TECHNISCHE UNIVERSITÄT DRESDEN

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Robust Design Optimization of Electromagnetic Actuator Systems Using Heterogeneous Models

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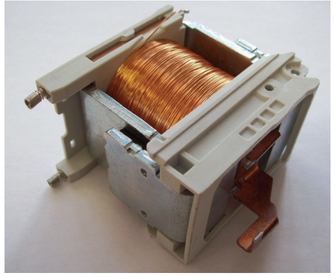
Outline

1. Introduction

Electromagnetic Actuators

- Fast actuation, medium forces and strokes
- High energy density
- Design varies in a very wide range



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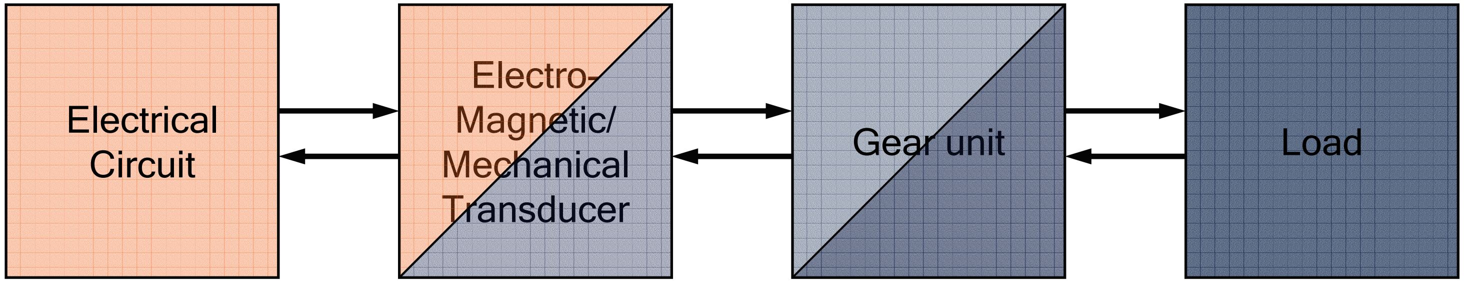
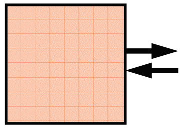
Electromagnetic Actuator Systems



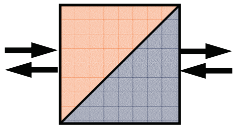
- Reluctances forces
- Electrodynamic forces
- Solid state actuators

2. Models



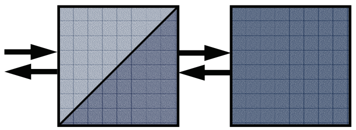
Electrical Circuit

- Kirchhoffian network models
- Network equations, element relations



Electromagnetic transducer

- Maxwell's and material equations
- Generalized Kirchhoffian network models
- Static (and dynamic) finite-element-models



Gear and load

- Kinematic and dynamic models, rigid body mechanics
- Equation of motion, element relations

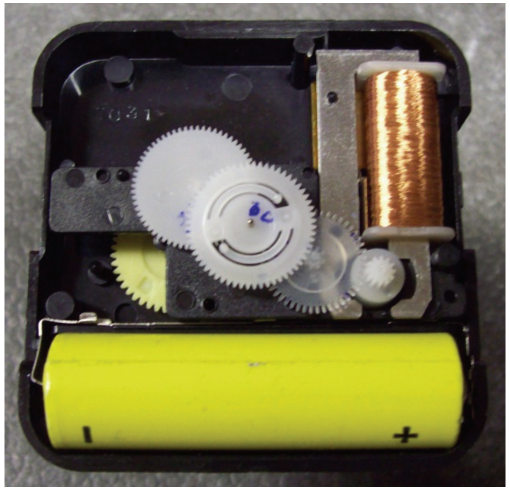
System model characteristics of electromagnetic actuators

- *Multiphysics models* including electrical, magnetic, mechanical, thermal and other domains
- *Non-linear effects* in all subsystems, e.g. electronic components behavior, magnetic hysteresis, mechanical material behavior
- *Time-dependent models* with rather different time constants of the subsystems, e.g. of the electrical and thermal
- *Heterogeneous system models* which couple subsystems from different simulation tools, e.g. network simulators and finite-element-solvers

3. Examples

- **Electromechanical clock**
- **Tripping unit of a circuit breaker with a Magnetic Shape Memory alloy**
- **Electromagnetic Braille printer**

