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Robust and Reliability-Based Design Optimization of Electromagnetic Actuators Using Heterogeneous Modeling with COMSOL Multiphysics and Dynamic Network Models

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Outline

1. Introduction
2. Electromagnetic Actuator Model
3. Optimization of the Actuator
4. Robustness Analysis and Optimization
5. Conclusions

1 Introduction

Electromagnetic Actuators

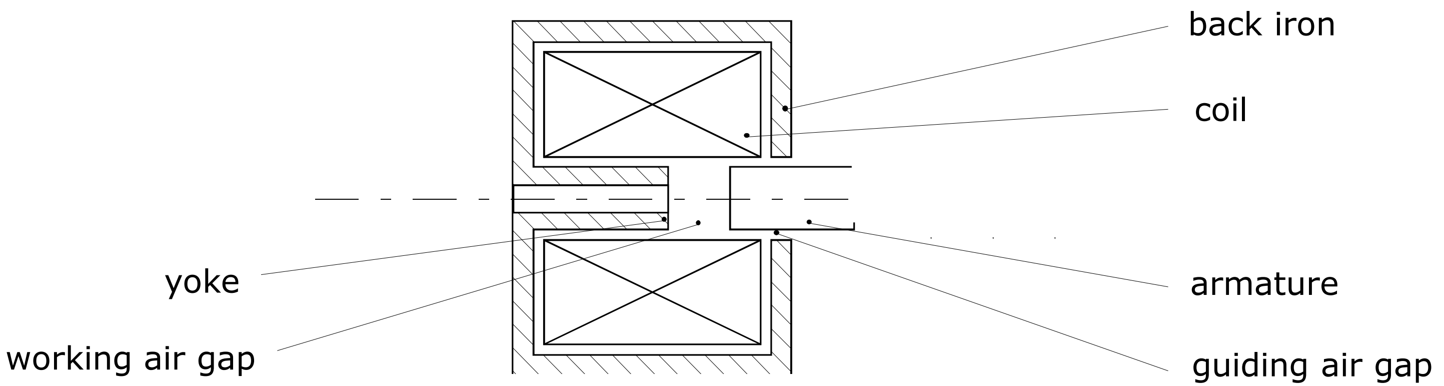
- Fast actuation, medium forces and medium strokes compaired to other actuation principles
- High energy density, low cost
- Design varies in a very wide range

Source: Magnet Schultz Ltd.

Source: Deutsche Fotothek

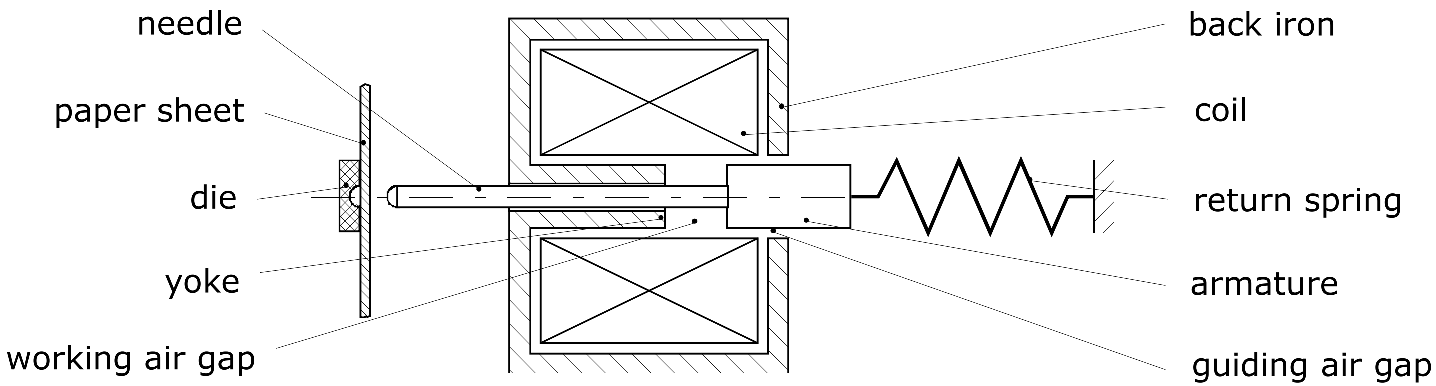
Electromagnetic Actuators

- Minimum of elements: armature, yoke with a back iron, working air gap, parasitic guiding air gap and coil
- Bi-directional cause-effect relations between electric and magnetic field



Braille Printer

- Needle which embosses the paper
- Paper as a nonlinear elasto-plastic counterforce load
- Dynamic forces of the masses
- Nonlinear magnetic material behavior



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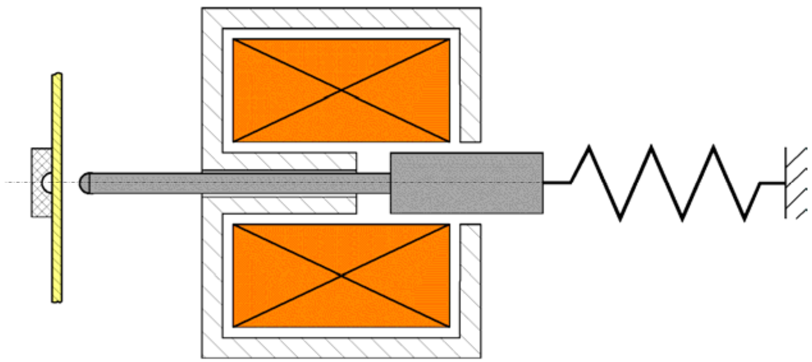

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   - Static Magnetic Model
   - Heterogeneous Dynamic Model
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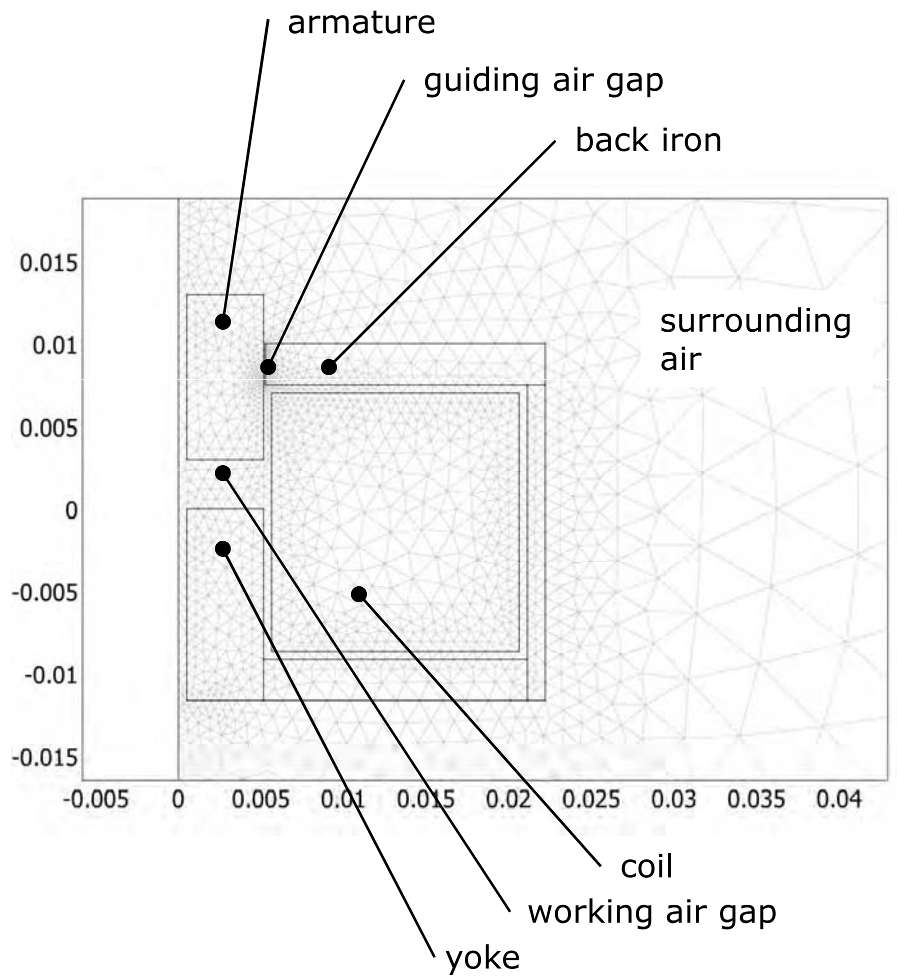
2 Electromagnetic Actuator Model

