Probabilistic Optimization of Polarized Magnetic Actuators by Coupling of Network and Finite Element Models

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1. Dresdner-Probabilistik-Workshop
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Outline

- Objective
- Concept of Probabilistic Design
  - Design Optimization with Regard to the Tolerances
  - Computation of Output Distributions
- Polarized Magnetic Actuators
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  - Modeling Approach
- Probabilistic Simulation and Optimization
  - Nominal Optimization
  - Tolerance Simulation
  - Robust Design Optimization
- Conclusions

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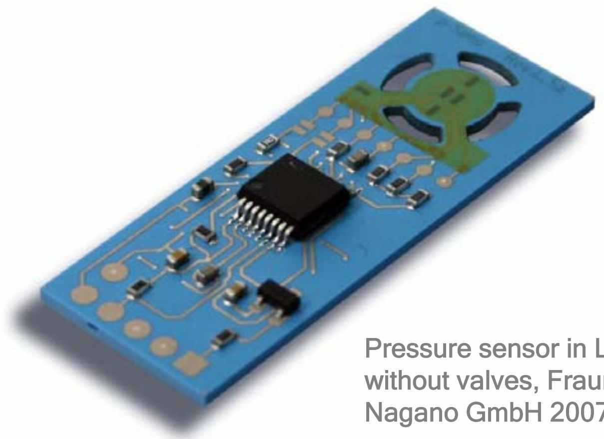
Objective

- Designing a bistable magnetic actuator for a pneumatic microvalve of an integrated pressure sensor in LTCC Multi Layer Technology
- Finding a fast acting bipolar magnetic system that features pre-defined holding forces by algorithmic design optimization
- Including the effects of geometrical and material properties tolerances on the system behavior into optimization
- Computing the distributions of the system function variables

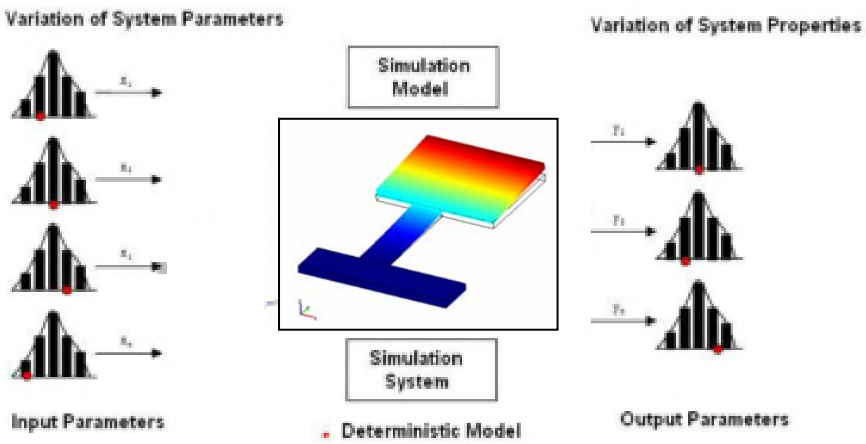


Pressure sensor in LTCC Technology without valves, Fraunhofer IKTS, ADZ Nagano GmbH 2007

Concept of Probabilistic Design

Design Optimization with Regard to the Tolerances

- Distributed input parameters:
  - Dimensional tolerances
  - Scattering of material properties
  - Shifting of ambient conditions
  - Wear and tear
  - Human influence
- Simulation model:
  - Analytic model
  - Lumped element model
  - FE-model
- Calculation of distributed output parameters (function)