Electromechanical clock

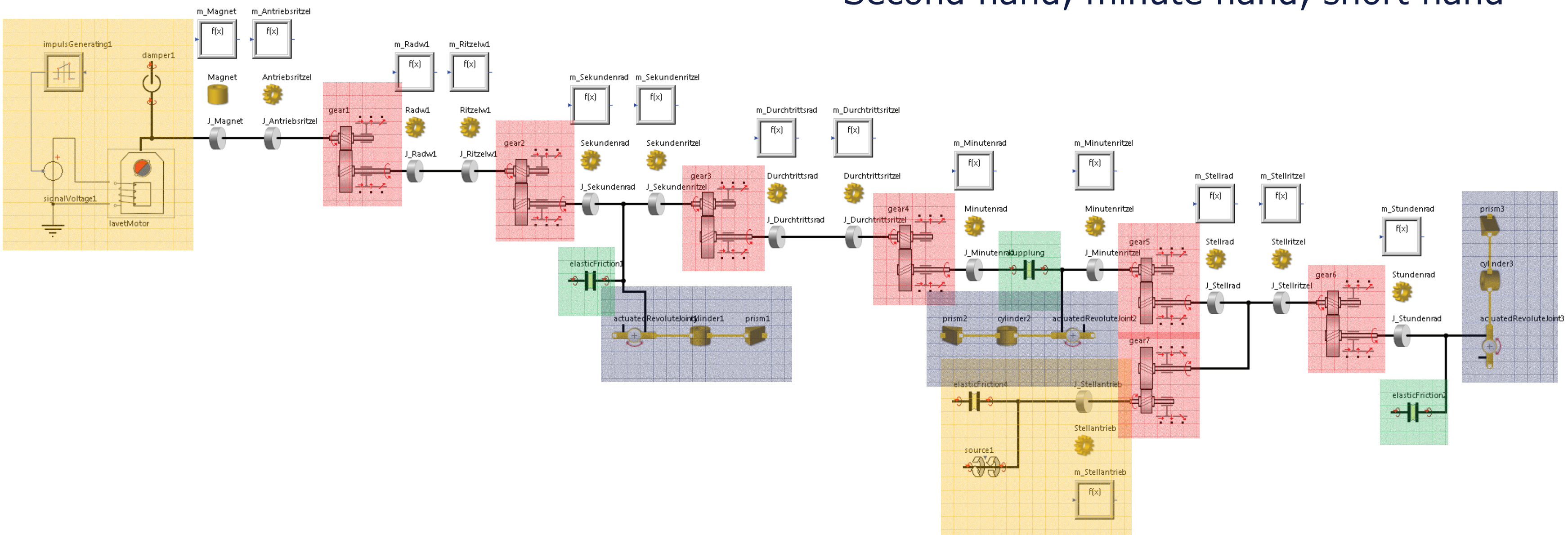


System Dynamics Model

- Rigid bodies with point-mass
- Elasticities, stoppers
- Friction, damping
- Implemented in *SimulationX*

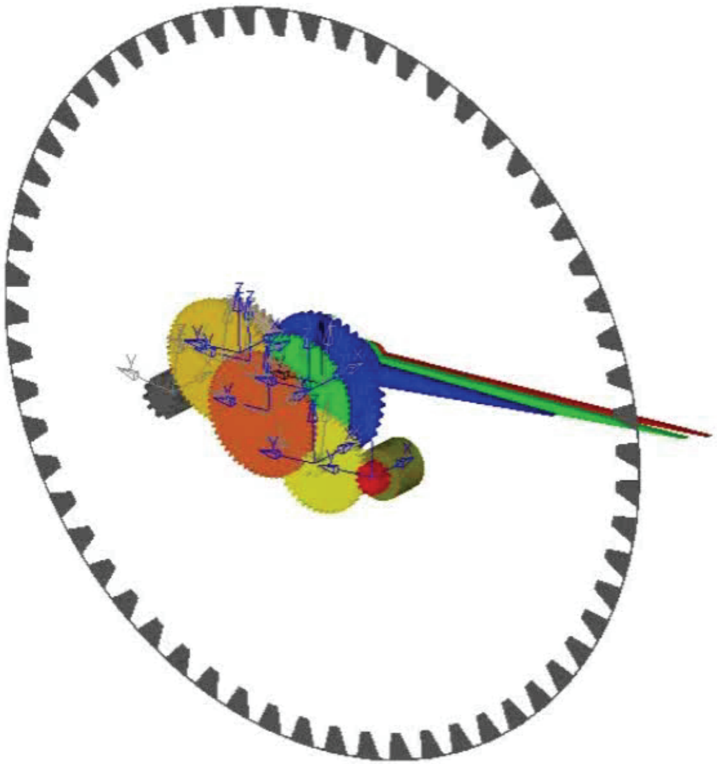
Actuator System

- Lavet step motor
- Electrical control unit
- Six gears
- Manual correcting actuator with an additional gear
- Friction clutches
- Second hand, minute hand, short hand