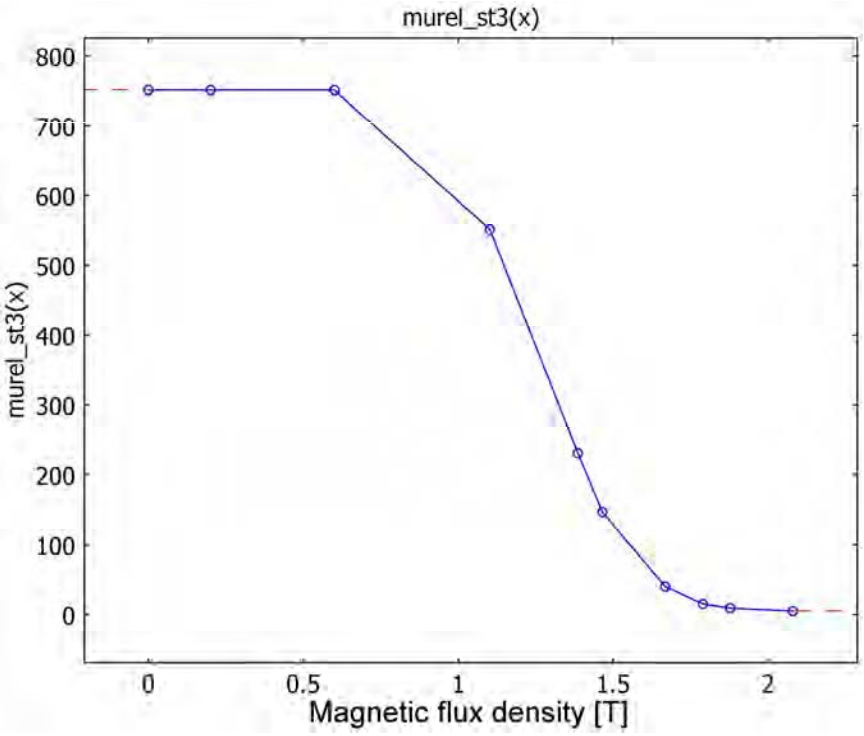
Static Magnetic Model – FEA Model

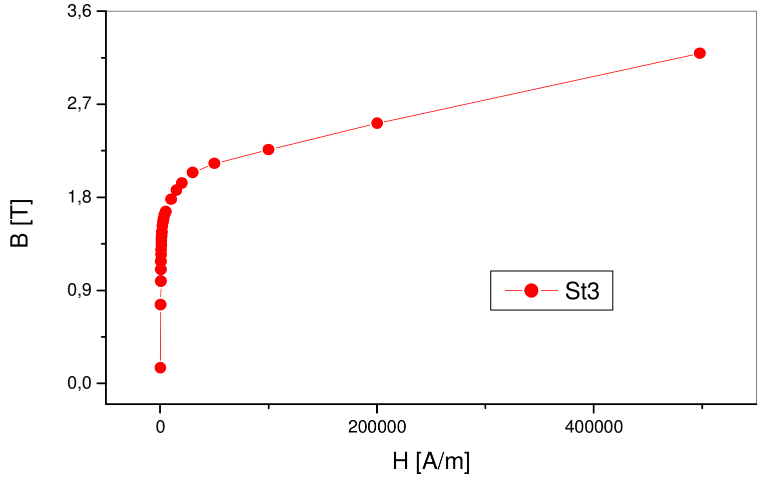
- COMSOL Multiphysics 3.5a
- *emqa* application mode, axial symmetry
- Currents in the angular direction only
- MATLAB scripts
- Input design parameters and results handled with ASCII-files
- Non-linear ferromagnetic material in the form $\mu_{\mathrm{rel}}(B)$
- Free meshing with normal mesh size
- 5,000 to 10,000 DoF, UMFPACK direct solver



Static Magnetic Model – Magnetic Material

- Non-linear ferromagnetic material in the form $\mu_{rel}(B)$ as a look-up table stored in an ASCII file





Static Magnetic Model – Governing Equations

- Static behavior by Maxwell's equation using the magnetic vector potential $\mathbf{A}$; $\mathbf{j}_{\text{ext}}$ - external current density, σ – conductivity, μ - permeability

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{j}_{\text{ext}}$$

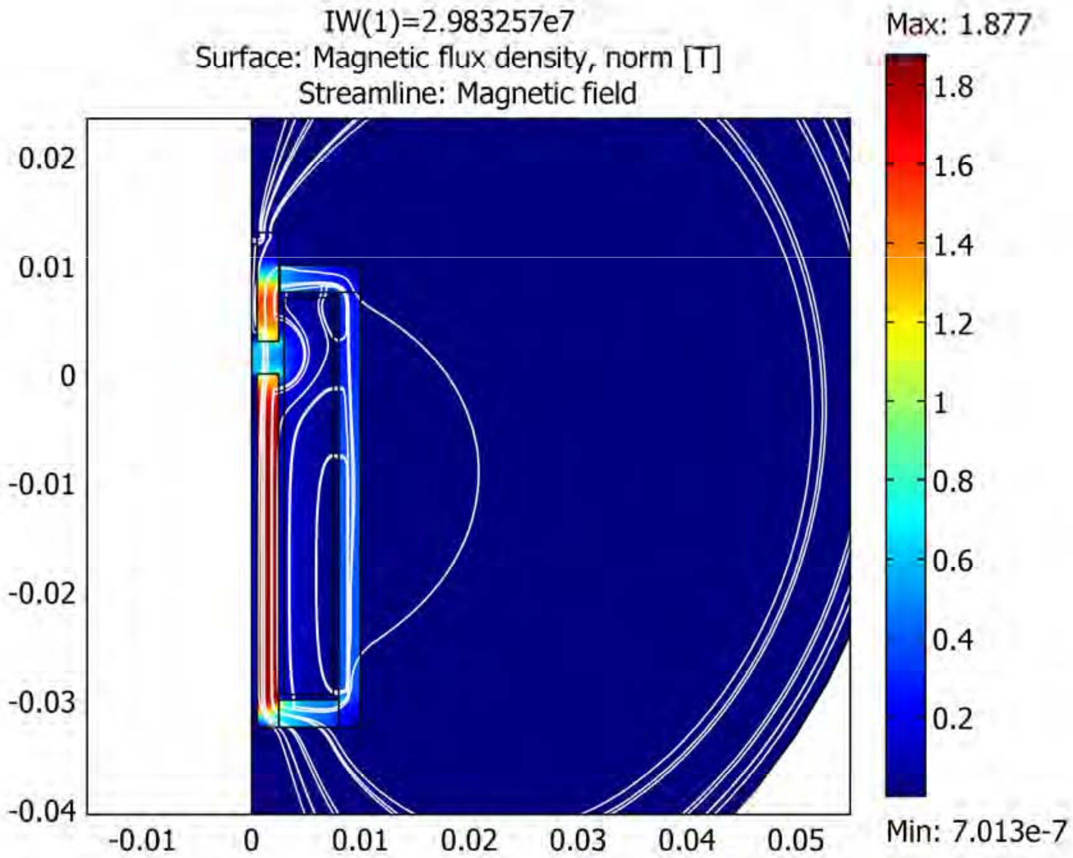
- Magnetic force $\mathbf{F}$ on the armature by integration of the Maxwell's surface stress-tensor on an arbitrary surface S surrounding the armature

$$\mathbf{F} = \int_S \left[\frac{1}{\mu_0} (\mathbf{B} \cdot \mathbf{n}) \mathbf{B} - \frac{1}{2\mu_0} \mathbf{B}^2 \cdot \mathbf{n} \right] dS$$

