Combining Simulation and Machine-Learning for Real-Time Load Identification in Sensorial Materials

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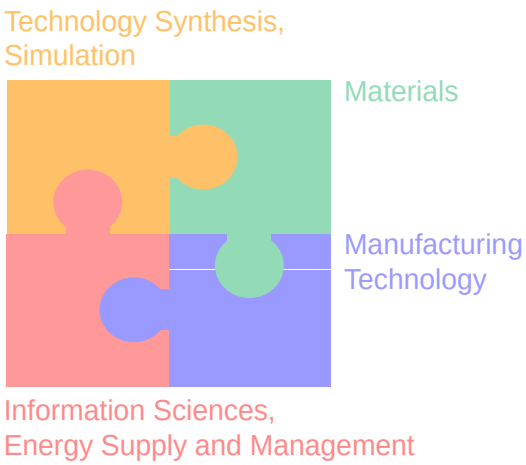
Introduction

ISIS Sensorial Materials Scientific Centre

- ISIS:
  Integrated Solutions in
  Sensorial Structure Engineering
- Scientific centre at the
  University of Bremen, Germany
- Founded in Nov. 2008
- Approx. 60 members from
  - Production engineering,
  - Physics/electrical engineering,
  - Computer science, robotics, and
  - Biological/chemical engineering



Outline

In this presentation:

- Motivation: Sensorial Materials
- Vision: Monitoring Complex Structures with Intelligent Agents
- Our Machine-Learning Approach to Real-Time Load Identification
- Evaluation Scenario: A Simple Rubber Plate
- Conclusion and Outlook

Motivation

Structural Analysis vs. System Identification

- In classical structural analysis we calculate the system answer based on a predefined model e.g. for the material and the boundary conditions of the system.

  → system answer, e.g. displacements/strain
- In classical material science we apply sensors to verify our models (e.g. measuring displacements or strains).

  → material laws
- In classical system identification we perform a series of measures of system answers to derive the system properties (model).

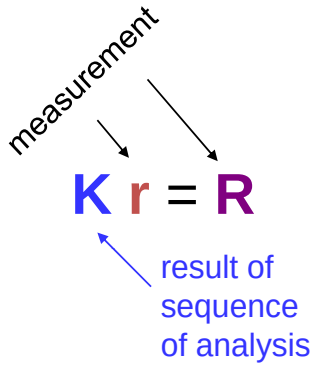
  → system characteristics, e.g. stiffness

Motivation

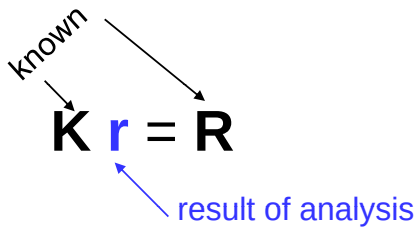
Structural Analysis vs. System Identification

- Basic approaches – different perspectives

System identification



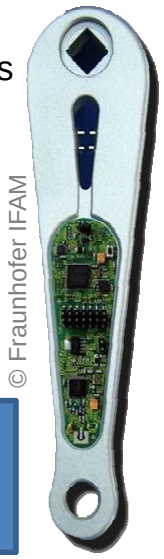
Structural analysis



Motivation

Sensorial Material

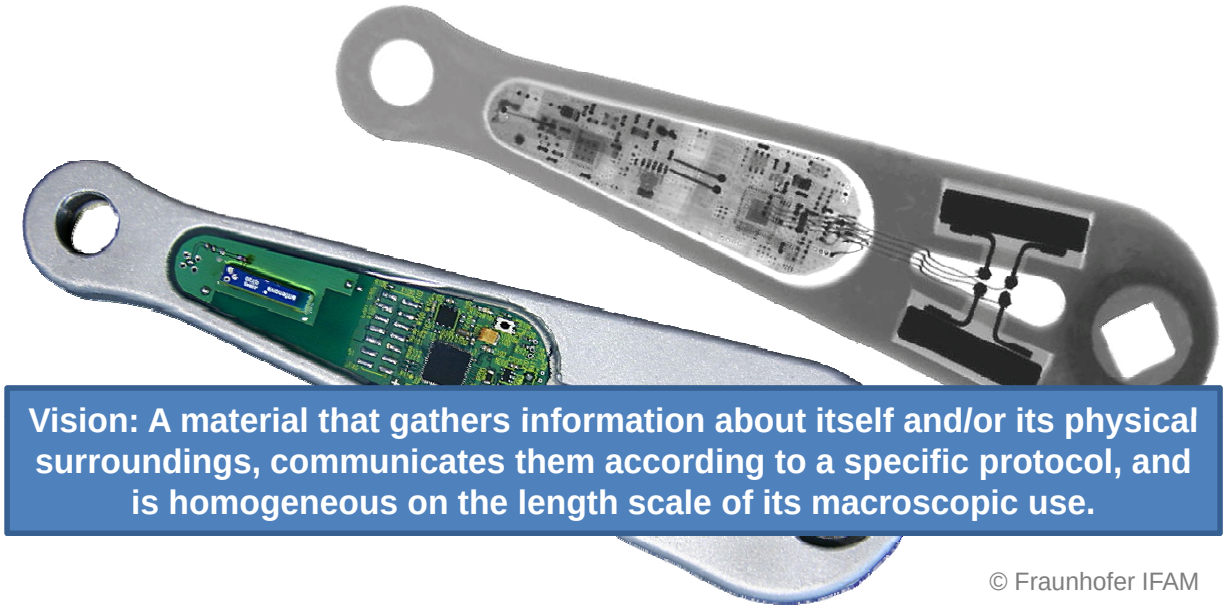
- "Sensorisation" means **to equip technical structures with an analogue of a nervous system** by providing a network of sensors, communication facilities linking these and specific hardware as well as computational methods to derive meaning from their combined signals.
- Sensors detect if **"overloading"** occurs:
  - Strain is beyond the yield limit
  - A predefined number of load cycles was reached
  - …



Instead of designing once and testing event-based or in predefined intervals, the material is continuously monitoring itself by means of sensors.