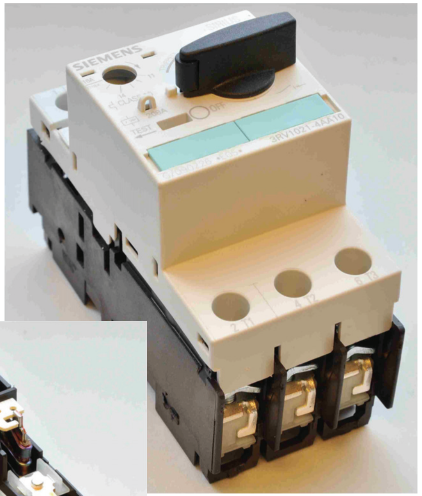
Dynamic System Model

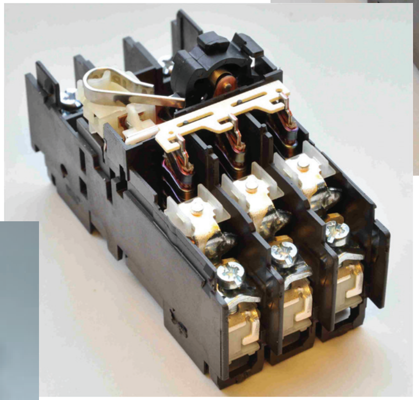
- Objectice → Minimizing power consumption

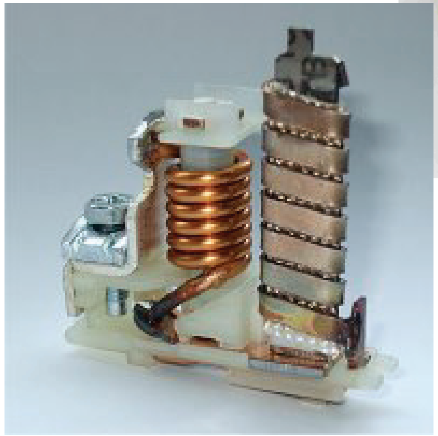


Tripping unit of a circuit breaker with a MSM alloy

- Used to break overloads and short circuits in power grid systems
- Tripping unit with solenoid and thermostatic bimetall
- Solenoid works as a sensor and actuator as well







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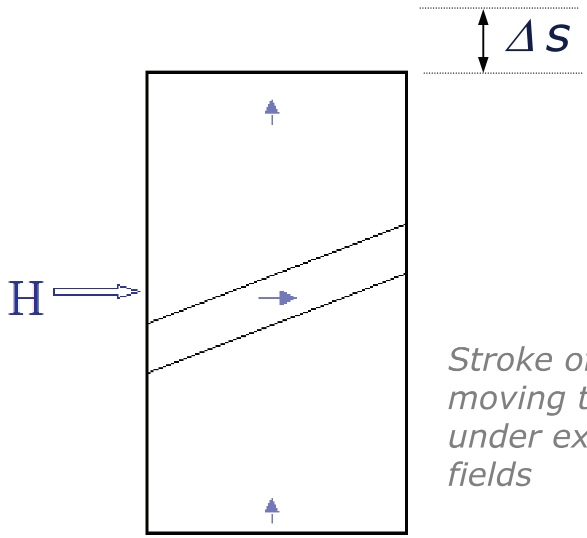
Magnetic Shape Memory (MSM) alloy

- Innovative principle based on so called magnetic shape memory alloys, e.g. NiMnGa alloy system
- External magnetic field controls the crystal orientation and shape
- Effect is reversible with a remarkable hysteresis



