
## The power supply and amplifier limit the allowable Jerk and Snap



Jerk control is needed to keep the amplifier output voltage below the supply voltage  
 Snap control is needed to keep the voltage change below the "slew rate" of the amplifier

# Day 2 (afternoon)

## Force of magnetic field to ferromagnetic material



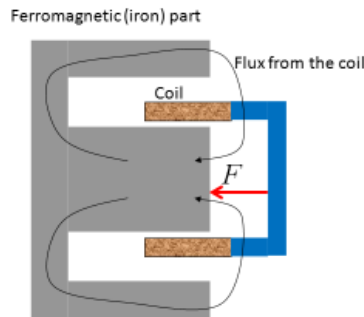
Steepness of  $10^5$  possible

"Magnetic pressure"  $P_m \approx \frac{F}{2 A_g} \approx \frac{B_g^2}{2 \mu_0}$   $1T \rightarrow 0.4 \text{ Mpa (4bar)}$   
 \* See book for full derivation

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Actuation and Power Electronics – Reluctance Actuators

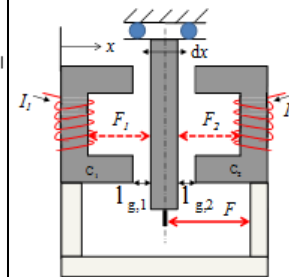
## A Lorentz actuator als "electromagnet"



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Actuation

## Balancing with two variable reluctance actuators



$$F = F_2 - F_1$$

$$= \left( \frac{n I_2}{l_{g,2}} \right)^2 \frac{A_g \mu_0}{4} - \left( \frac{n I_1}{l_{g,1}} \right)^2 \frac{A_g \mu_0}{4} = \frac{n^2 A_g \mu_0}{4} \left( \frac{I_2^2}{l_{g,2}^2} - \frac{I_1^2}{l_{g,1}^2} \right)$$

In the mid-position:  $l_{g,1} = l_{g,2} = l_g$ :

$$F = \frac{n^2 A_g \mu_0}{4} \left( \frac{I_2^2 - I_1^2}{l_g^2} \right)$$

With:  $I_2 = I_s + \Delta I$  and  $I_1 = I_s - \Delta I$  we get:

$$F = \frac{n^2 A_g \mu_0}{4} \left( \frac{(I_s + \Delta I)^2 - (I_s - \Delta I)^2}{l_g^2} \right) = \frac{n^2 A_g \mu_0}{4} \left( \frac{4 I_s \Delta I}{l_g^2} \right)$$

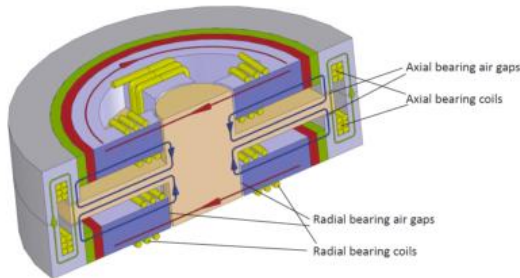
$$\frac{F}{\Delta I} = \frac{I_s n^2 A_g \mu_0}{l_g^2}$$

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Actuation and Power Electronics – Reluctance Actuators

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## Magnetic bearing in 5 DOF

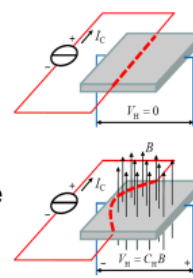


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Actuation and Power Electronics – Reluctance Actuators

## Flux measurement is difficult but can be done

- Two principles are applicable:
  - Insert Hall sensor in air gap
  - Use coil around gap
- Also here noise is an issue