Concept of Probabilistic Design

Computation of Output Distributions

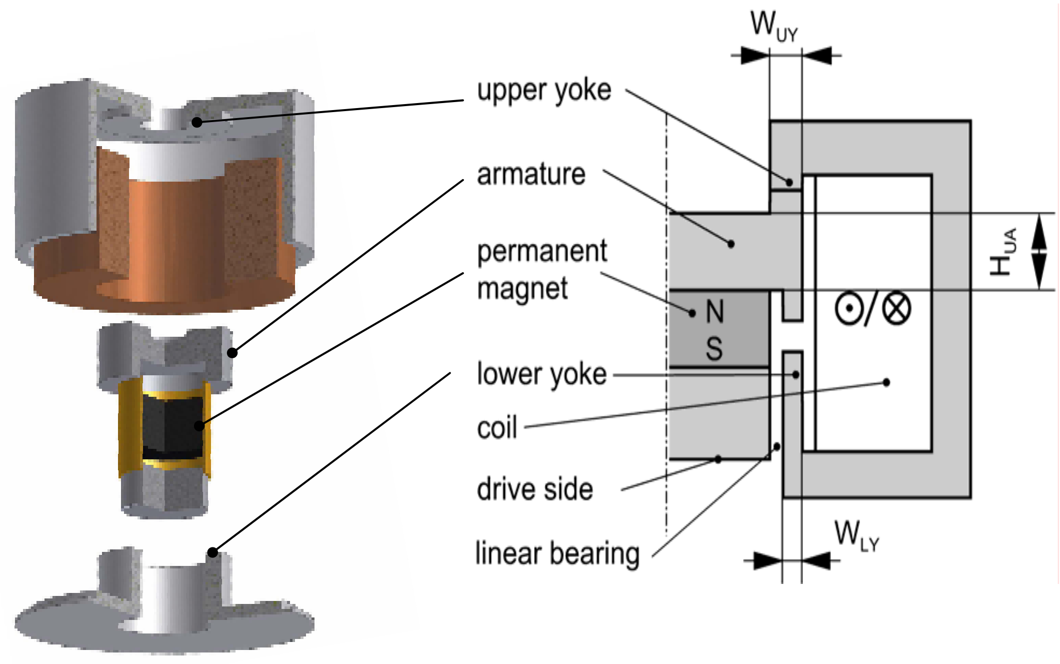
- Monte Carlo sampling
  - Random sample
  - Bad convergence properties
  - Exponential increase of the computational effort with the number of DOF‘s
  - Weak demands on the model

- Moment Method (implemented in OptiY)
  - Analytical approximation for the distribution functions by second order analysis
  - Good convergence properties
  - Quadratic increase of the computational effort with the number of DOF‘s
  - Deterministic model required

Polarized Magnetic Actuators

Working Principle

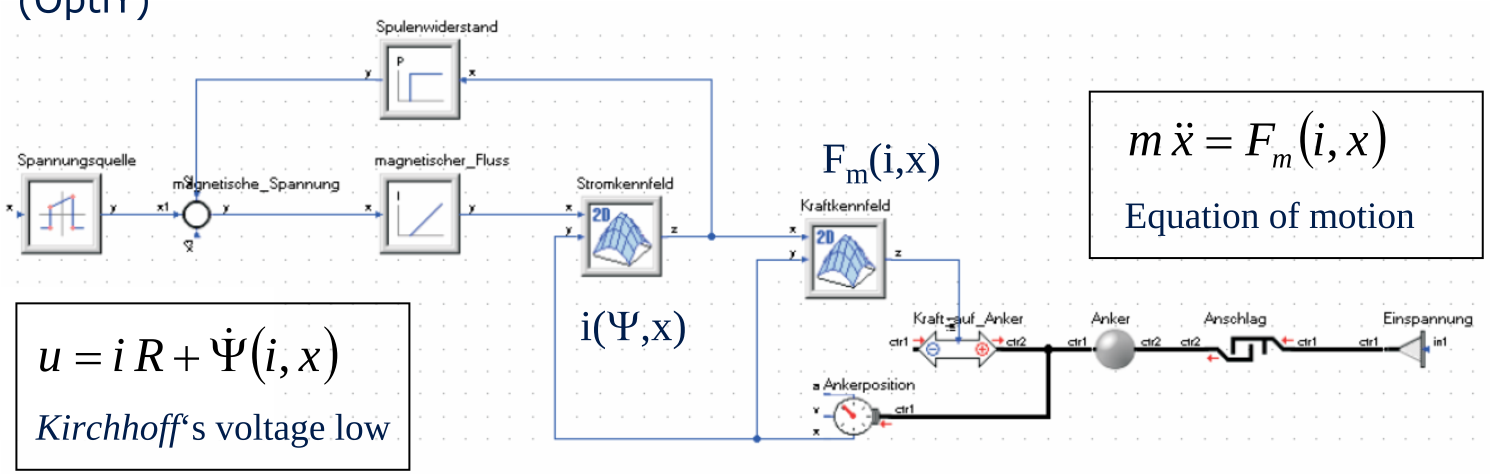
- Components:
  - Armature with permanent magnet
  - Linear bearing
  - Air-core coil
  - Upper and lower yoke
  - Back iron
- Function:
  - Bistable in both end positions
  - Controlled by +/- current pulses