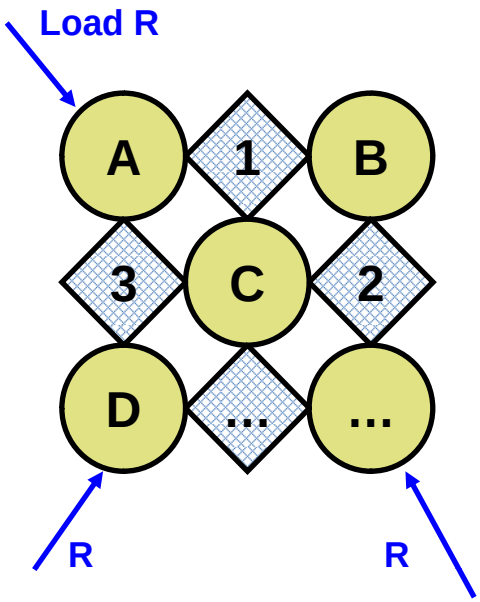
Motivation

Increase Sensor Density of Sensorial Structures



Vision: A material that gathers information about itself and/or its physical surroundings, communicates them according to a specific protocol, and is homogeneous on the length scale of its macroscopic use.

Structure Monitoring With Intelligent Agents

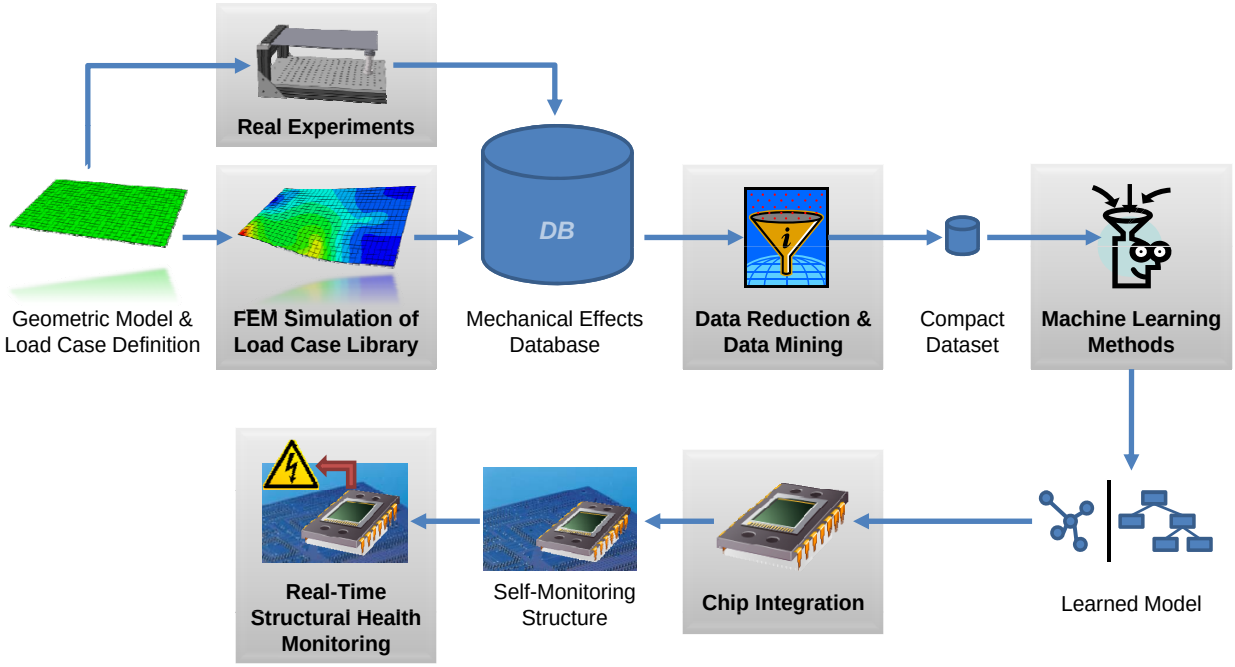


FE substructure simulation based on mechanical model

Sensor element answering to applied loading

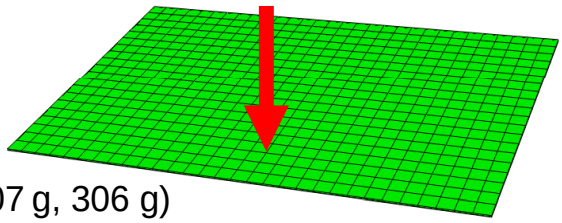
Sub-structuring with compatibility conditions

Our Approach Towards Sensorial Structures



Evaluation Setup

Simple Nitrile Rubber Plate Scenario

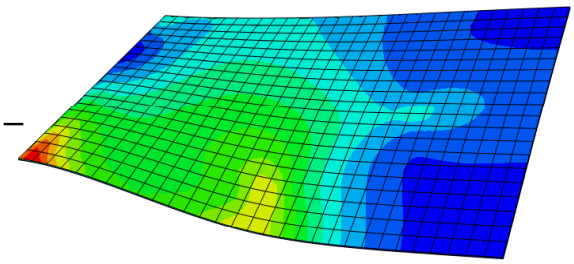


- Application of different load cases

  In our evaluation:
  - 150 different load positions
  - Three different masses (103 g, 207 g, 306 g)

- Can we infer properties of an unknown load case from only a few observed deformation effects?

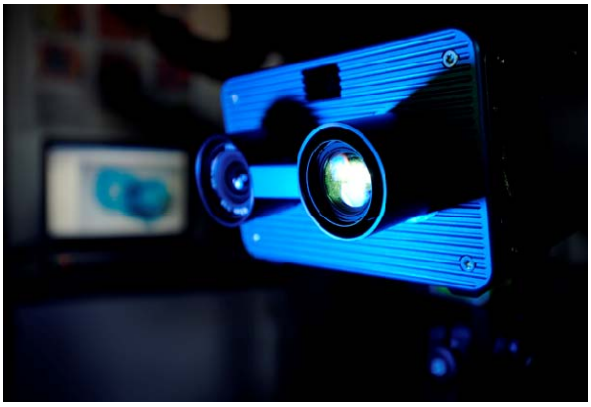
  In our evaluation:
  - Can we infer load position, load mass, and displacement vectors – especially in-between sensor positions?