Stroke of a MSM alloy by moving twin boundaries under external magnetic fields

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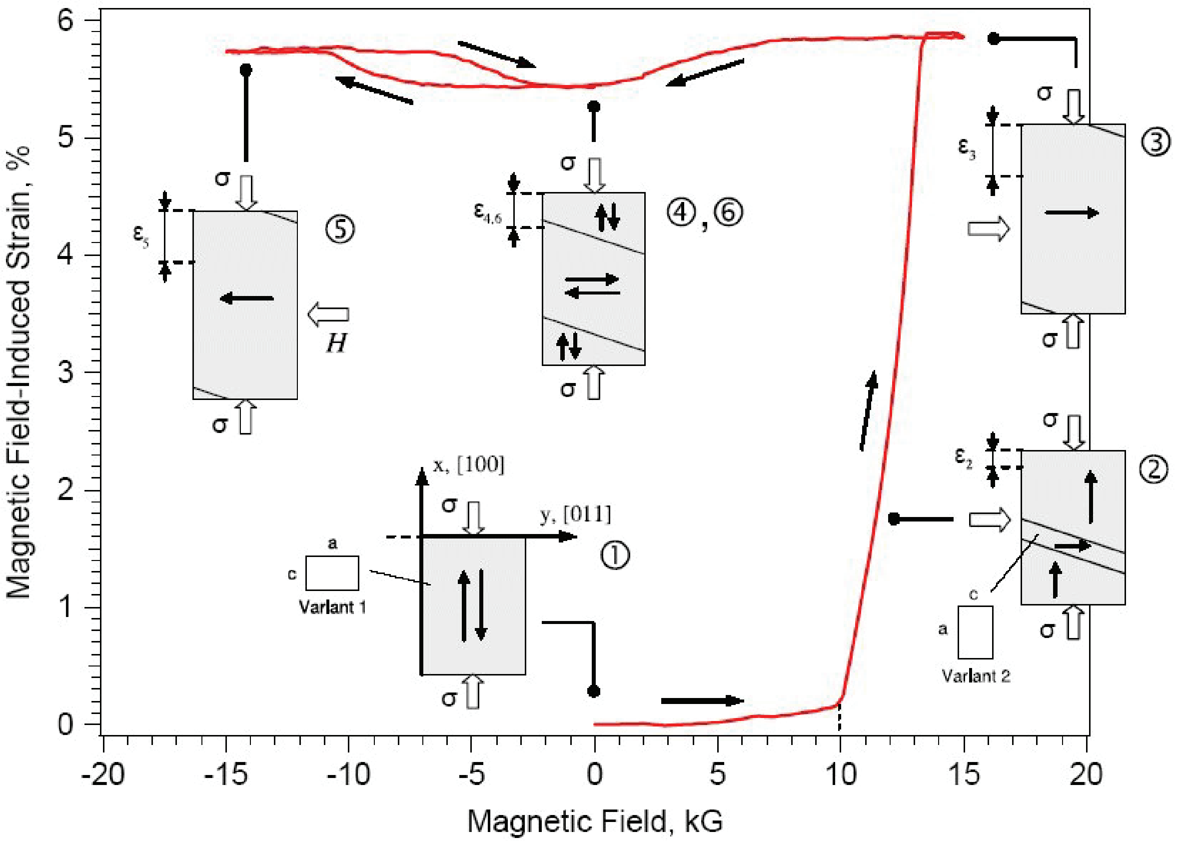
MSM hysteresis behavior