Polarized Magnetic Actuators

Modeling approach

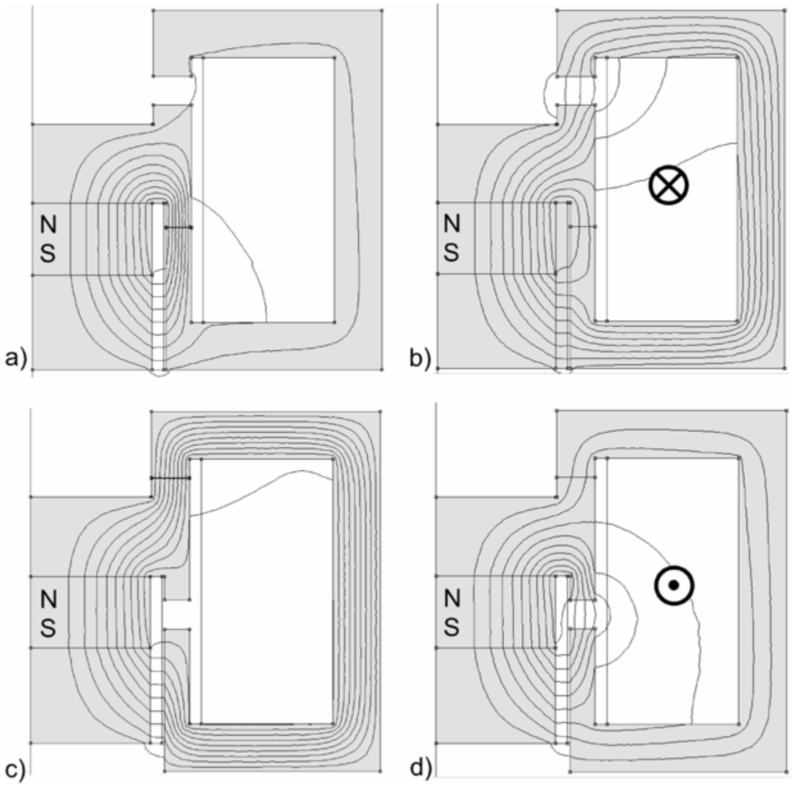
- Simulation of the dynamic behavior by a network model that includes look-up tables of magnetic flux linkage i(Ψ,x) and magnetic force $F_m(i,x)$
- Computation of the look-up tables by a FEA model
- Arrange the network model for design optimization and probabilistic simulation (OptiY)



Polarized Magnetic Actuators

Finite Element Analysis Model

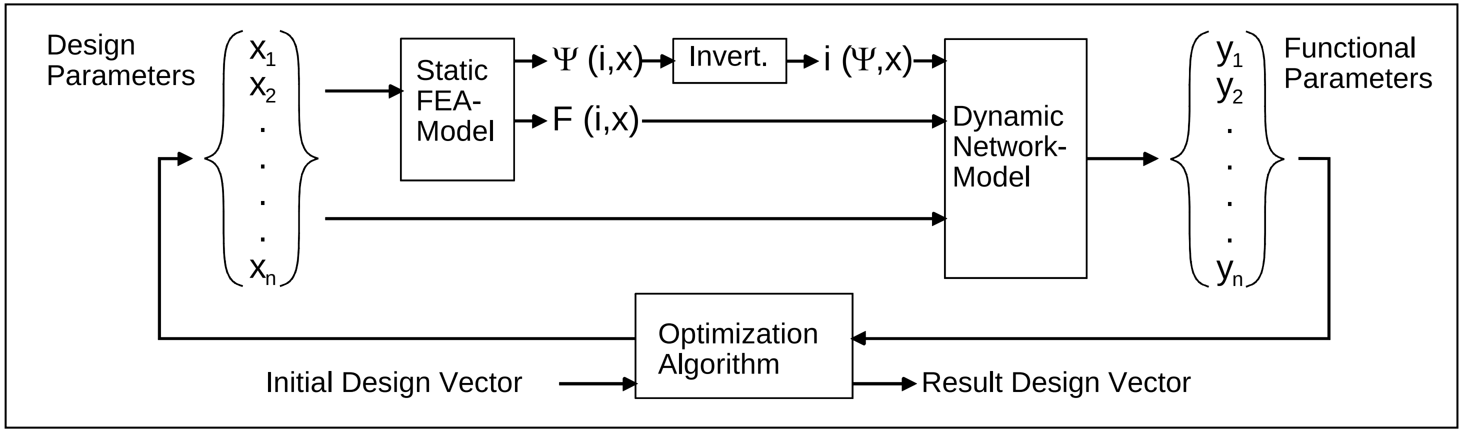
- Magnetostatic axiosymmetric 2D model
- Magnetic vector potential approach
- Implemented in FEMM 4.2
- Computation of look-up tables of flux linkage $\Psi(i,x)$ and magnetic force $F_m(i,x)$
- Reversing the flux linkage look-up table $\Psi(i,x) \rightarrow i(\Psi,x)$ by a Matlab routine