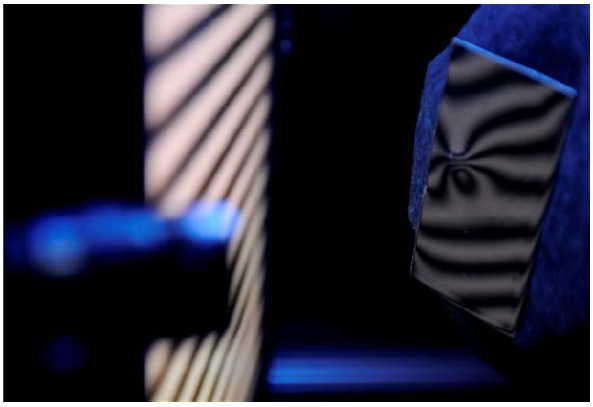


Sensor Input

Optical Surface Metrology Techniques

- Shearograhy / Fringe Projection to be used as reference to measure the *real* deformations that occurred
- Naturally, the data obtained by these methods will not be free of noise either...





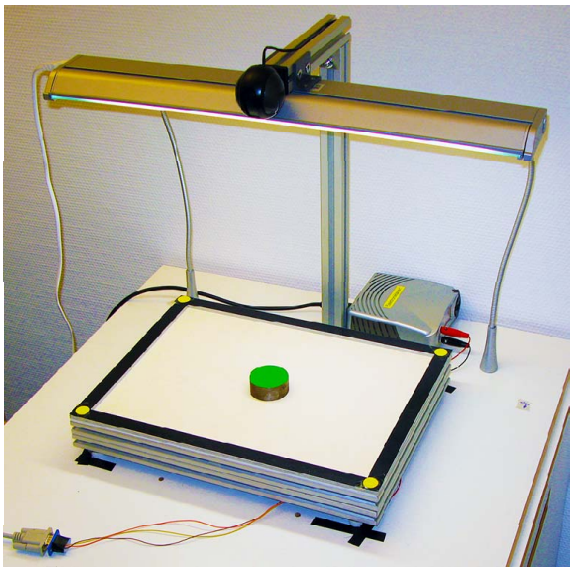
Load Inference Prototype

Simple Nitrile Rubber Plate Scenario

ISIS Functional Mockup:

- NBR-60 rubber plate 360 x 260 x 3 mm
- Fixed at all four edges

- Weights placed on top face
- Strain measurements on bottom face
- Camera records position and mass of loads



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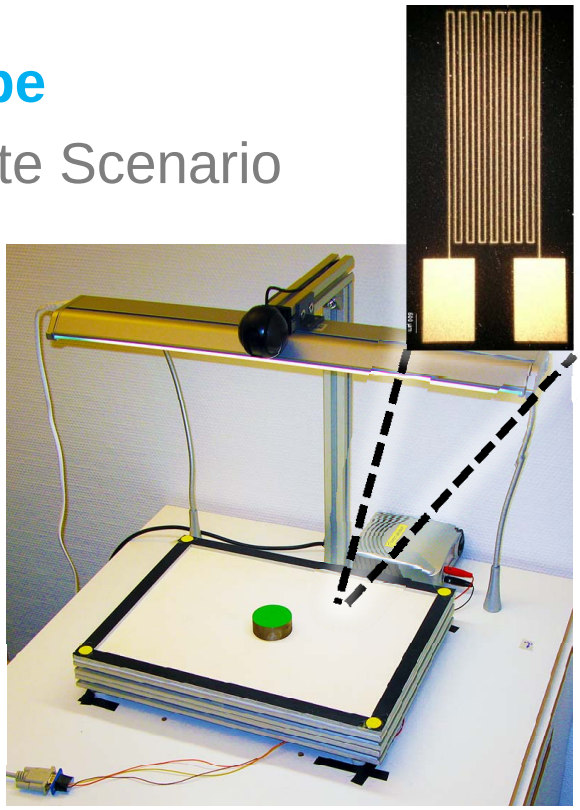
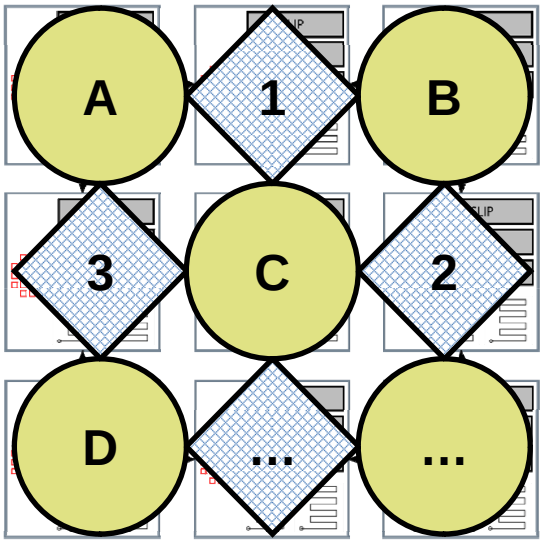
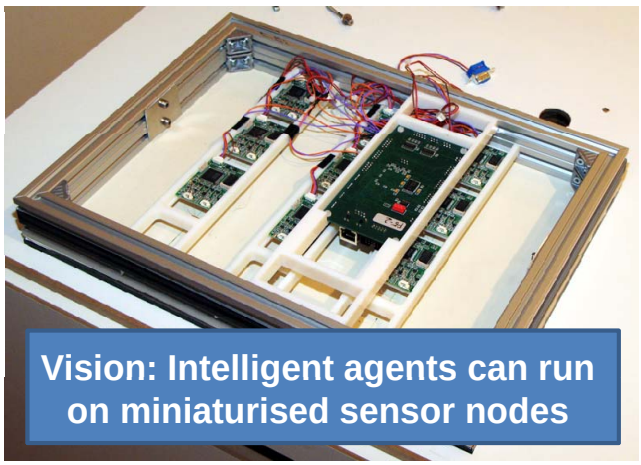