- Flux linkage Ψ which is necessary to compute the dynamic behavior of the actuator-load system by the dynamic model

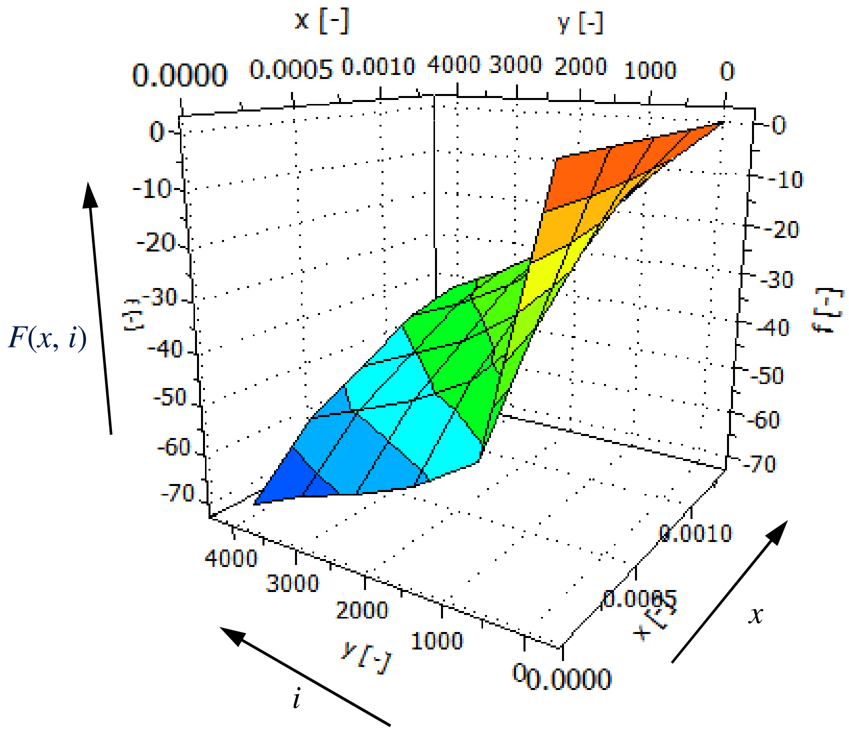
$$\Psi = \int_{\mathbf{A}_\Psi} \mathbf{B} \, d\mathbf{A}_\Psi$$

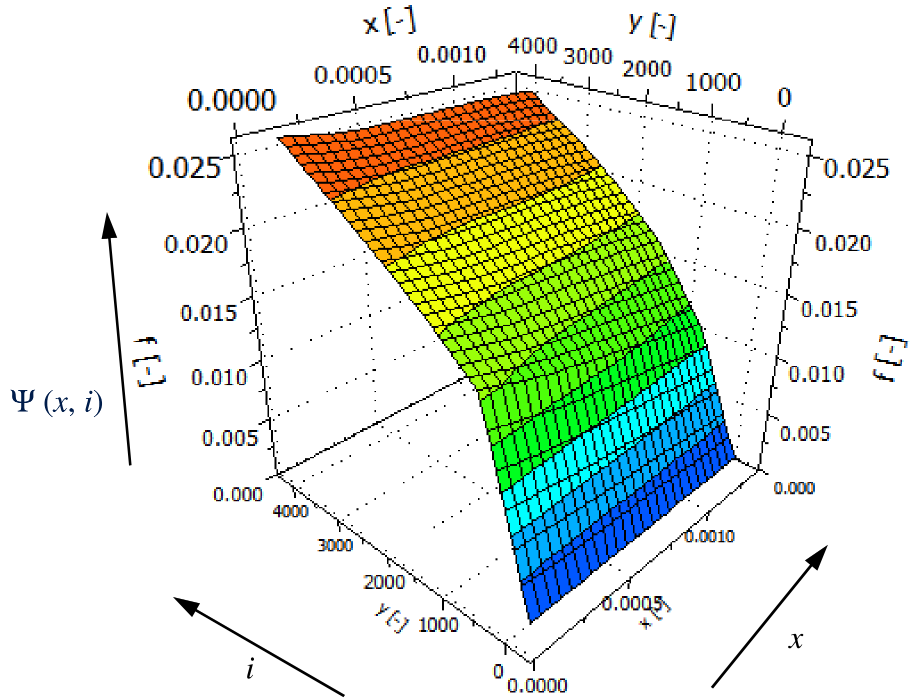
Static Magnetic Model – Results



Static Magnetic Model – Results

- Look-up tables $F(x, i)$, $\Psi(x, i)$





2 Electromagnetic Actuator Model

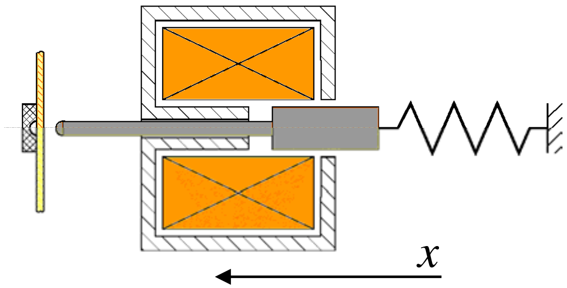
Heterogeneous Dynamic Model – Governing Equations

- ODE for the mechanical dynamics along the coordinate x;
  m – moved mass of the needle and the armature, F_{load} – summarized reaction force of the paper and the return spring

$$m\,\ddot{x} = F_{mag,x}(i,x) - F_{load,x}(x)$$

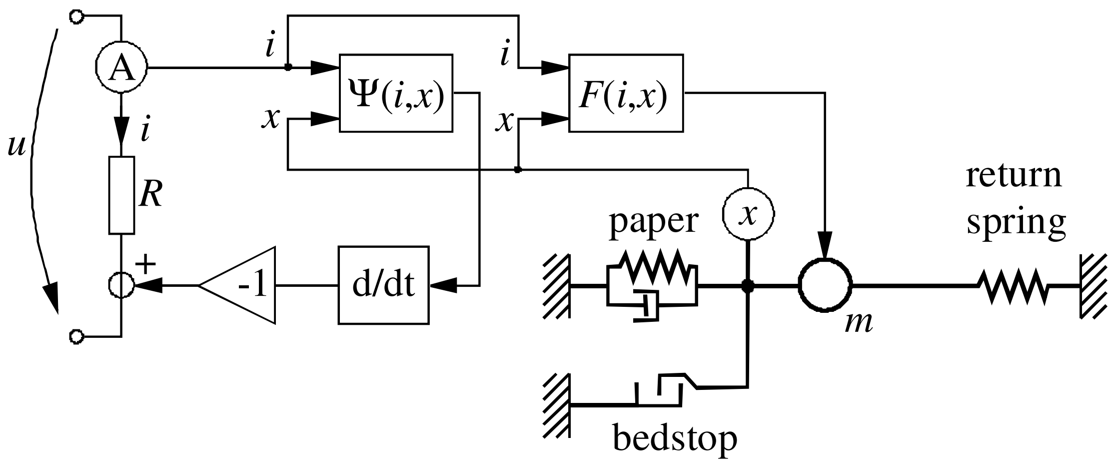
- Kirchhoff's voltage law;
  u - terminal voltage, iR - Ohmic voltage drop, $\mathrm{d}\Psi/\mathrm{d}t$ - induced back-emf (electromotive force)