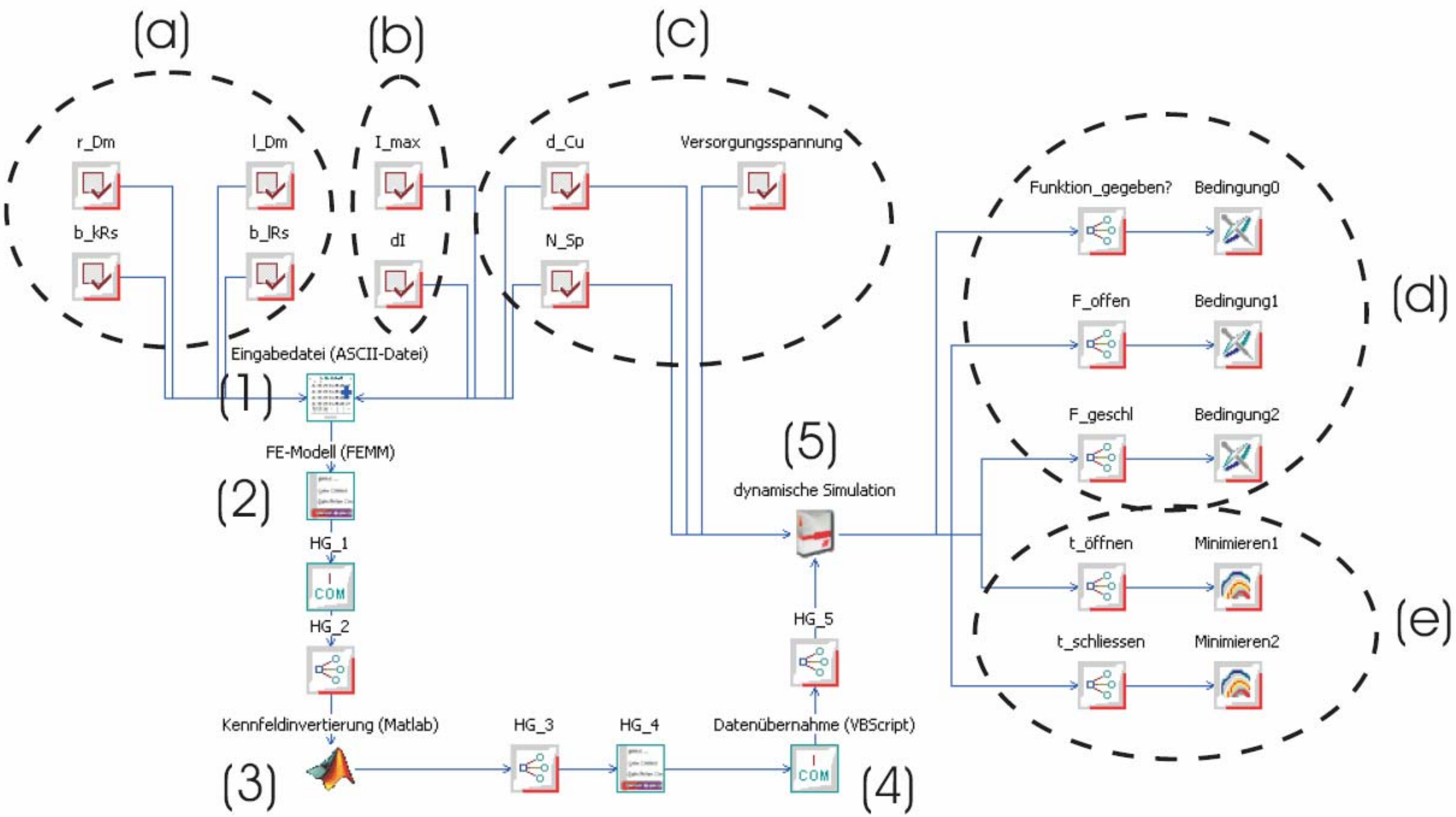


Polarized Magnetic Actuators

Model Coupling for Probabilistic Simulation and Optimization

- Arranging the data flow by the OptiY 3.0 tool
- Computation of the look-up tables on each iteration step of the optimization
- Allows the design to be changed and to be optimized
- Starting with a preliminary design (analytic approach, network model)





(a)
(b)
(c)
(d)
(e)
r_Dm
l_Dm
I_max
d_Cu
Versorgungsspannung
b_kRs
b_lRs
dI
N_Sp
Eingabedatei (ASCII-Datei)
(1)
FE-Modell (FEMM)
(2)
HG_1
HG_2
Kennfeldinvertierung (Matlab)
(3)
HG_3
HG_4
Datenübernahme (VBScript)
(4)
HG_5
(5)
dynamische Simulation
Funktion_gegeben?
Bedingung0
F_offen