Load Inference Prototype

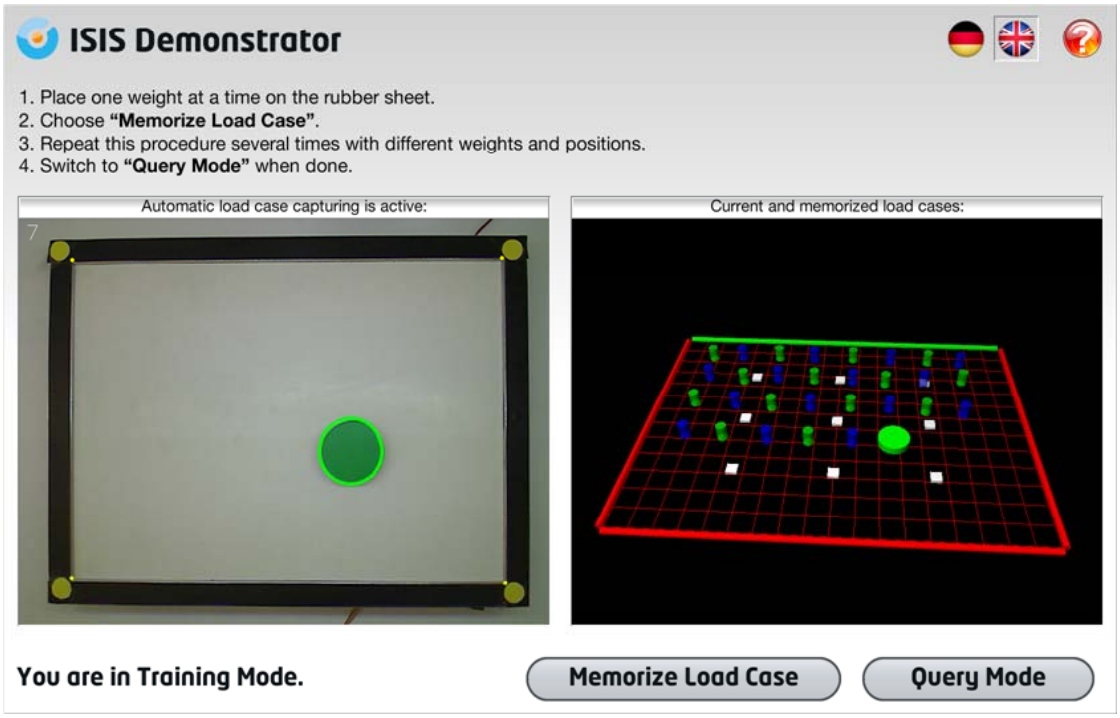
Realisation of a Robust Sensor Network





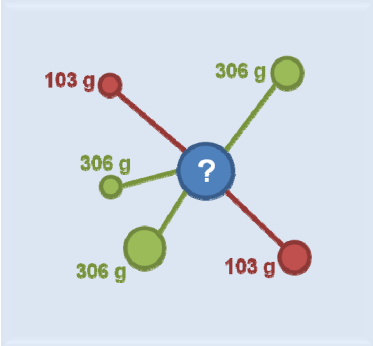
(Digital circuits currently miniaturisable to approx. 6 mm² per node / 1-2 cm² with analogue circuits)

Evaluation Setup

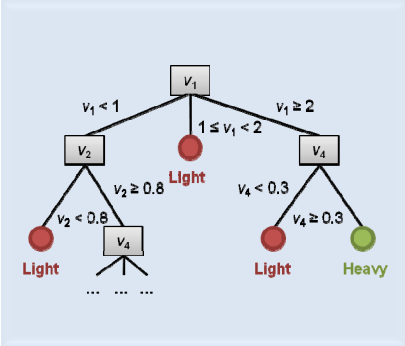


Machine Learning Methods

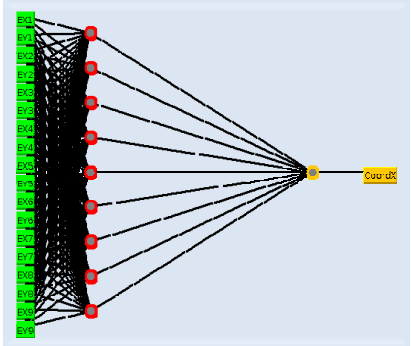
k-Nearest-Neighbour | C4.5 Decision Trees | Neural Networks