$$u = i\,R + \dot{\Psi}(i,x)$$



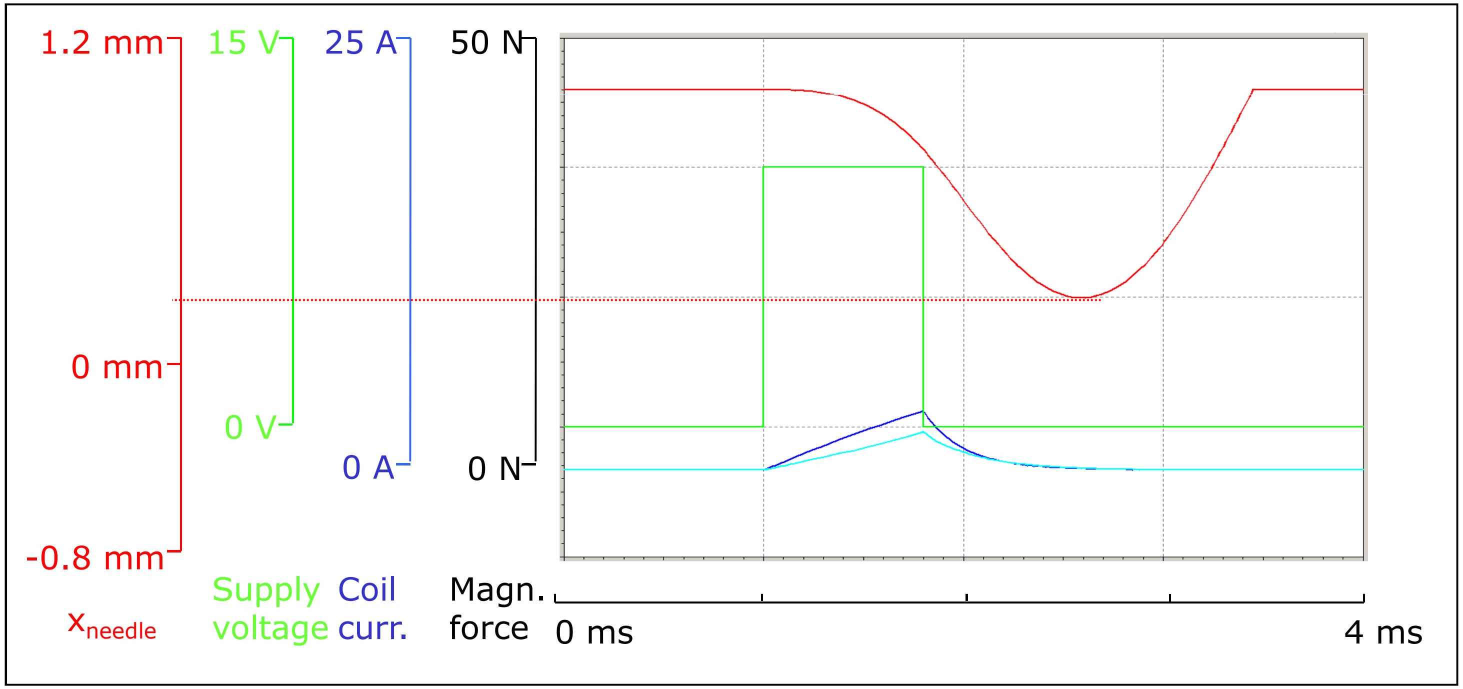
Heterogeneous Dynamic Model – Network

- Generalized Kirchhoffian network model in *SimulationX*
- Involving look-up tables $F(x, i)$, $\Psi\,(x, i)$ from the static model
- Dynamic behavior $F(t)$, $x(t)$
- Eddy currents and hysteresis are neglected
- Embossing sufficient or not (0...1), cycle time t_{cycle} (to be minimized)

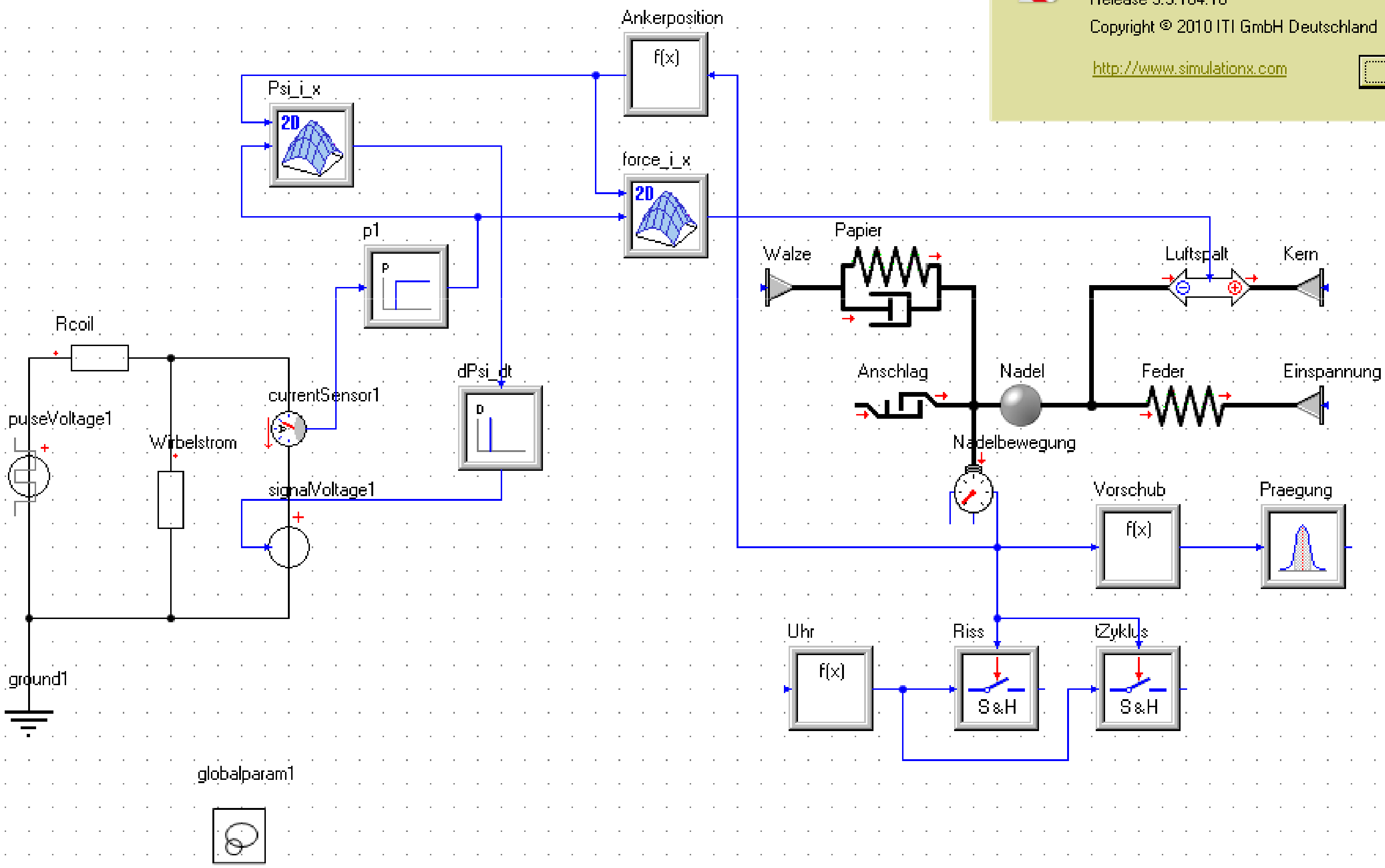


Heterogeneous Dynamic Model – Simulation results

- Embossing sufficient or not → $x_{needle\text{-}max}$ = -0.55 mm
- Cycle time t_{cycle} → to be minimized