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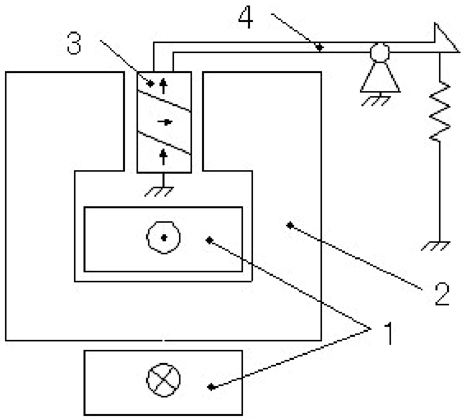
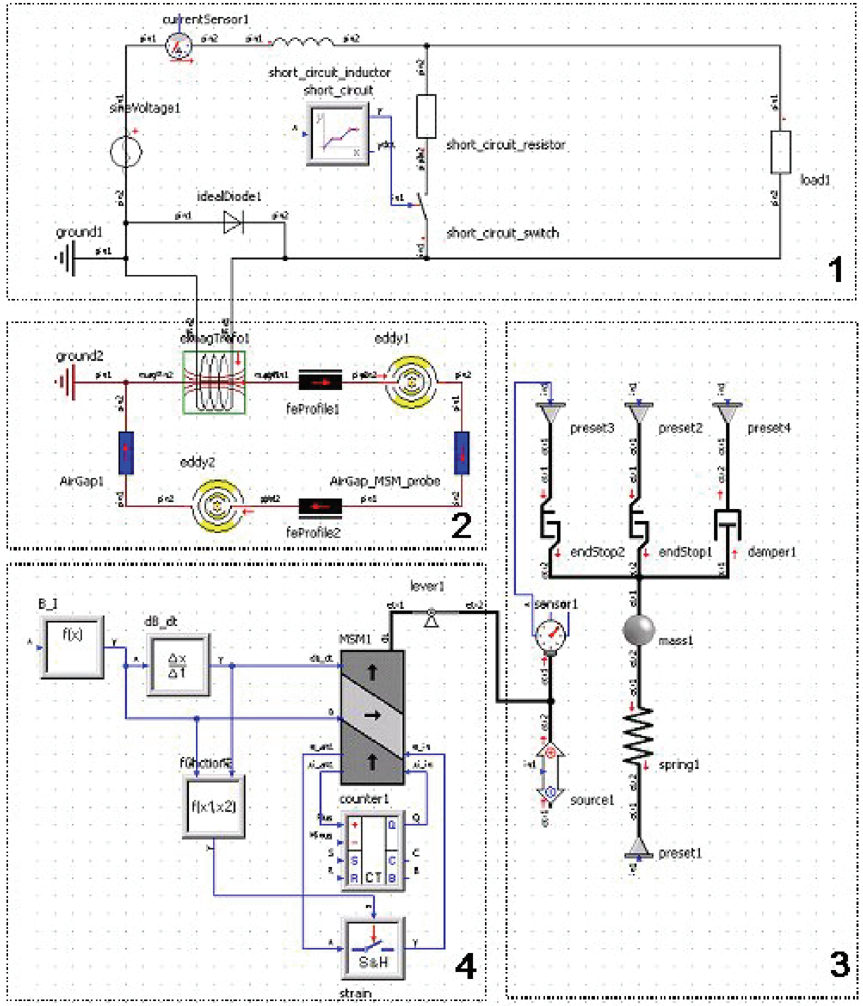
Tripping Unit Principle and Dynamic System Model