Numerical Regression of Load Position, Mass, and Displacement Vectors

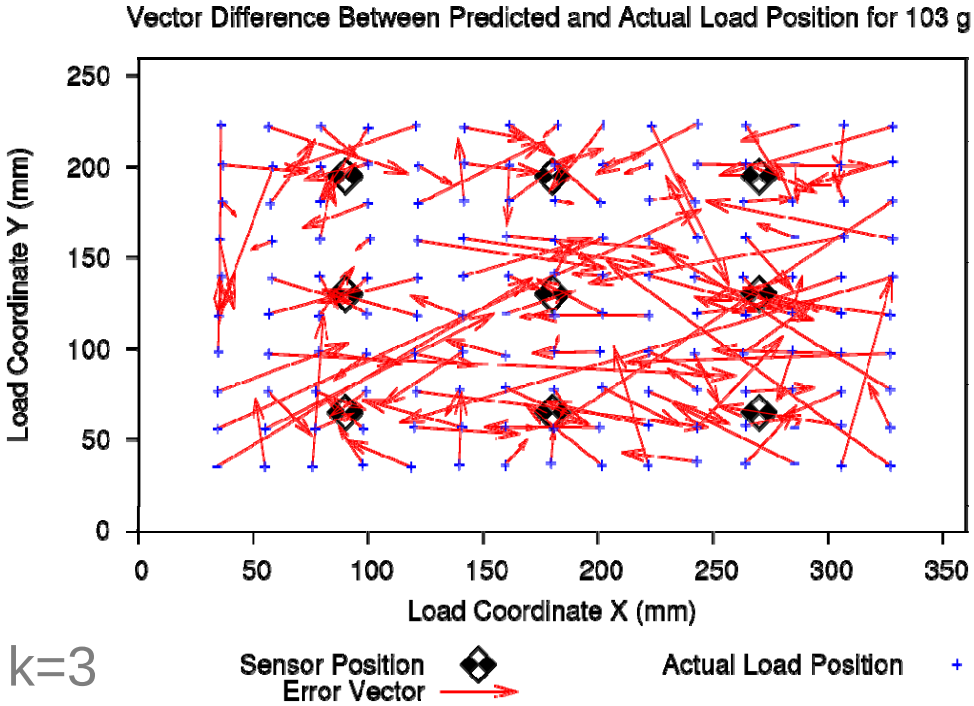


Mass Classification



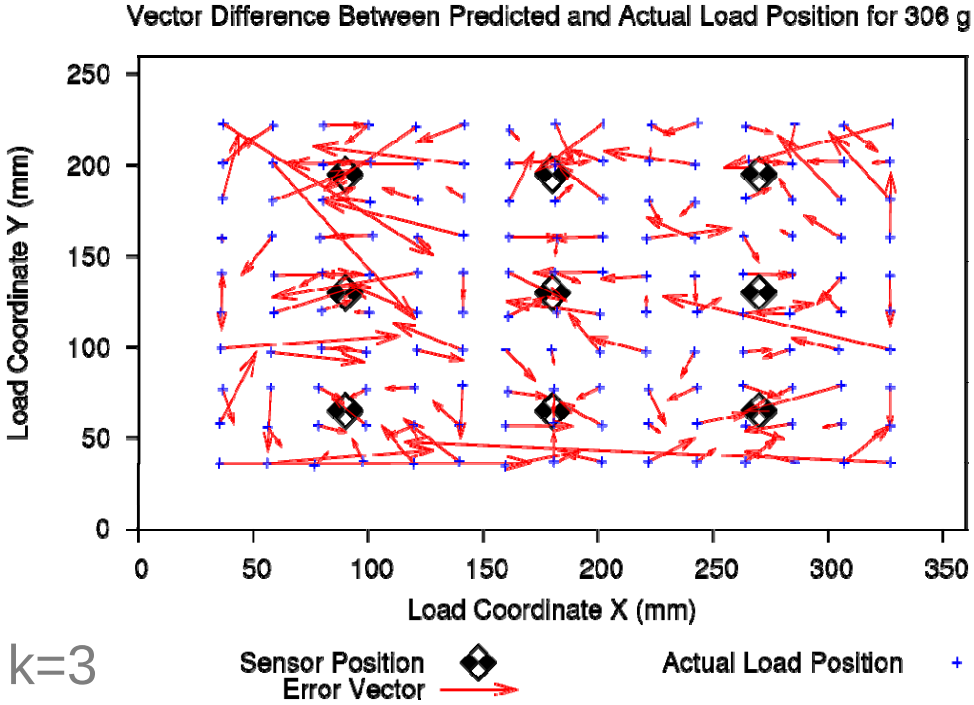
Numerical Regression of Load Position and Mass

