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Self-adaptive Smart Materials: A new Agent-based Approach .

Introduction

Overview

- Introduction
  - Sensorial Materials explained
  - MPTO as approach towards optimized stiffness distributions.
  - Now add adaptivity: Motivation.
- Approaches towards adaptive stiffness on material level.
- Approaches towards decision-making in adaptive materials.
- Conclusion, Outlook

Introduction

Sensorial Materials: Vision.

„Sensorial Materials gather data about their environment and/or their own state. They process these data locally and use the information derived internally, or communicate it to the external world.“

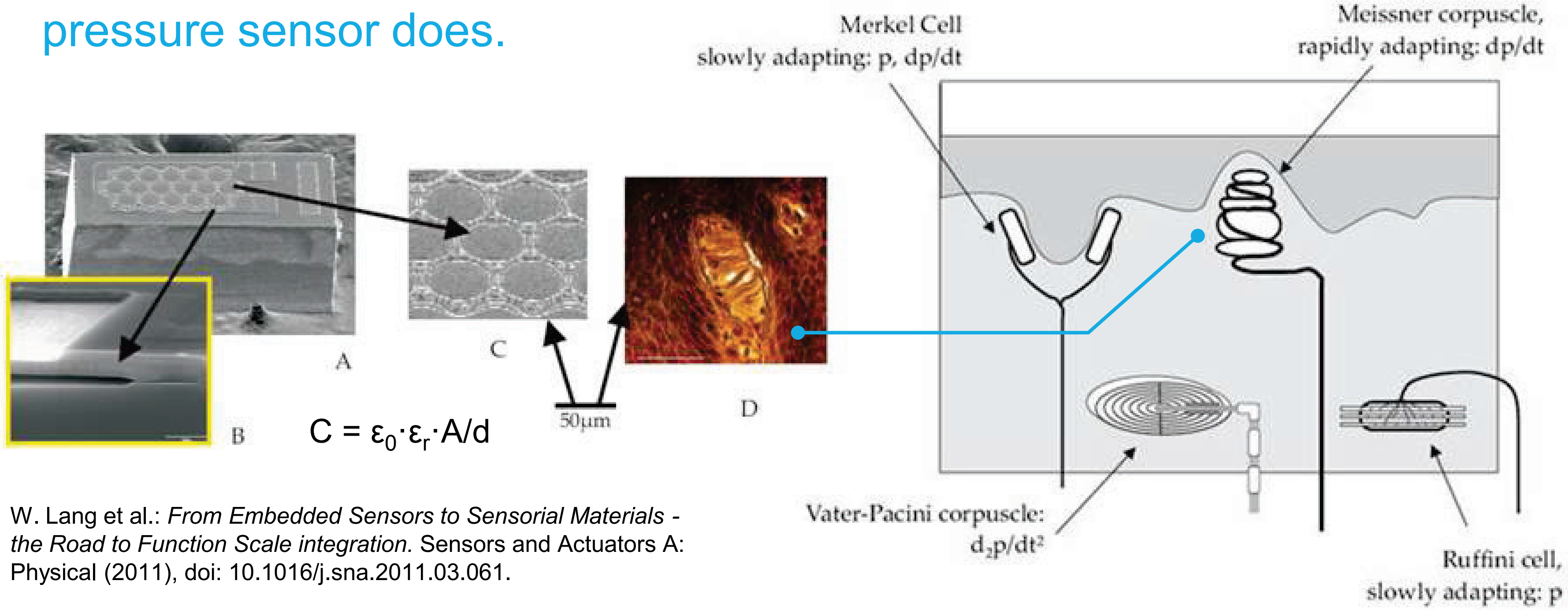
Introduction

Delimitation: An Example.

> *„Tactile sensing is more than just a pressure sensor – instead, it links several types of sensor signals and includes levels of distributed and centralized data evaluation.“*

Tactile sensing - more than merely sensors:

What the skin, and what a pressure sensor does.



$C = \varepsilon_0 \cdot \varepsilon_r \cdot A/d$

W. Lang et al.: *From Embedded Sensors to Sensorial Materials - the Road to Function Scale integration.* Sensors and Actuators A: Physical (2011), doi: 10.1016/j.sna.2011.03.061.