1 Electrical conductor
2 Iron core
3 MSM element
4 Latch mechanism



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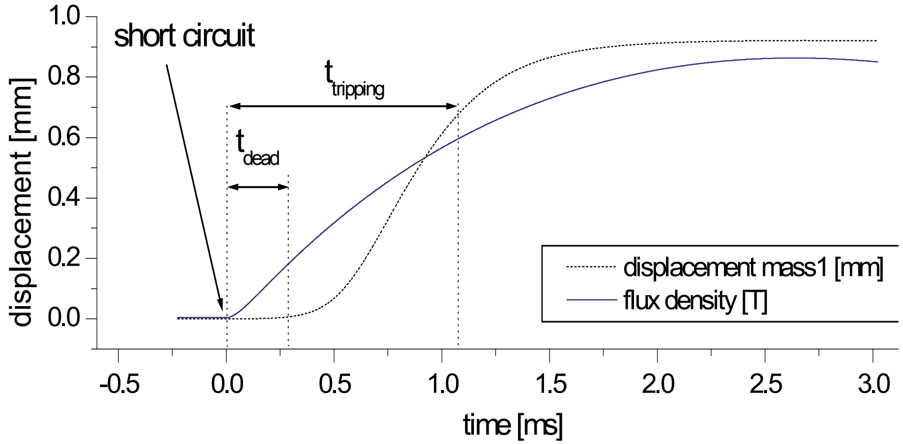
Design Optimization

- Based on the system model
- Objective → Tripping time and overall volume to be minimized



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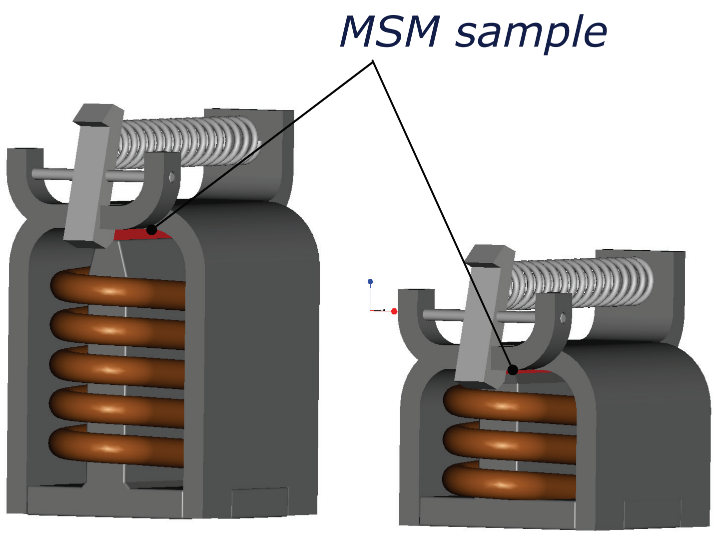
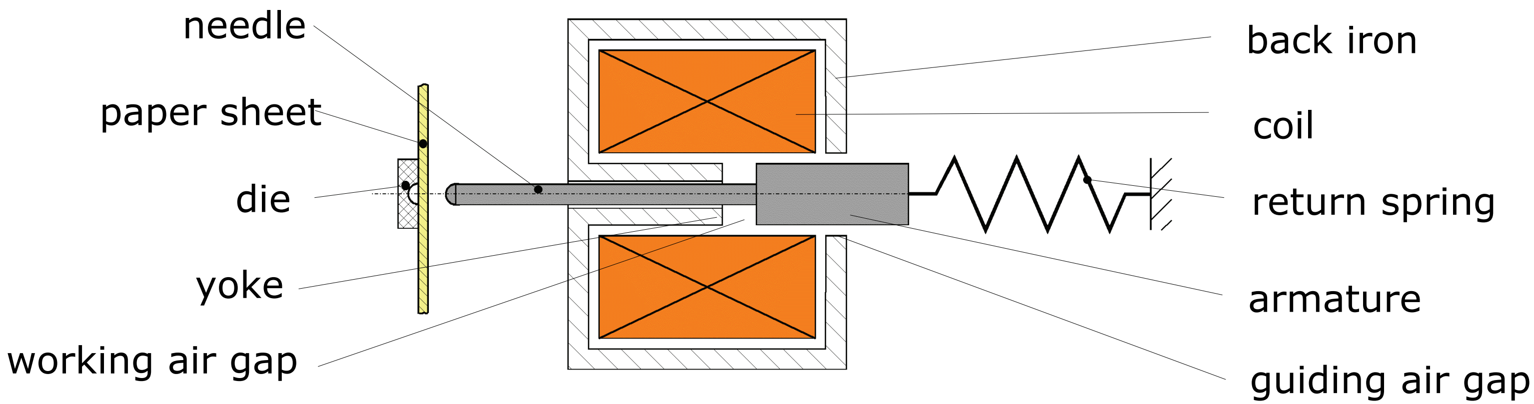