Experimental Results — k-NN Location Error



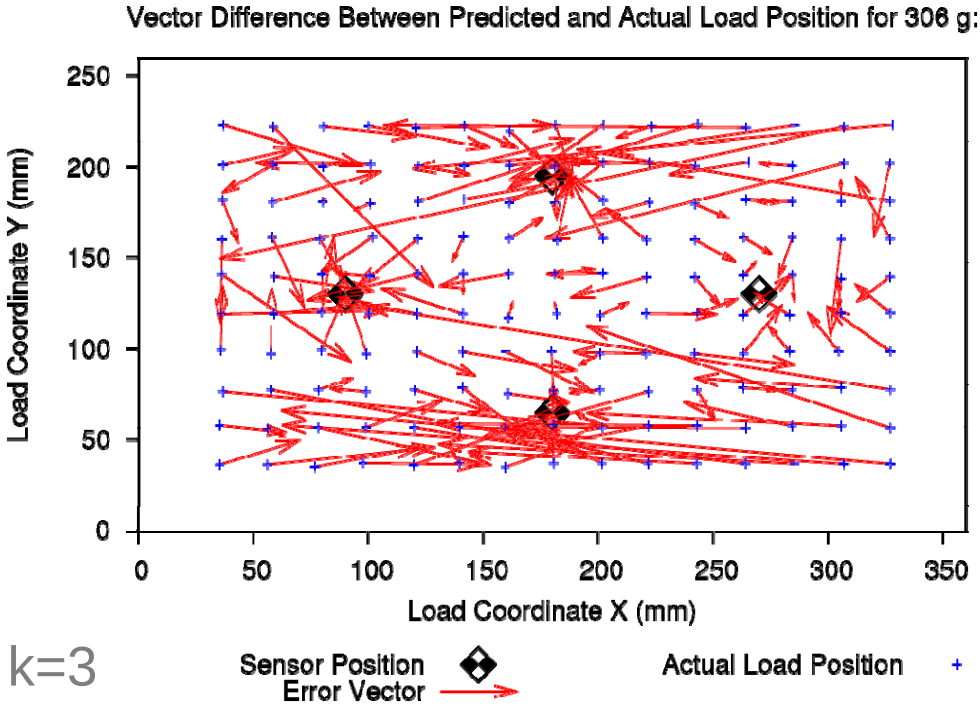
k=3

Experimental Results — k-NN Location Error



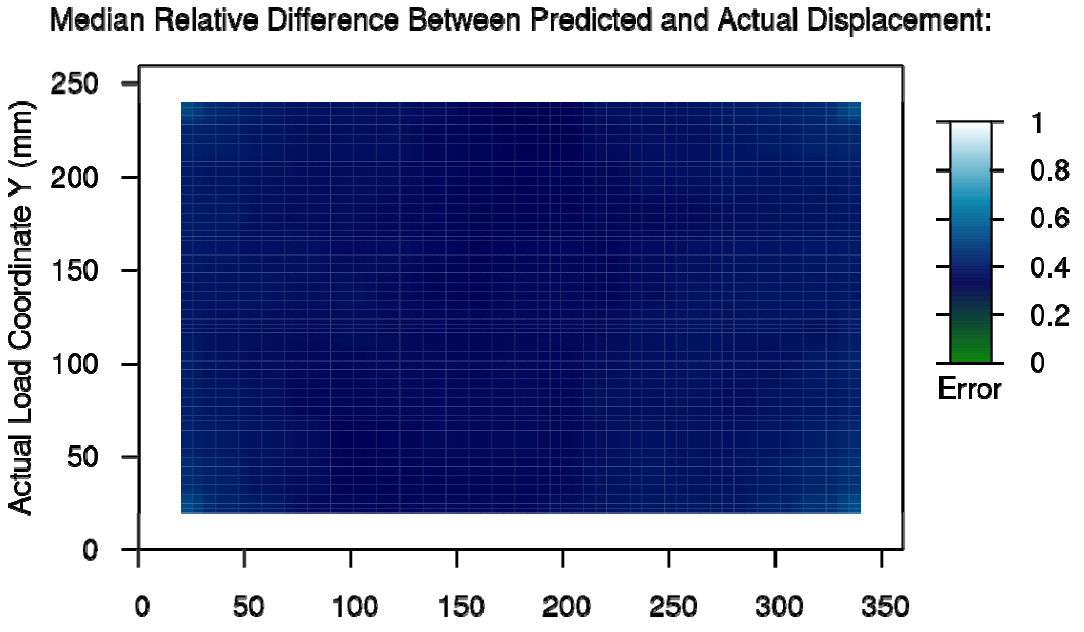
k=3

Experimental Results k-NN Location Error



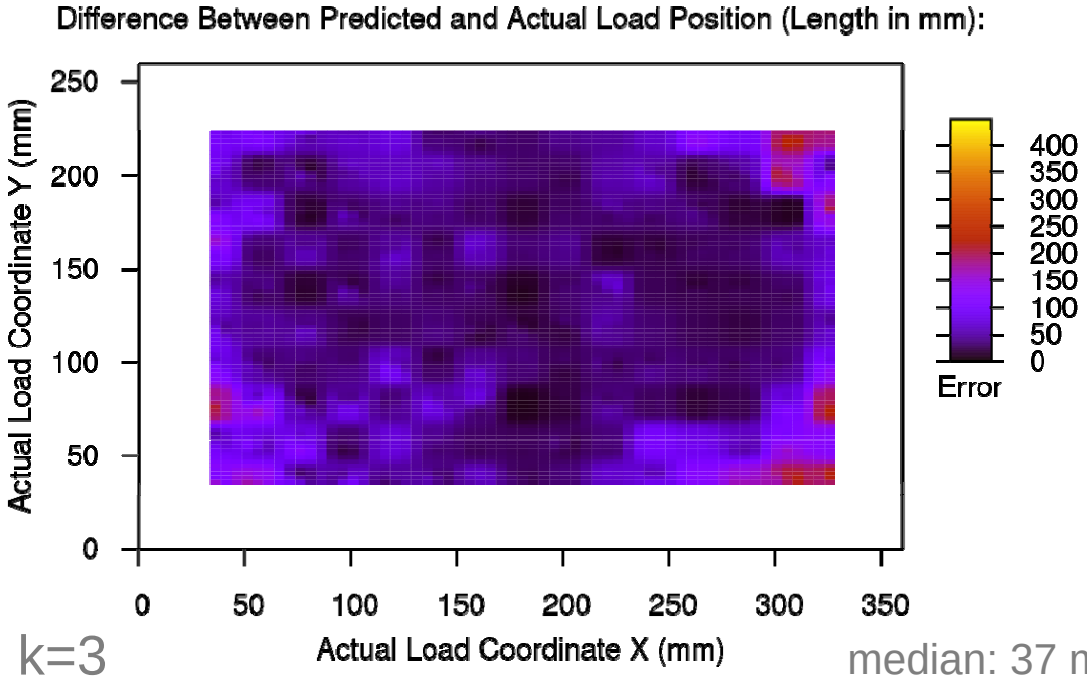
k=3

Experimental Results k-NN Displacement Error



k=4 overall median: 0.36

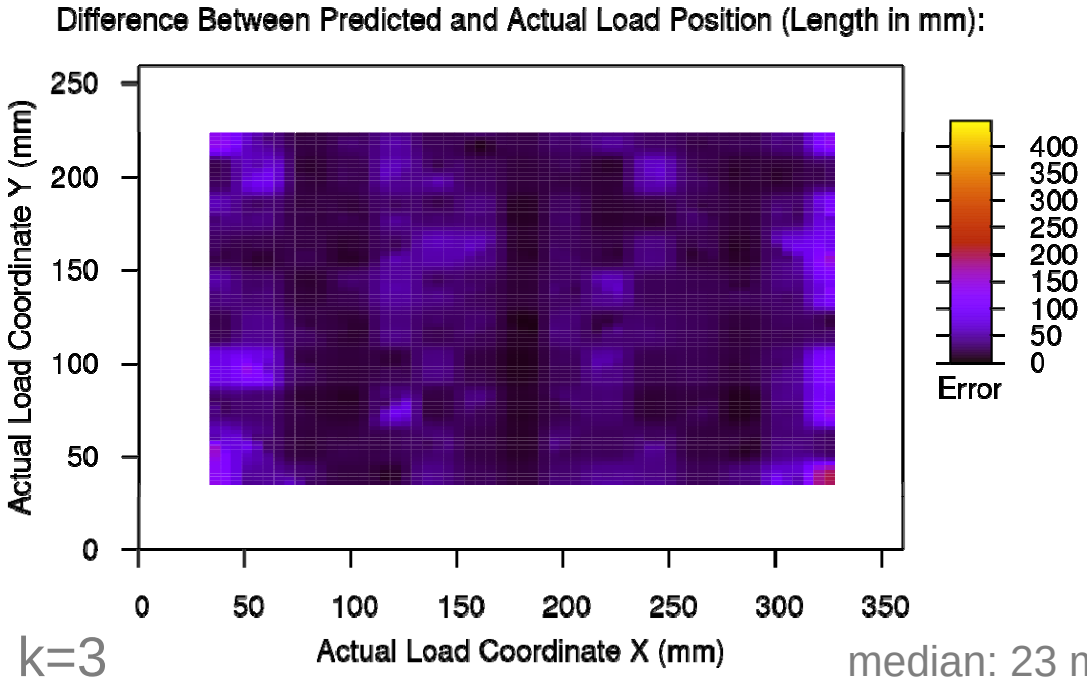
Experimental Results — k-NN Location Error