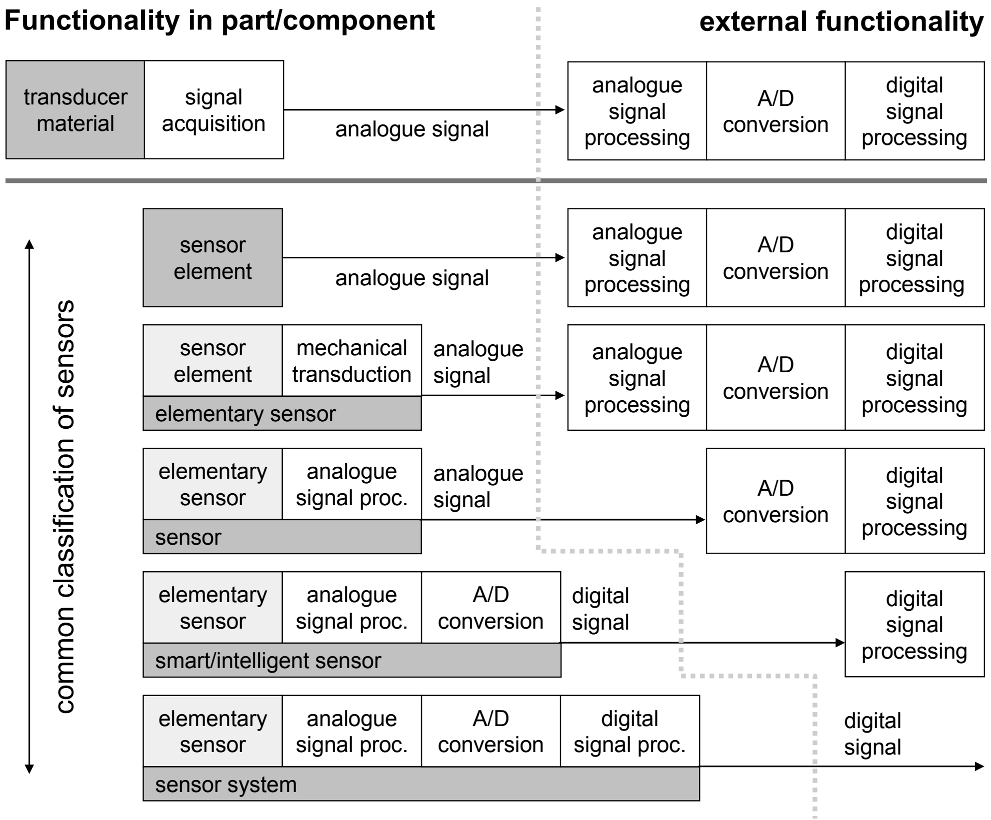
Introduction

Moving Functionality into the Material.

Moving from sensorized structure to material integration, we relocate functionality from the external world first to the surface, then into the volume of a host material.

> *„The drawing to the right describes the steps from a sensor to an integratable sensor node - as yet without data evaluation.“*

Adapted from Lee, S. H., 2010, Diploma thesis, Bremen Institute for Mechanical Engineering (BIME), Supervisor: Prof. K. Tacht.



Functionality in part/component

external functionality

transducer material | signal acquisition → analogue signal → analogue signal processing | A/D conversion | digital signal processing

common classification of sensors

sensor element → analogue signal → analogue signal processing | A/D conversion | digital signal processing

sensor element | mechanical transduction (elementary sensor) → analogue signal → analogue signal processing | A/D conversion | digital signal processing

elementary sensor | analogue signal proc. (sensor) → analogue signal → A/D conversion | digital signal processing

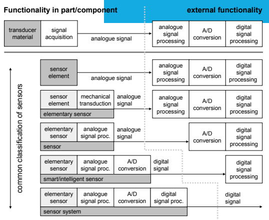
elementary sensor | analogue signal proc. | A/D conversion (smart/intelligent sensor) → digital signal → digital signal processing

elementary sensor | analogue signal proc. | A/D conversion | digital signal proc. (sensor system) → digital signal