Heterogeneous Dynamic Model – SimulationX 3.3



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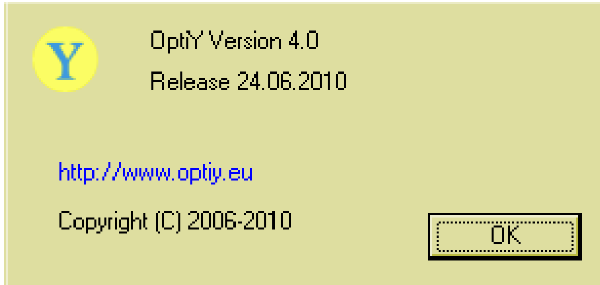
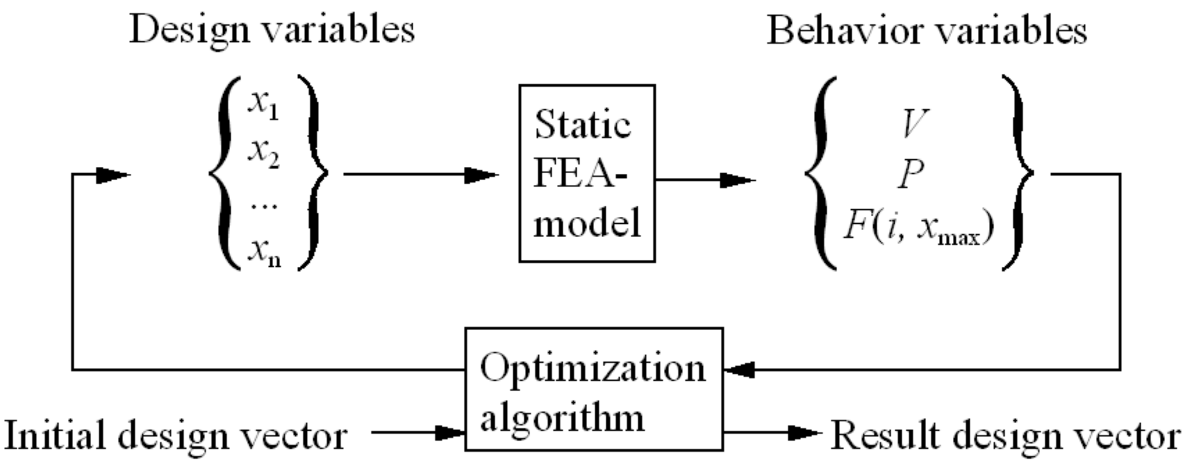
3 Optimization of the Actuator

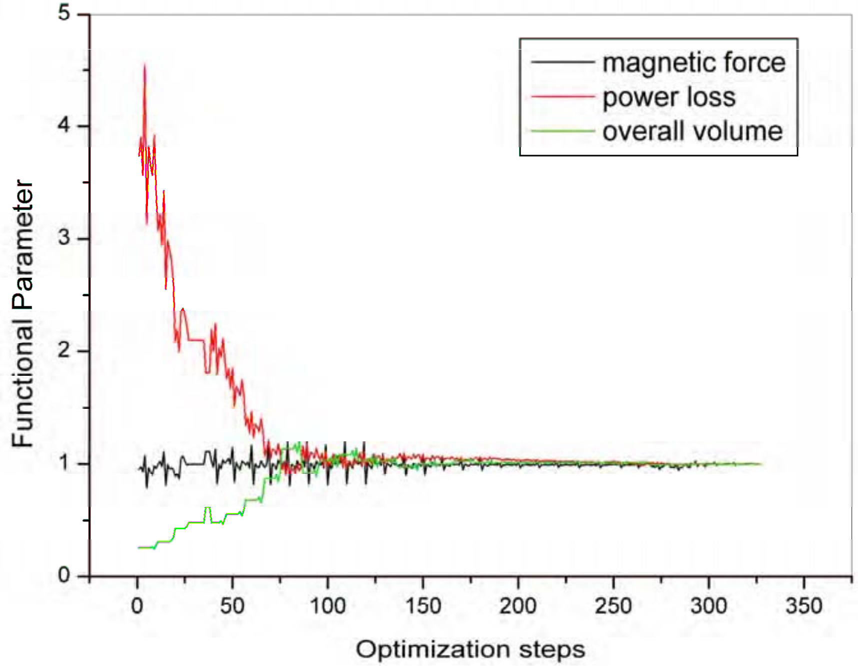
Nominal Optimization Using the Static Magnetic Model





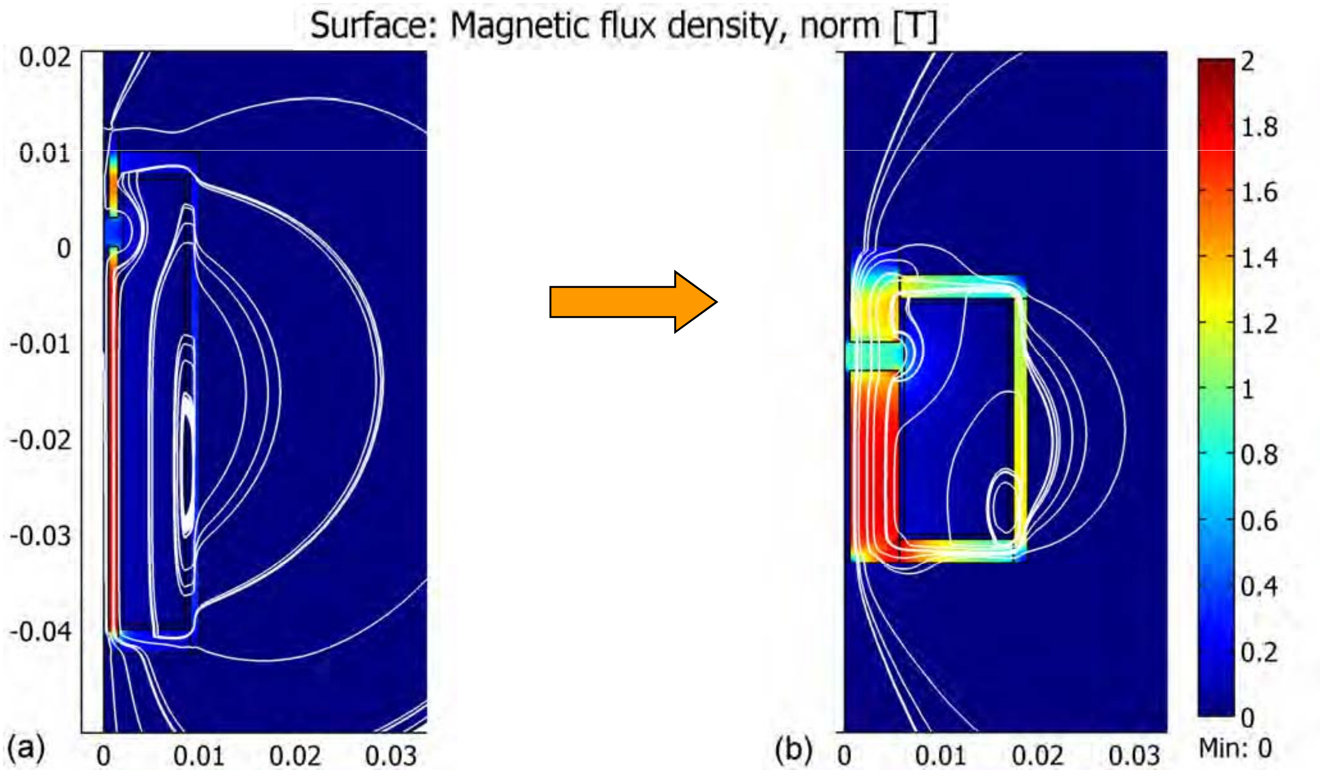
Nominal Optimization Using the Static Magnetic Model

- Constraints: magnetic force at maximum stroke $F(x_{max})$, power losses
- Objective: minimum overall volume
- Gradient-based optimization algorithm, 7 design variables