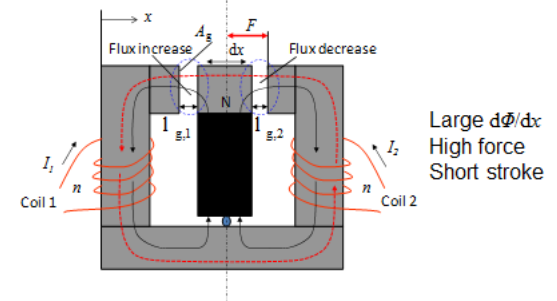


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## Superposition of the PM and current induced magnetic flux



Large  $d\Phi/dx$   
 High force  
 Short stroke

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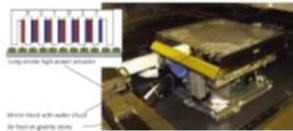
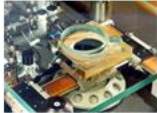
Actuation and Power Electronics – Reluctance Actuators

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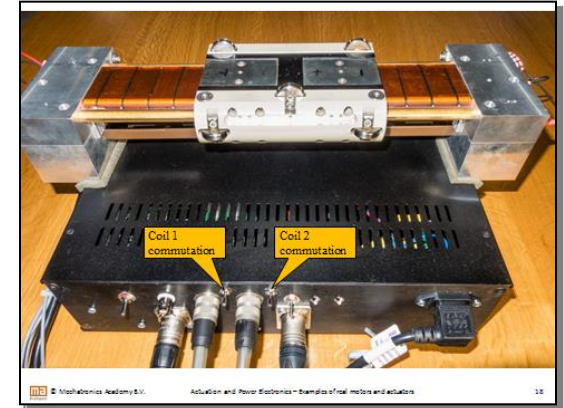
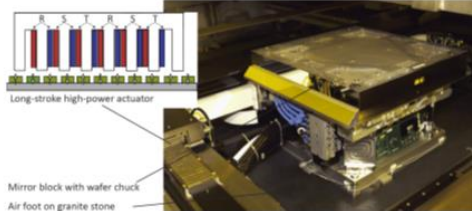
# Day 3 (morning)

## Two examples

- Hard commutated two-phase linear motor
- Sinusoidal commutated three-phase linear motor

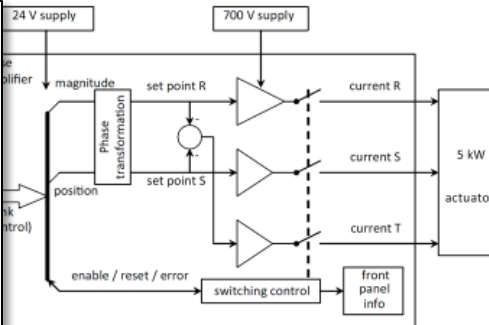
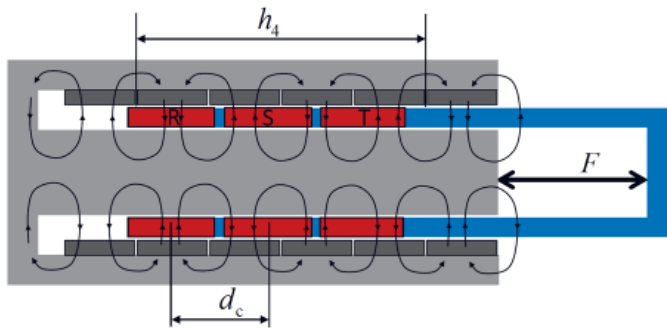


## Three phase commutated linear motor LIMMS

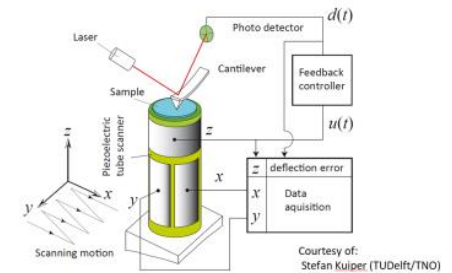


## Requires three phase amplifier

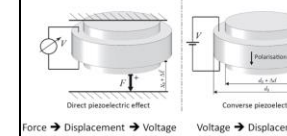
## Three phase Commutation of three moving coil sections