Bedingung1
F_geschl
Bedingung2
t_öffnen
Minimieren1
t_schliessen
Minimieren2

Probabilistic Simulation and Optimization

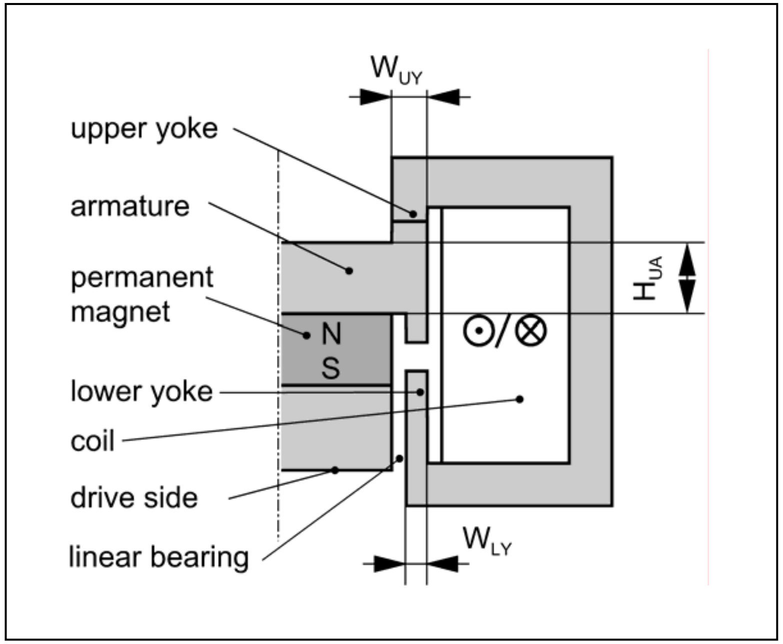
Steps in Tolerance Analysis and Optimization

- Nominal Optimization → Set of design parameters for an optimal function
- Sensitivity Analysis → Importance of the tolerances to the function
- Design for Minimal Rejections → Set of design parameters for an optimal function with regard to the tolerances

Probabilistic Simulation and Optimization

Nominal Optimization

- Input Parameters for optimization:
  - Width of the upper yoke W_{UY}
  - Width of the lower yoke W_{LY}
  - Height of the armature H_{UA}