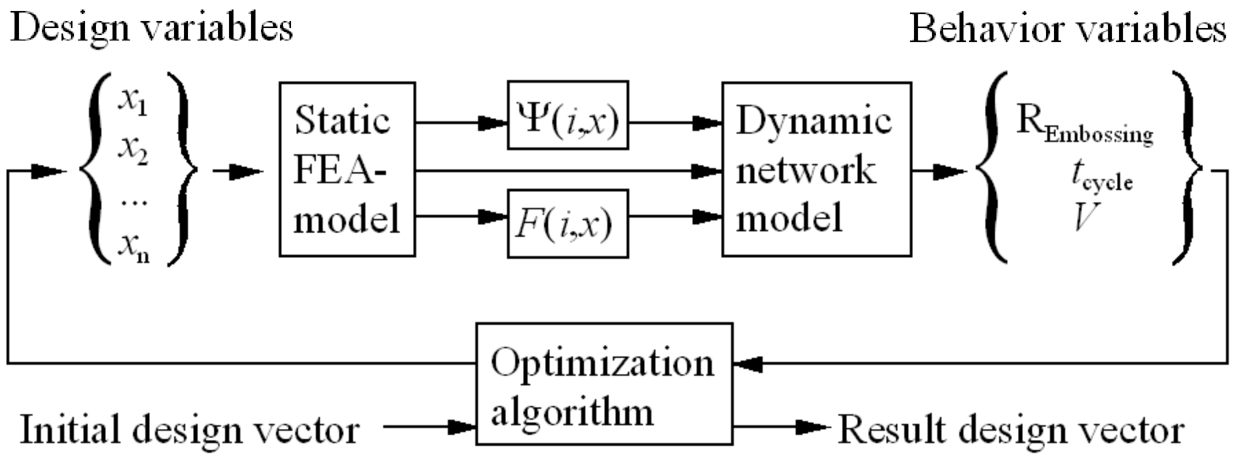


Nominal Optimization Using the Static Magnetic Model

- Preliminary design (a), optimized design (b)



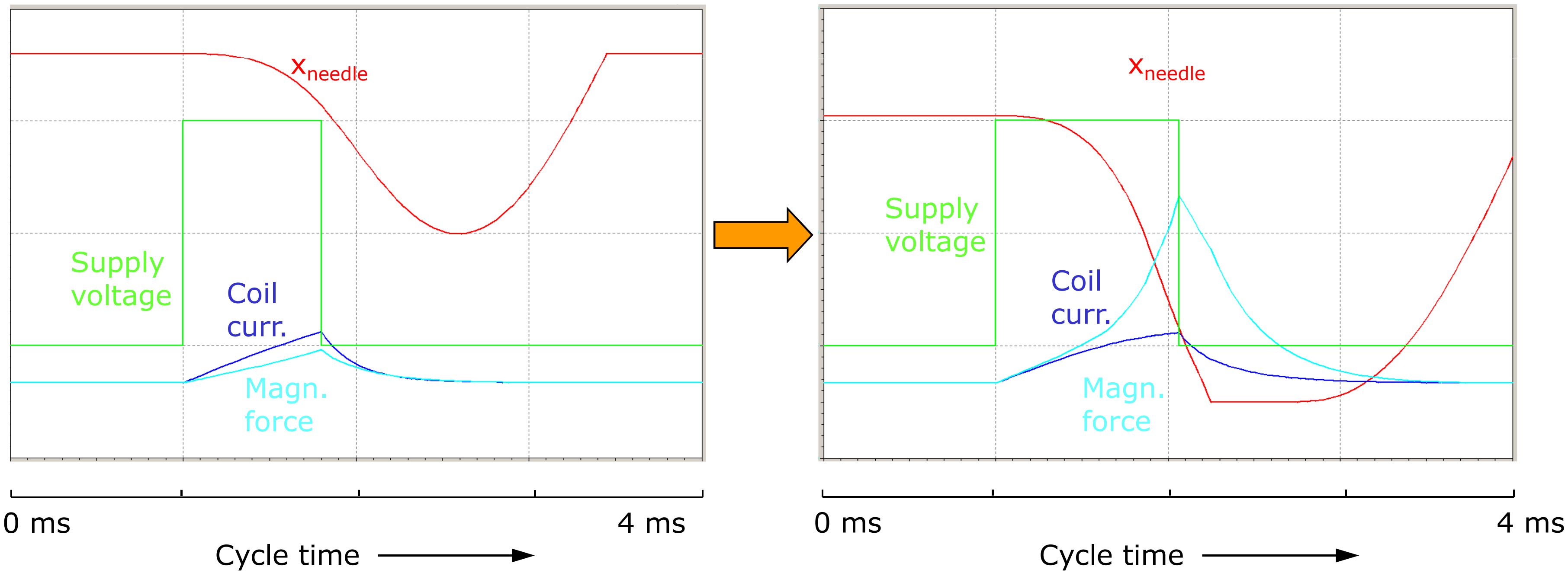
Nominal Optimization Using the Heterogeneous Dynamic Model