k=3

median: 37 mm

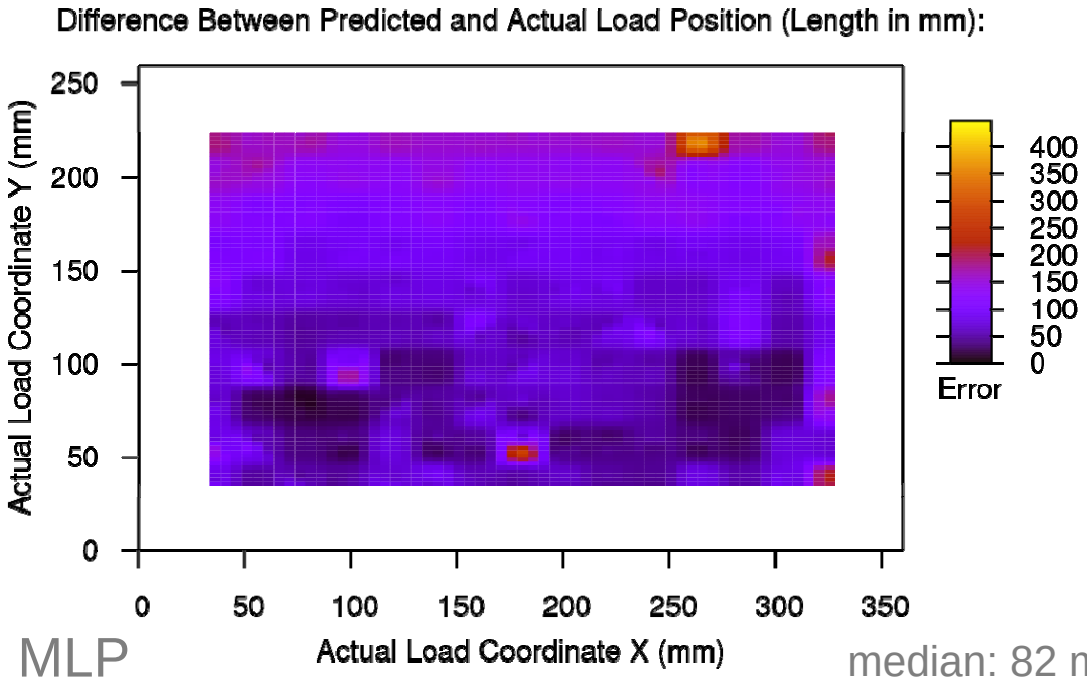
Experimental Results — k-NN Location Error