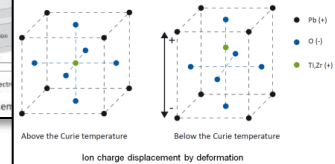
## AFM scanner main components



## Used both for actuation and sensing



## Piezoelectric principle


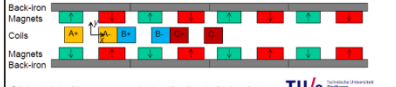




# Day 3 (afternoon)

## Actuator vs motor

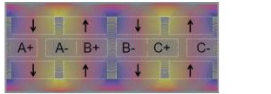
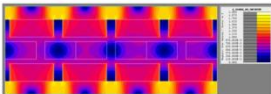
- Extension of stator and/or translator structure
- Single-phase winding vs multi-phase winding
- Pulsating fields vs traveling waves

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## Finite element simulations (periodical section)

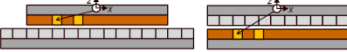
- Magnetic flux  $\varphi$
- Magnetic flux density  $B$

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## Moving-magnet vs moving-coil

- Magnet array is finite, increases modeling complexity
- Force is acting on coil volumes, torque arm is larger for moving-magnet planar motors
- Modeling and control is more complex in moving-magnet case, however, the levitated structure is less complex

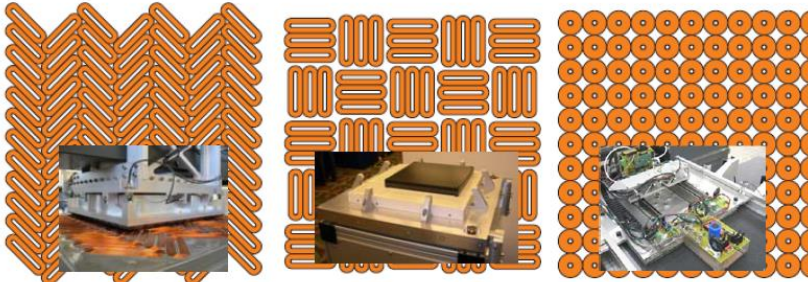


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## Geometries

- Several moving-magnet planar motor topologies have been manufactured and studied

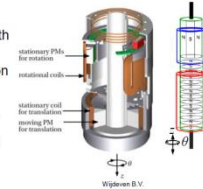
HPPA (TU/e) EPM (Philips) COPAM (TU/e)



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## Series mounted rotary and linear actuator


- Two motors mounted in series
  - Two magnet arrays with different orientations
  - Two coil sets of coils on the stator
  - Increasing stroke requires elongation of both magnet and coils
  - Physically decoupled



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## Linear motor with integrated contactless energy transfer system

Linear moving-coil motors requires moving cables for power supply



Advantages:

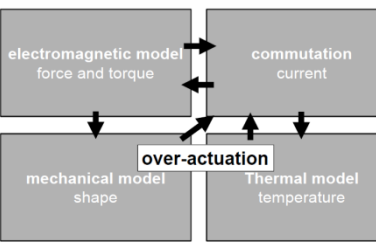
- ✓ Low electric losses
- ✓ High power density

Disadvantages:

- ✗ Wear
- ✗ Dynamical distortion
- ✗ Abrasion

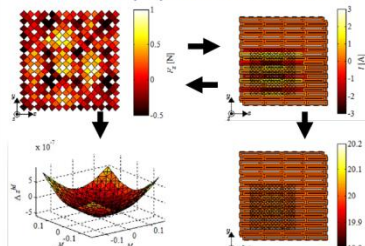
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## Multi-physical model



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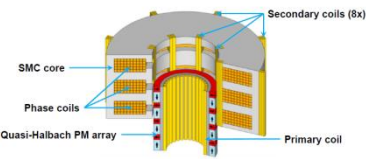
## Multi-physical framework



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## Integrated Tubular Topology

- Tubular motor
- Coaxial transformer



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