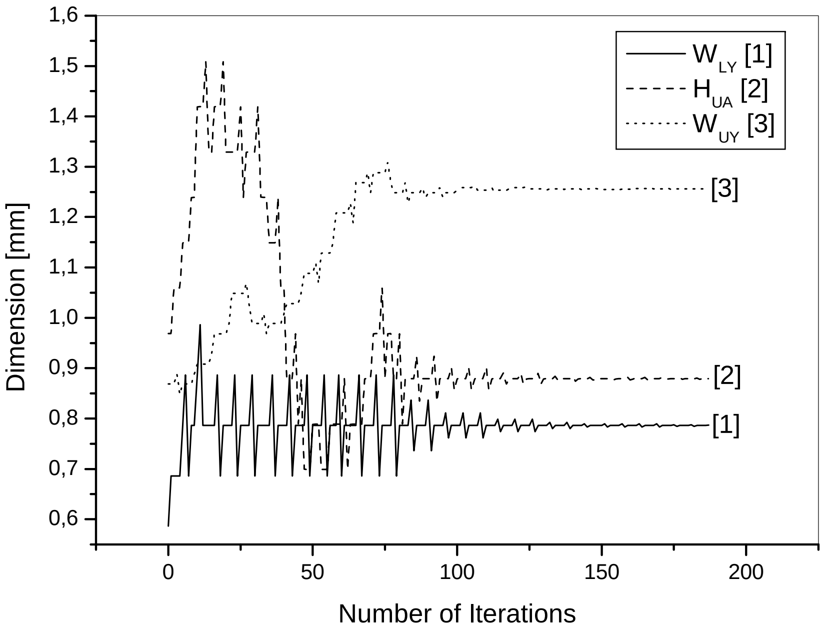


- Output Parameters for Optimization:
  - Upper holding force F_{op} → constrained [2 N;5 N]
  - Lower holding force F_{cl} → constrained [-10 N; -5 N]
  - Switching time for opening t_{op} → find minimum
  - Switching time for closing t_{cl} → find minimum

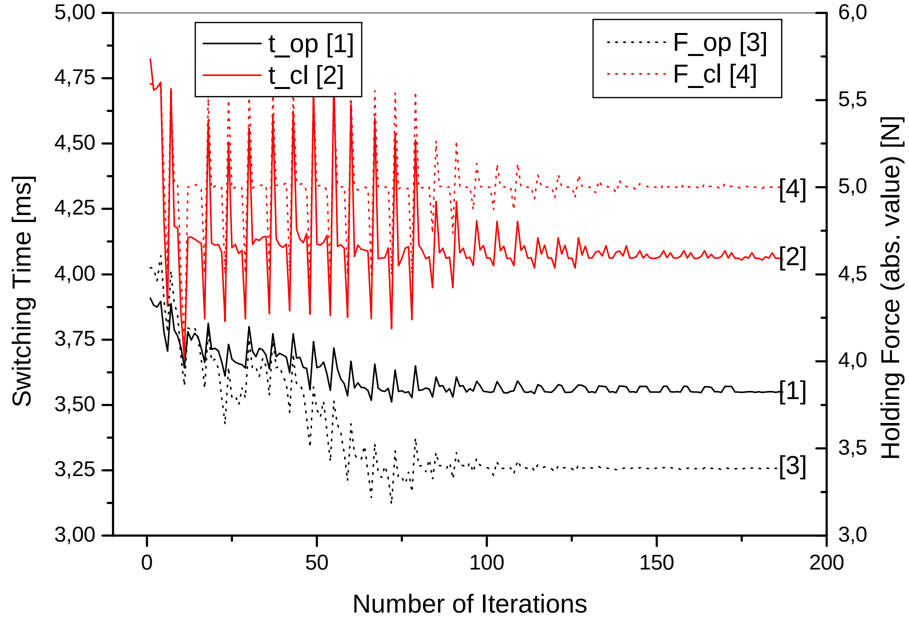
Probabilistic Simulation and Optimization

Nominal Optimization

- Design variables iteration process



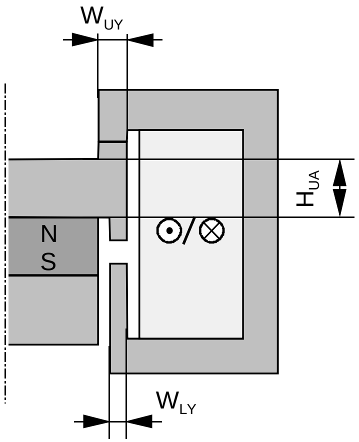
- Function variables iteration process



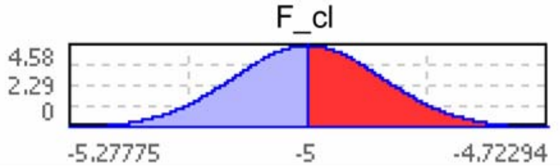
Probabilistic Simulation and Optimization

System Failure Analysis

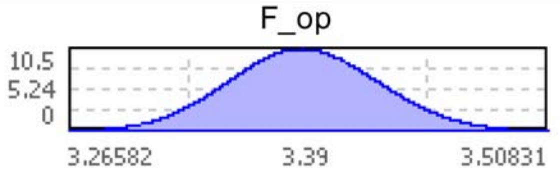
- Design variables tolerances:
  - W_{LY}, W_{UY} +/- 0.1mm (6σ)
  - Voltage +/- 0.25V (6σ)
  - Normally distributed