k=3

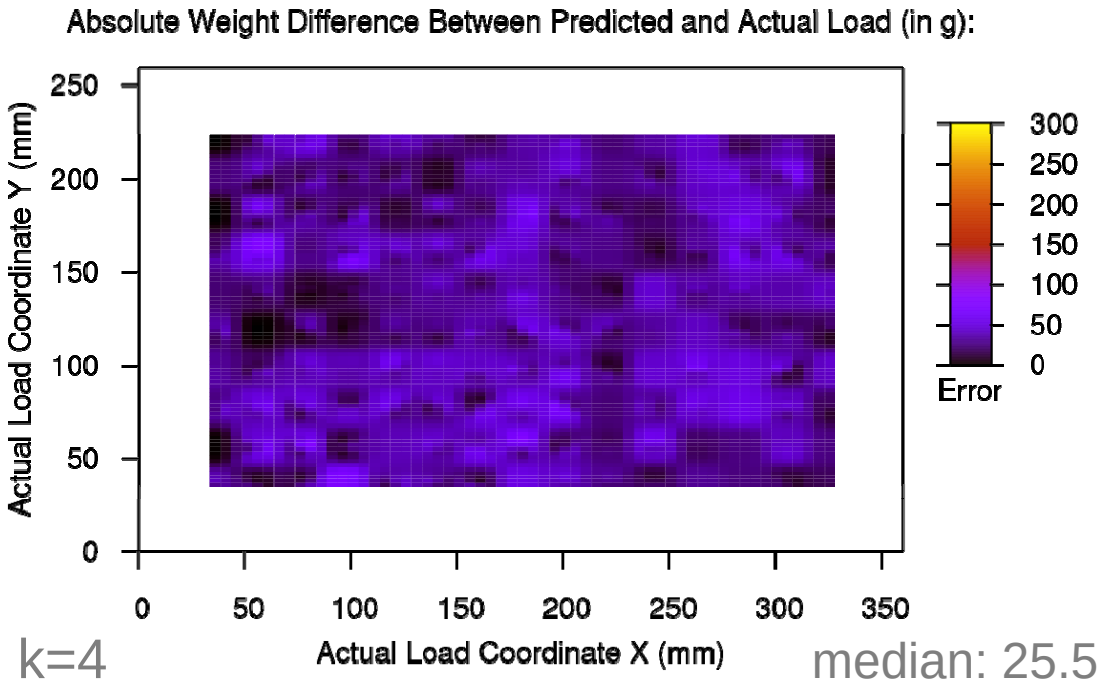
median: 23 mm

Experimental Results Perceptron Location Error



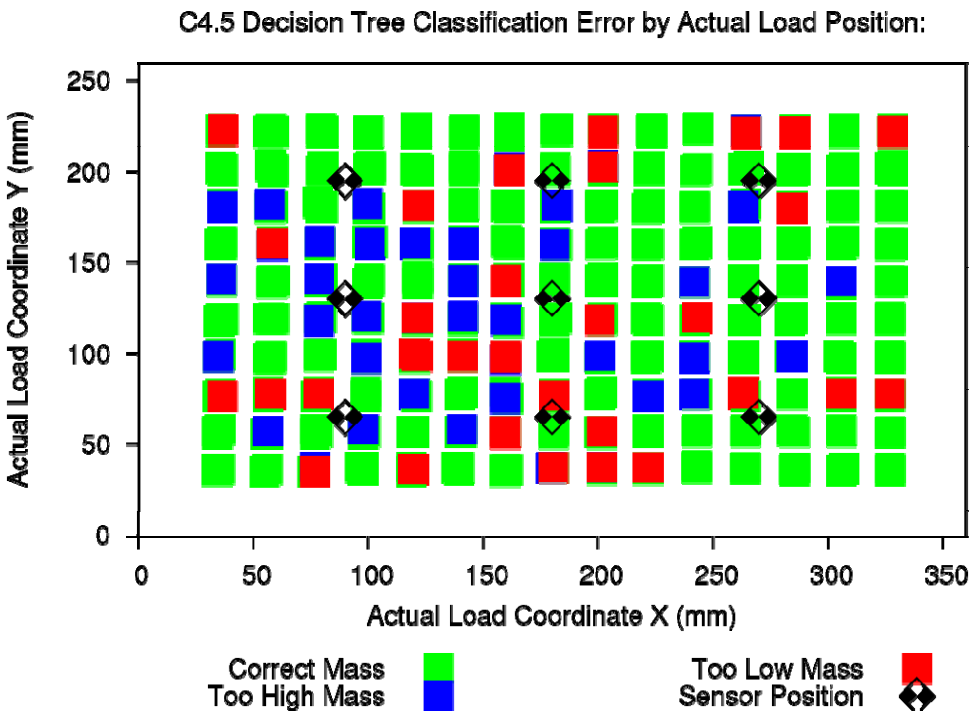
MLP median: 82 mm

Experimental Results k-NN Mass Error



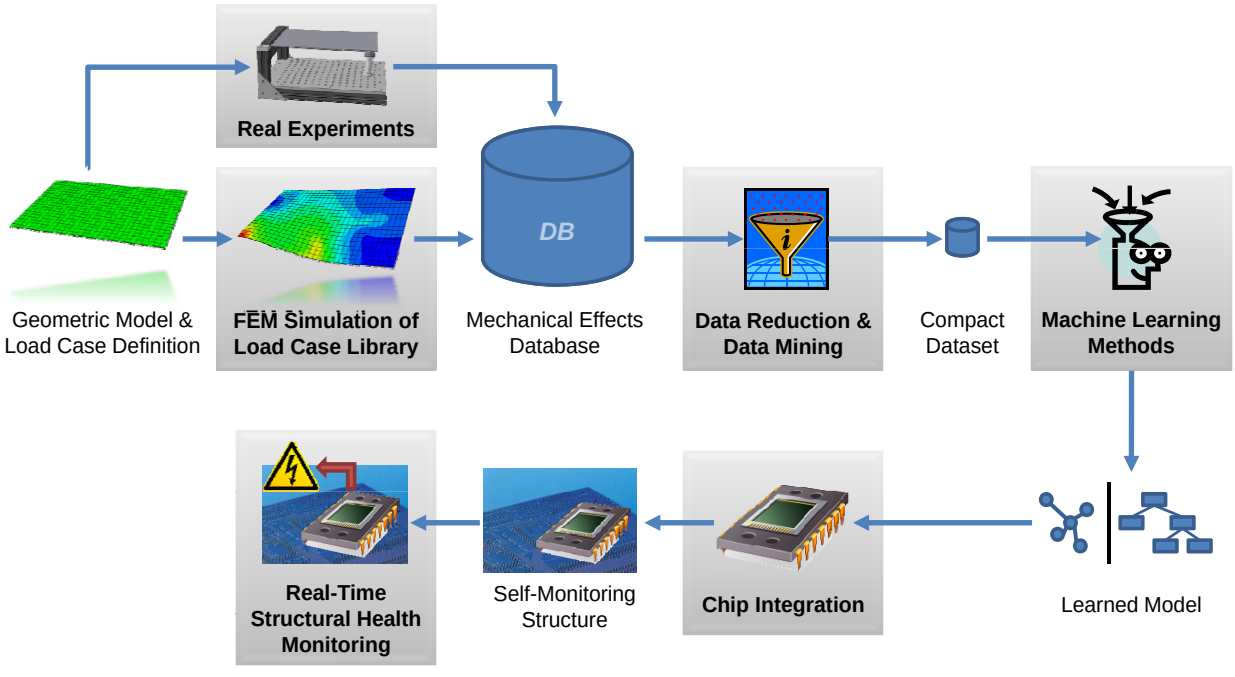
k=4 median: 25.5 g

Experimental Results C4.5 Classification Error

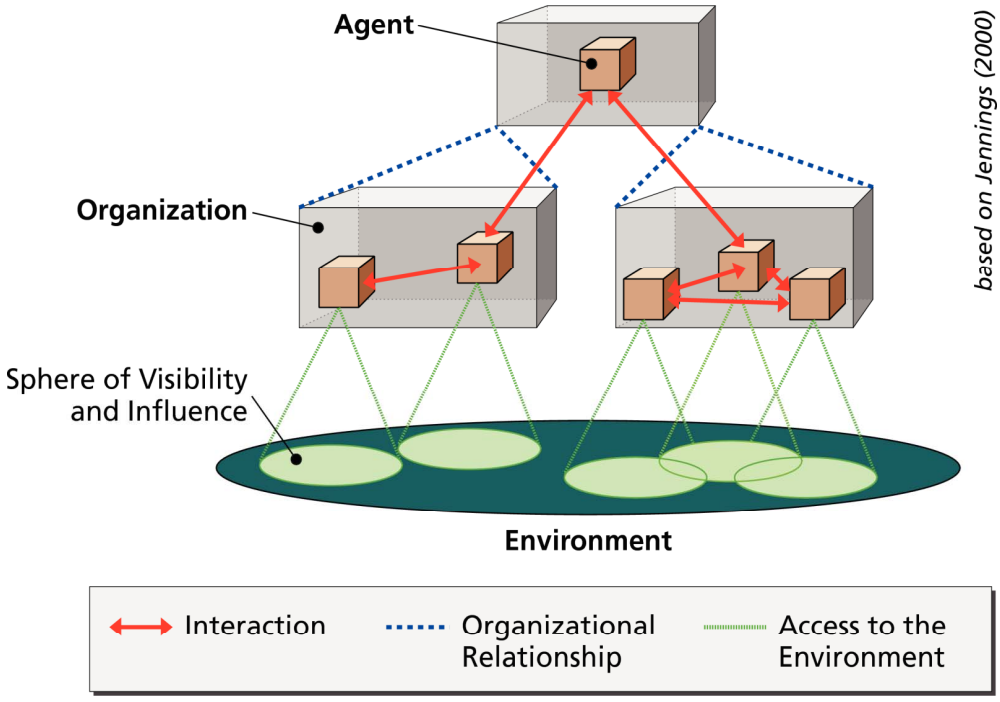


81.1% correct

Our Approach Towards Sensorial Structures



Structure Monitoring With Intelligent Agents



Conclusion and Outlook

Achieved so far

- ✓ Implementation of a robust sensor network and conceptualization of a functional mockup system
- ✓ Shown: Simple machine learning methods already yield acceptable results on noisy sensor data.
- ➤ The machine learning algorithms and learned models are simple and small enough to be integrated into a System-on-a-Chip

Next steps

- ➤ Further improvement of electric signal measurement components (e.g., reduction of noise).
- ➤ Utilization/development of more elaborate machine learning approaches with better noise tolerance.
- ➤ Examination of distributed Multi-Agent monitoring approaches (e.g., organisation, communication).