Nominal Optimization Using the Heterogeneous Dynamic Model

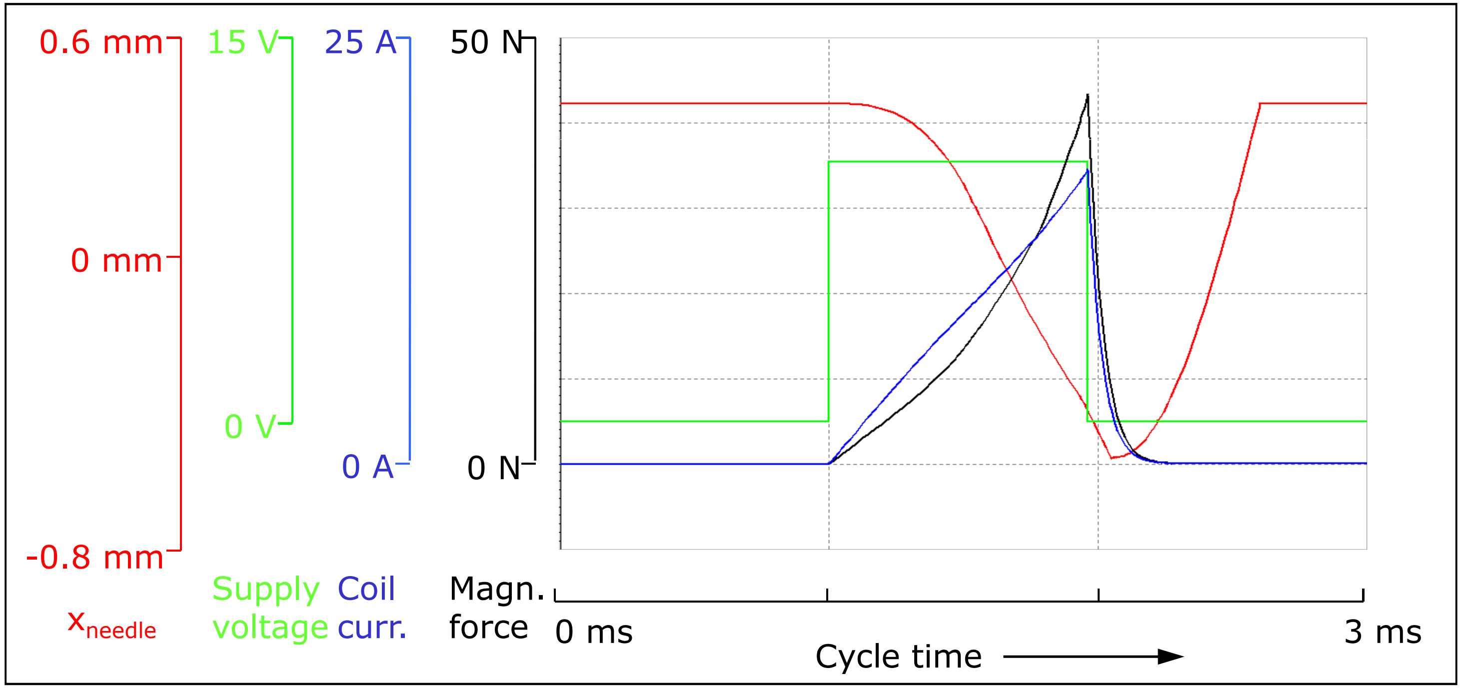
Slim preliminary design

Compact design after static optimization



Nominal Optimization Using the Heterogeneous Dynamic Model

- Minimum cycle time 2,6 ms



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   - Probabilistic Analysis
   - Robust Design Optimization
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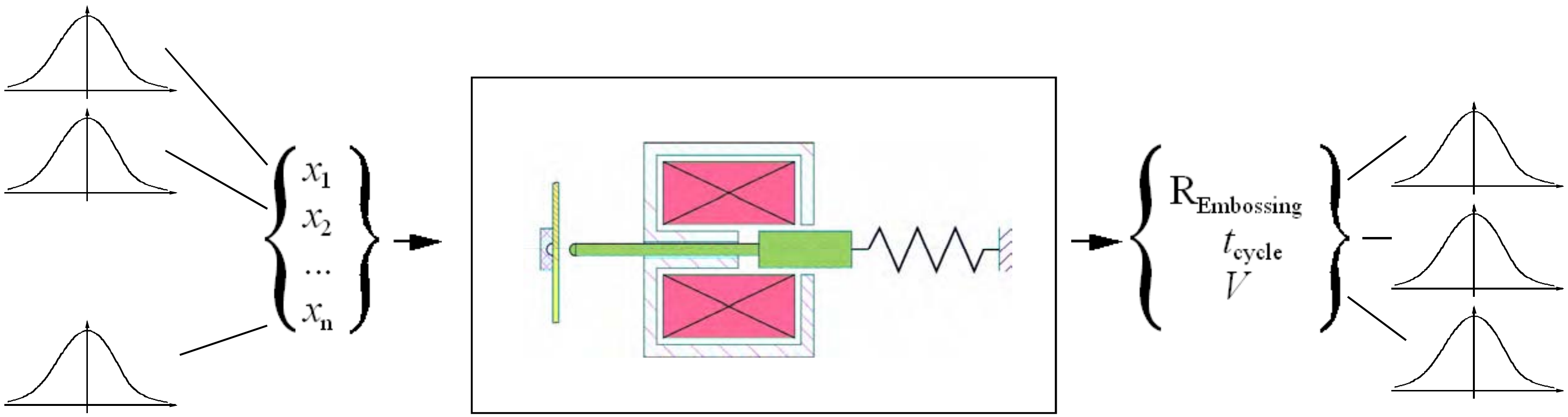
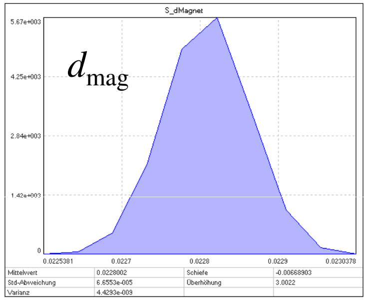
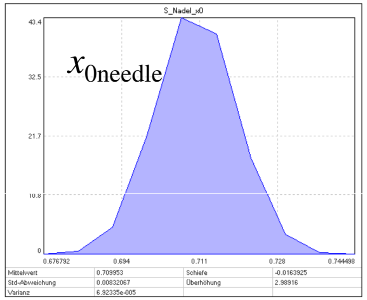
4 Robustness Analysis and Optimization

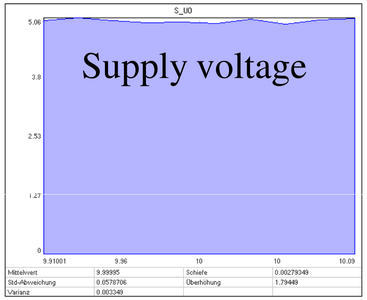
Principle of Robustness Analysis

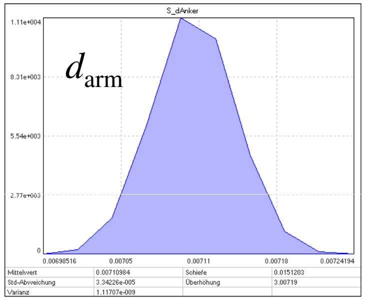


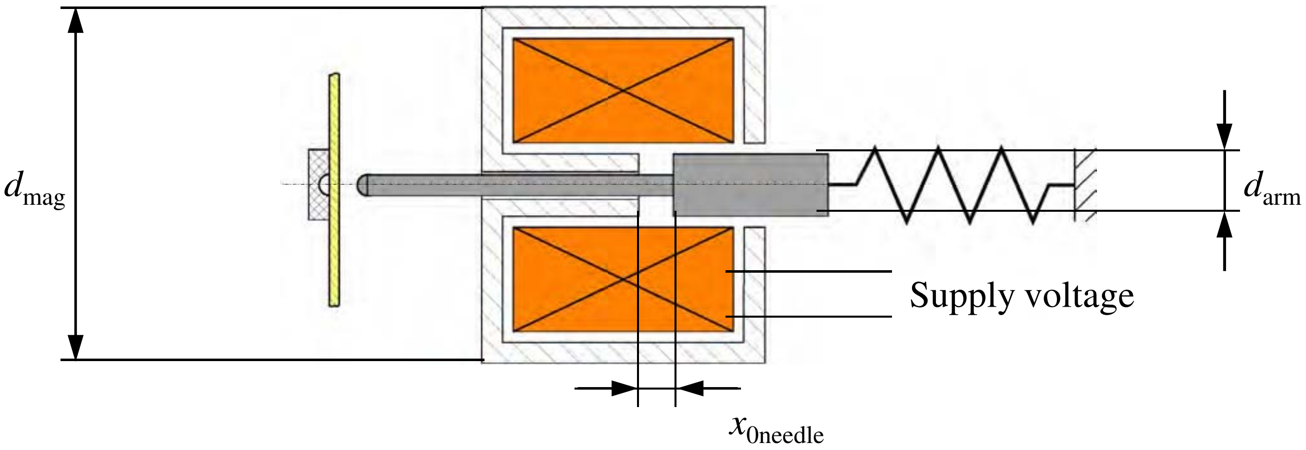
Robustness Analysis of the Braille Printer