- Function variables distributions:



Mean	-5.00034	Skewness	-0.0183588
Standard Dev	0.0876739	Kurtosis	2.99959
Variance	0.0076867	Partial Failure	0.498718



Mean	3.38539	Skewness	0.0484834
Standard Dev	0.038347	Kurtosis	2.99114
Variance	0.00147049	Partial Failure	0

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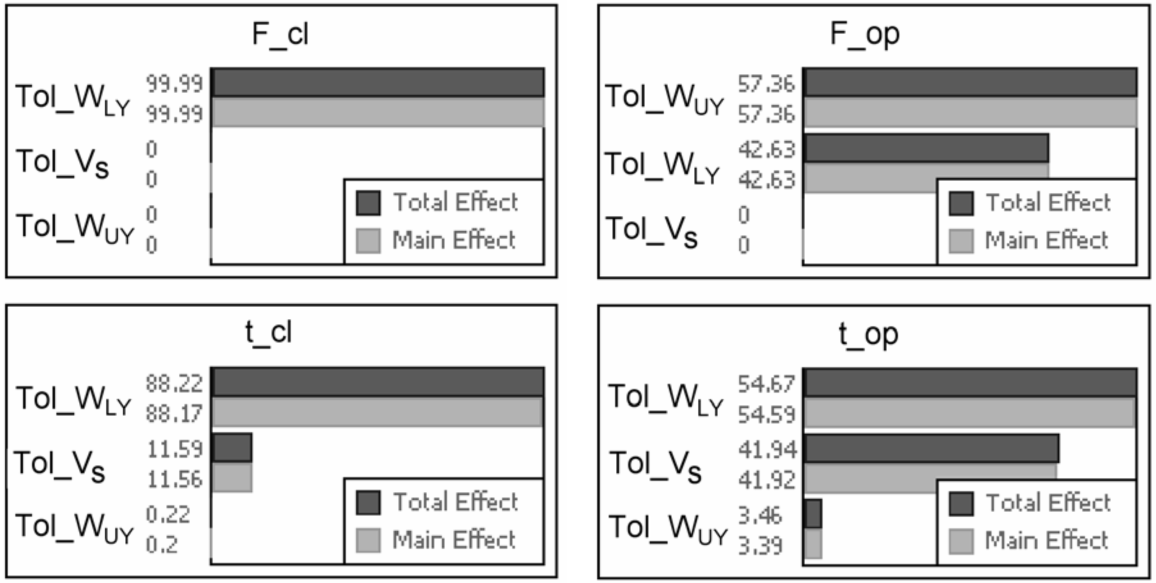
OptiY