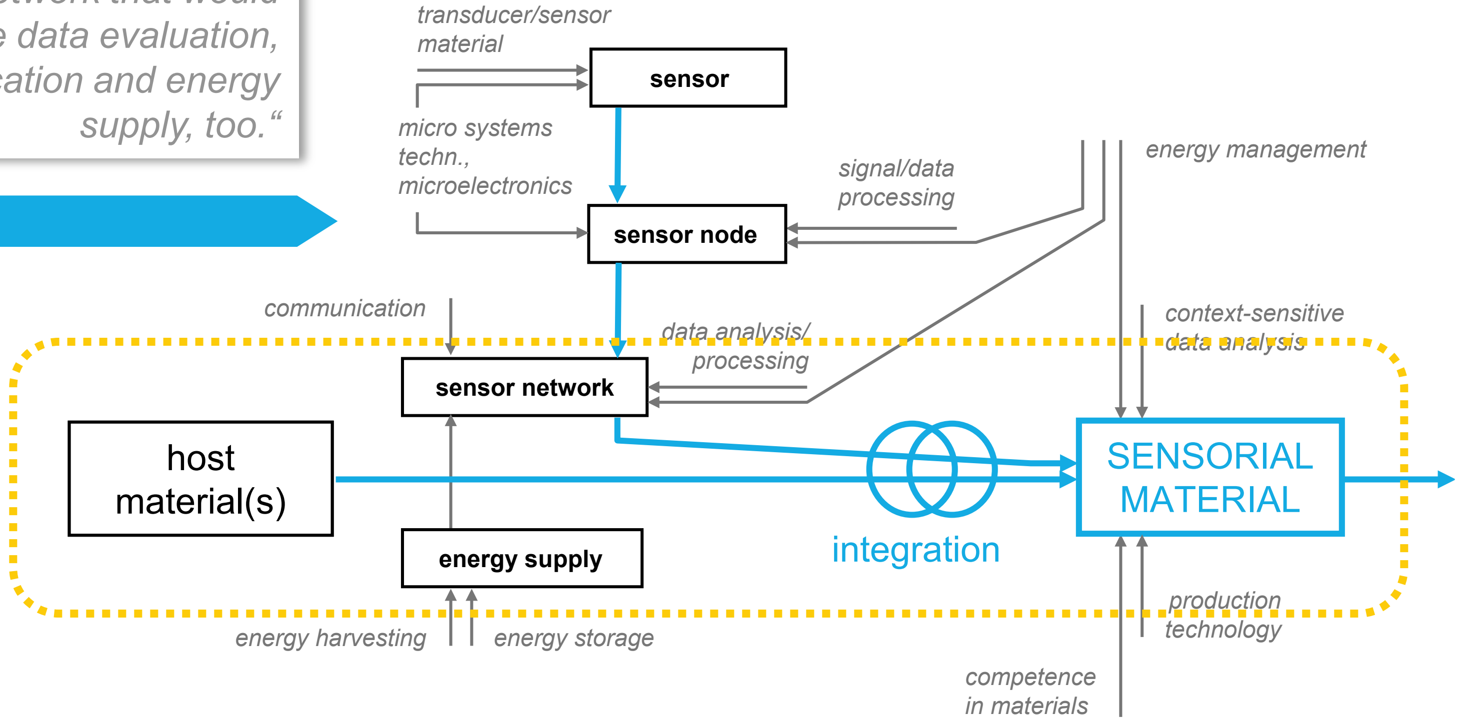
Introduction

Moving Functionality into the Material.

> „A Sensorial Material would comprise several such sensor nodes in a network that would provide data evaluation, communication and energy supply, too.“



Adapted from D. Lehmhus et al.: *When nothing is constant but change: Adaptive and Sensorial Materials and their impact on product design*. J. Intelligent Mat.l Syst. and Struc. (2013), DOI: 10.1177/1045389X13502855.



transducer/sensor material

sensor

micro systems techn., microelectronics

sensor node

signal/data processing

energy management

communication

sensor network

data analysis/ processing

context-sensitive data analysis

host material(s)