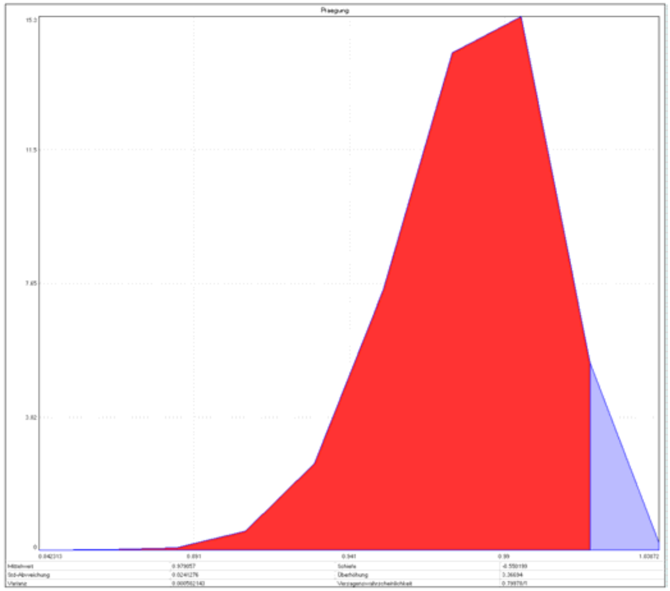


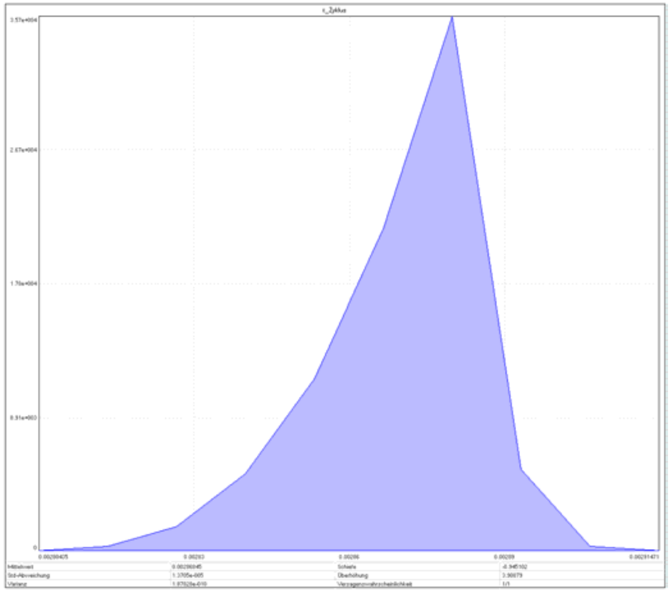




Probabilistic Analysis

- Latin-Hypercube sampling (LHS) around the nominal optimum with 200 samples
- Density functions of the system functionality (a) and of the cycle time (b)
- Failure probability of about 80 % at the nominal optimum

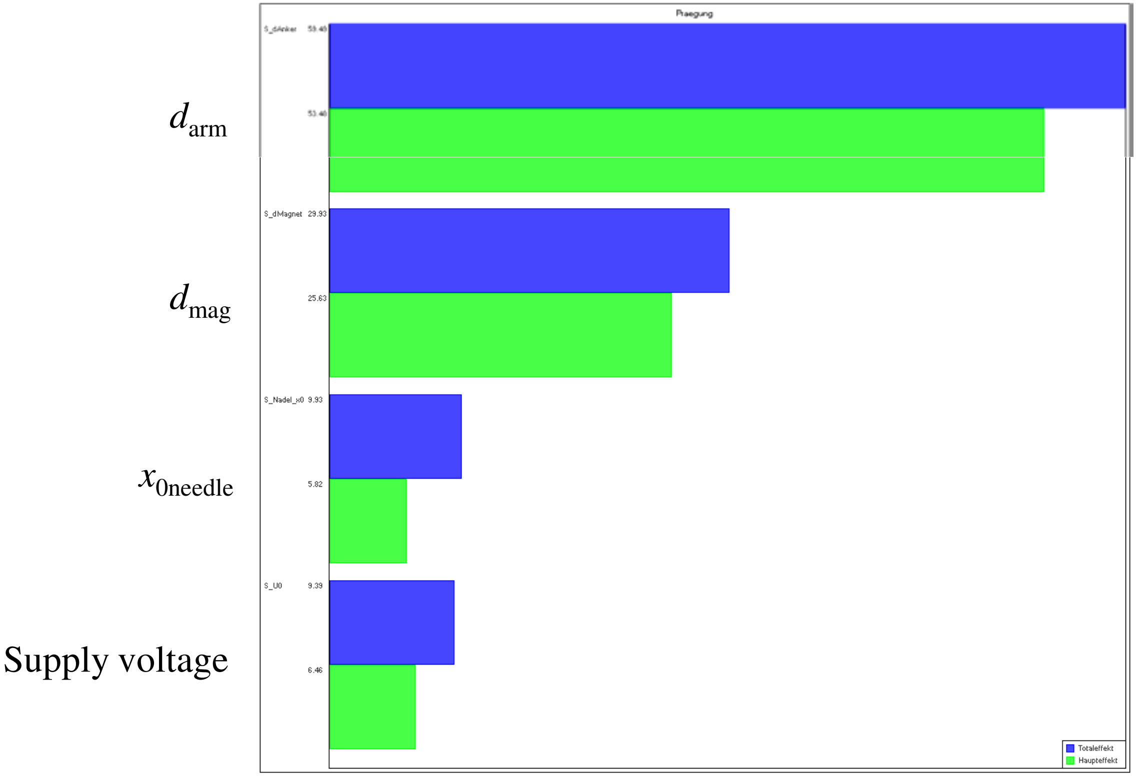
(a) 

(b) 

Probabilistic Analysis

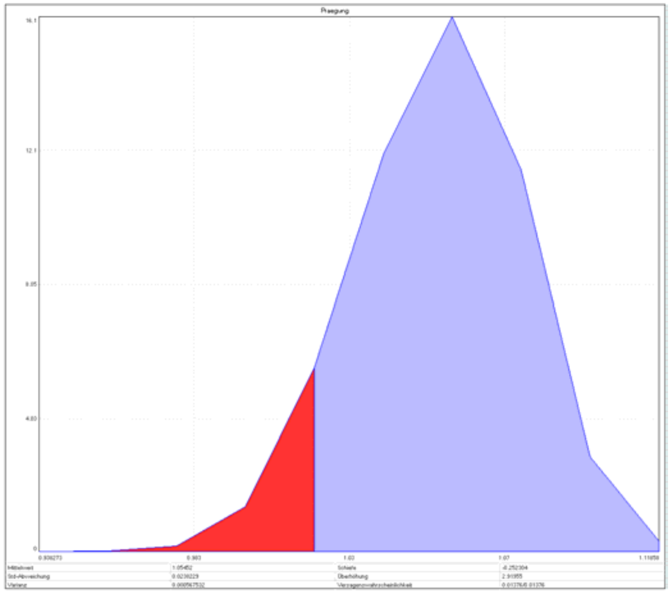
- Sensitivity analysis

System functionality



Robust Design Optimization

- Find a design of higher reliability
- Optimiziation using response surfaces instead of the system model
- LHS with a large sample size (100,000)

(a)


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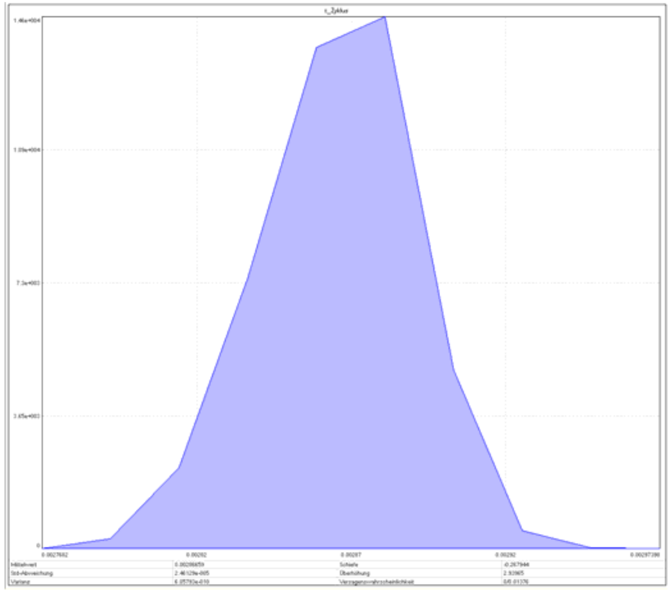

5 Conclusions

- Design optimization was performed based on a heterogeneous dynamic model.
- This model consists of a dynamic network model that includes look-up tables computed from a static FEA model.
- The look-up tables were computed in each iteration step of the optimization according to the change in the design.
- Starting from a preliminary design we obtained an optimum design for a defined set of requirements.
- The failure probability of this design was significantly improved by a robustness analysis and optimization.
- The final design meets requirements regarding functionality as well as reliability.
- OptiY 4.0, SimulationX 3.3, COMSOL Multiphysics 3.5a
- Quad-core PC running Windows
- The presented methodology can be applied to many similar design optimization processes.

Thank you for your attention.