Probabilistic Simulation and Optimization

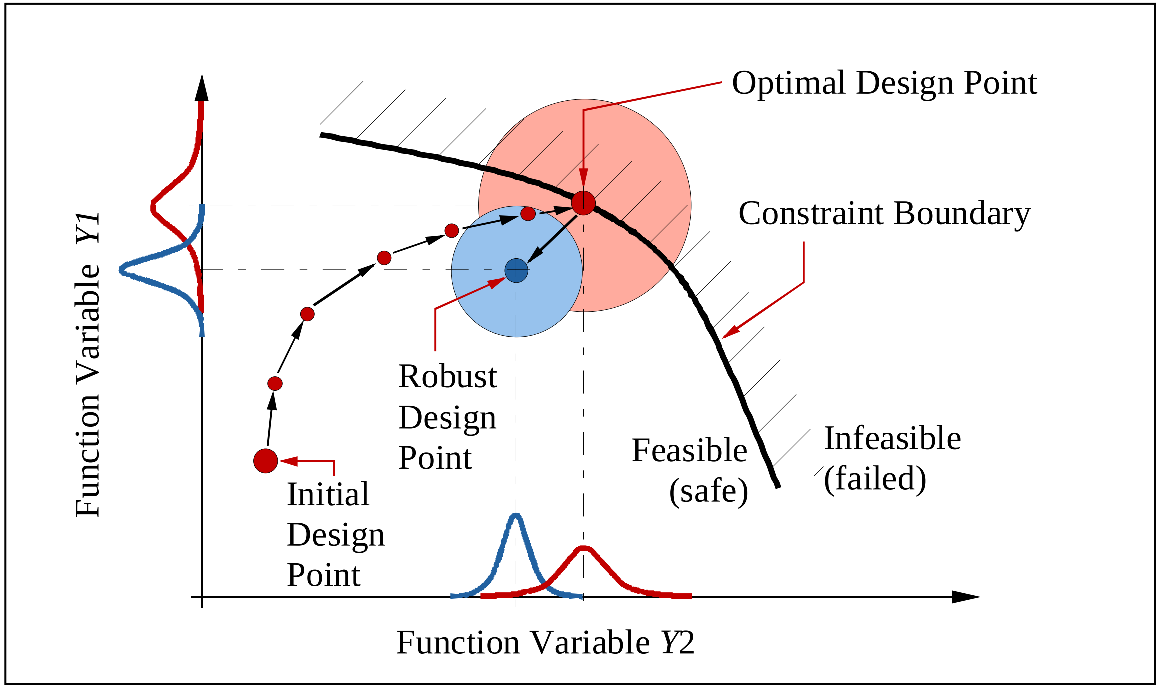
System Failure Analysis

- Pareto Charts:



Probabilistic Simulation and Optimization

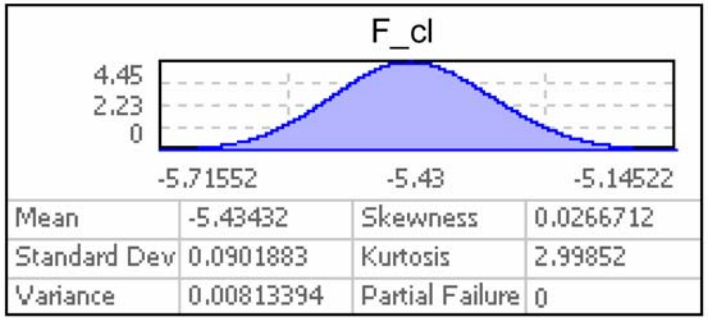
Design for Minimum Rejections

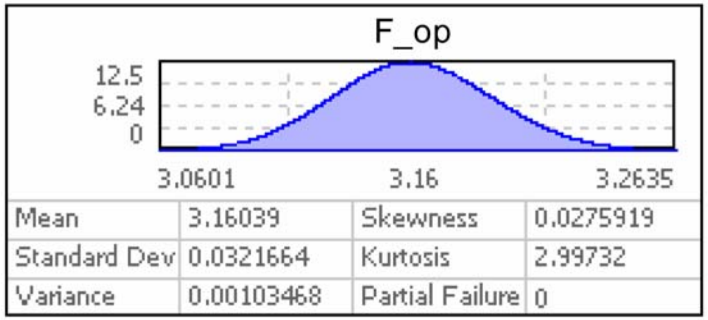


Probabilistic Simulation and Optimization

Probabilistic Design

- Minimizing the failure probability and the scattering of the function
- Optimization includes computing the distri-butions of the functional parameters on each iteration step
- Result is a design optimized for a set of func-tional requirements and design tolerances with a negligible failure probability





	Constr.	Initial Value	Optim. Value	Robust Value
F_{op}	[2N;5N]	4.7N	3.4N	3.2N
F_{cl}	[-10N;-5N]	-5.6N	-5.0N	-5.4N
t_{op}	Find Min.	4.1ms	3.6ms	3.5ms
t_{cl}	Find Min.	4.9ms	4.0ms	4.3ms

Conclusions

- By means of a bipolar magnetic actuator of a micro valve it was shown that algorithmic design optimization can be performed based on a dynamic network model that includes look-up tables computed from a static FEA model.
- The look-up tables were computed on each iteration step of the optimization according to the change in the design.
- The static holding forces were introduced as constraints, the switching times as optimization criteria to be minimized into the optimization process.
- The optimization algorithm can also handle design variables that are given in form of distribution functions, e.g. for finding a robust optimum.
- Also other dynamic properties can be included in the optimization, e.g. the velocity of the armature at certain points of the working stroke.
- In further models the eddy currents should have to be involved for more accurate results.
- The effort to merge the different simulation systems inside of the optimization tool OptiY is low.
- All computations were done on a quad core PC running windows.

Thank you for your attention.