Initial solution – 34 mm high

Optimized design – 22 mm high

Electromagnetic Braille Printer

- Based on a design with a minimum of elements
- Function:
  - A needle embosses paper sheets
  - Paper as a nonlinear elasto-plastic counterforce load
  - Dynamic forces of the masses
  - Nonlinear magnetic material behavior

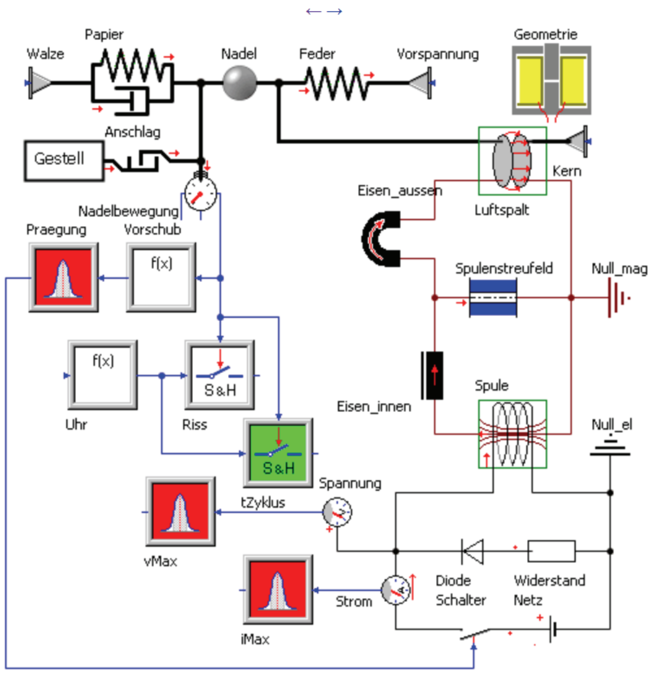


Actuator System Design

- *First stage* bases on a rough analytical static model

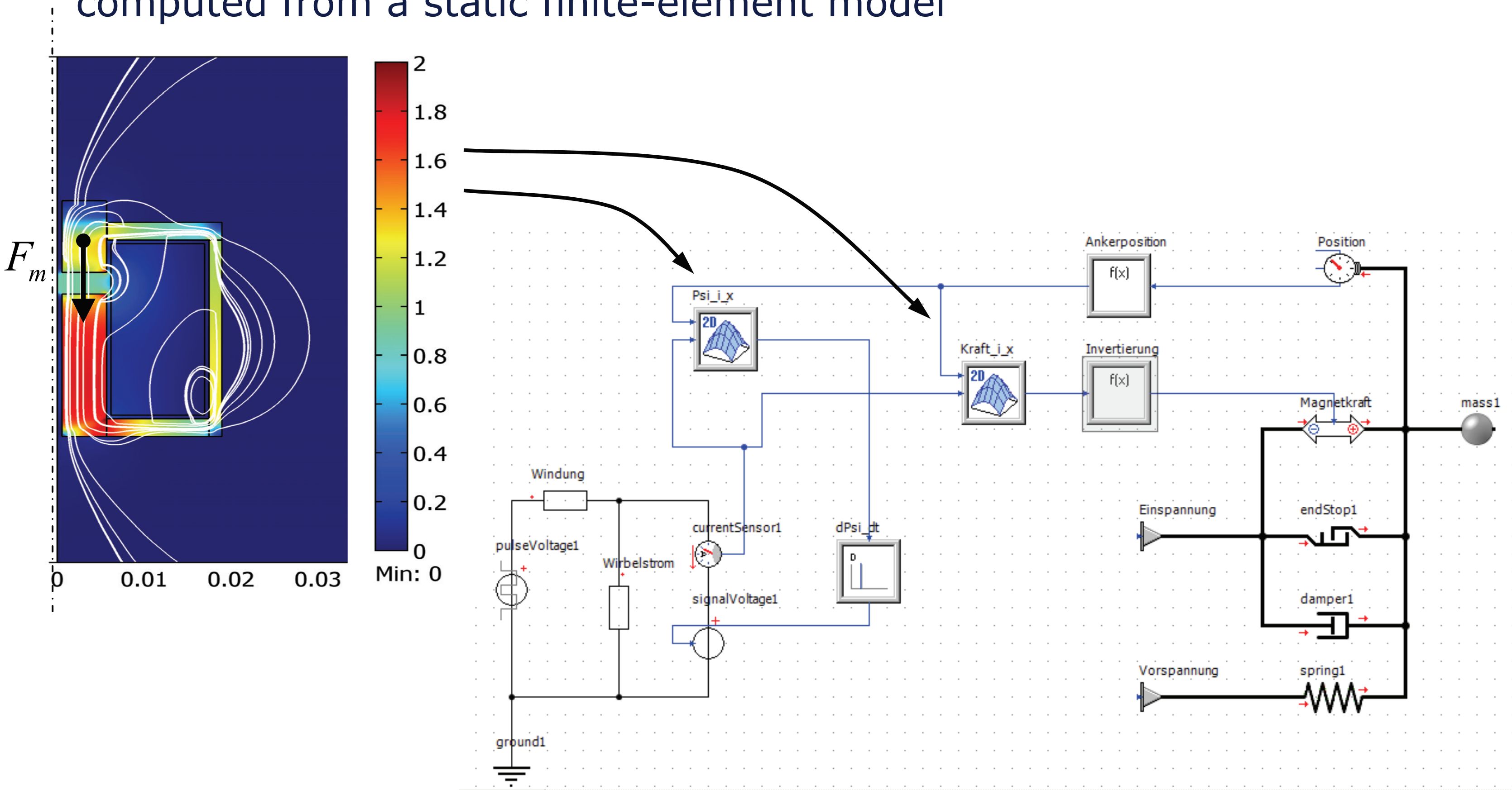
$$A_{\mathrm{Cu}}, A_{\mathrm{Fe}}, N = f(F_{\mathrm{mag}}, s_{\max}, V_0, P_{\mathrm{Cu}}, B_{\mathrm{m}})$$

- *Second stage* uses a dynamic network model
  - Kirchhoff’s network laws
  - Ampère’s circuitical law
  - Maxwell’s law of induction
  - Maxwell’s eq. for the magnetic force
  - ODE of motion



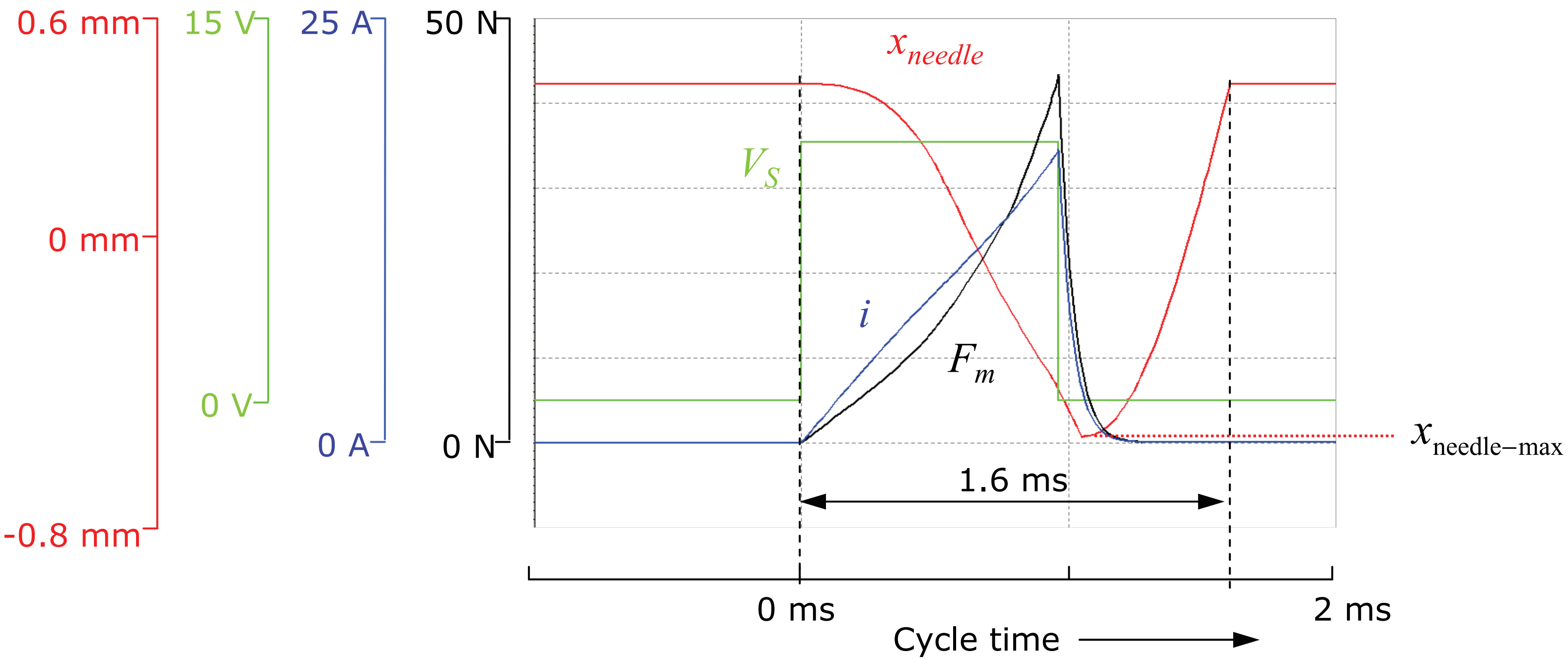
Actuator System Design

- *Third stage* applies a dynamic network model with characteristic diagrams of the magnetic force and the magnetic flux linkage computed from a static finite-element model



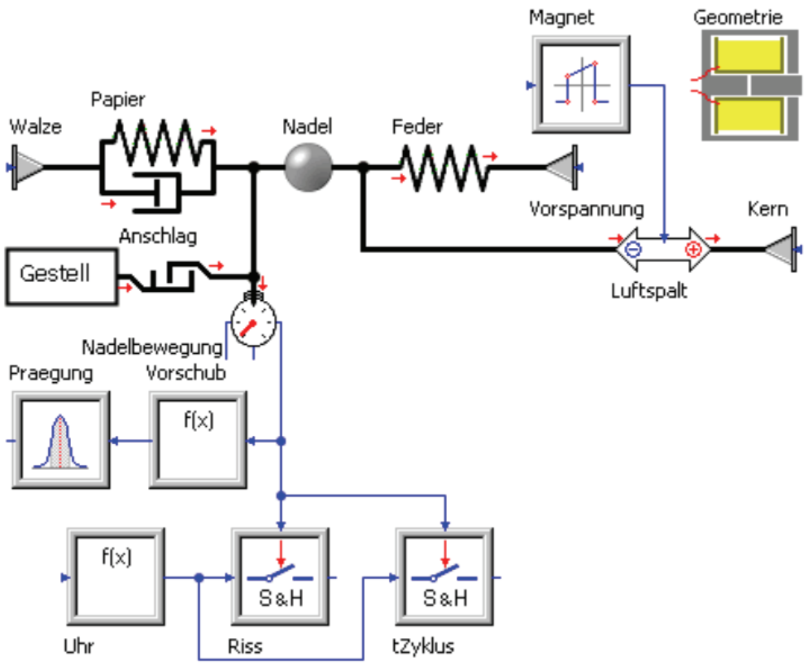
Simulated dynamic behavior

- Embossing cycle
- Objective of the design optimization → cycle time to be minimized



Simplified network model

- Magnetic transducer as time dependent force depending on geometry parameters
- Implemented in *SimulationX 3.4*
- Starting point for testing the interface *OptiSlang – SimulationX*



4. Challenges for design optimization

- System simulations are time-consuming due to
  - Multiphysics models
  - Heterogeneous models (e.g. network and finite element)
  - Non-linear behavior
  - Dynamic simulations (time range)
- Design space dimensions in the range of 5 … 100 typically
- Only small subspaces contain valid designs
- Constraint and objective functions often have a complicated shape