integration

SENSORIAL MATERIAL

energy supply

energy harvesting

energy storage

production technology

competence in materials

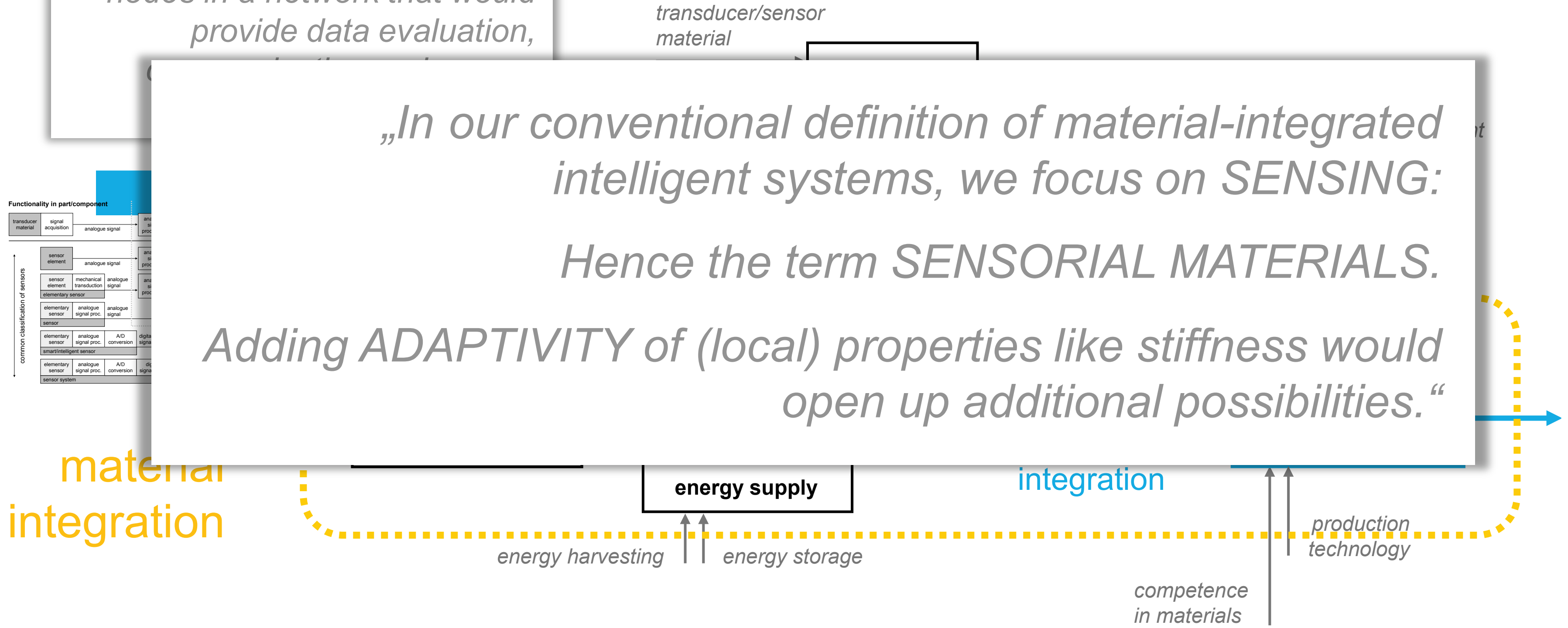
material integration

Introduction

Moving Functionality into the Material.

> „A Sensorial Material would comprise several such sensor nodes in a network that would provide data evaluation,

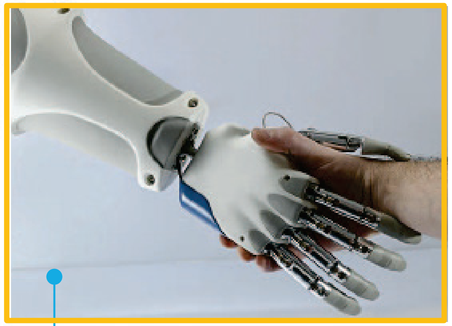
Adapted from D. Lehmhus et al.: *When nothing is constant but change: Adaptive and Sensorial Materials and their impact on product design*. J. Intelligent Mat.l Syst. and Struc. (2013), DOI: 10.1177/1045389X13502855.



> *„In our conventional definition of material-integrated intelligent systems, we focus on SENSING:*
>
> *Hence the term SENSORIAL MATERIALS.*
>
> *Adding ADAPTIVITY of (local) properties like stiffness would open up additional possibilities.“*

Introduction

Sensorial/Robotic Materials: Applications.



Shape Change

autonomous
flight
(fly-by-feel)

Load-bearing Structures

SHM
NDT support
MoD/predictive
maintenance

Tactile Sensing

safe/cooperative robotics
Human-Machine-Interaction

Soft Robotics

new articulation principles

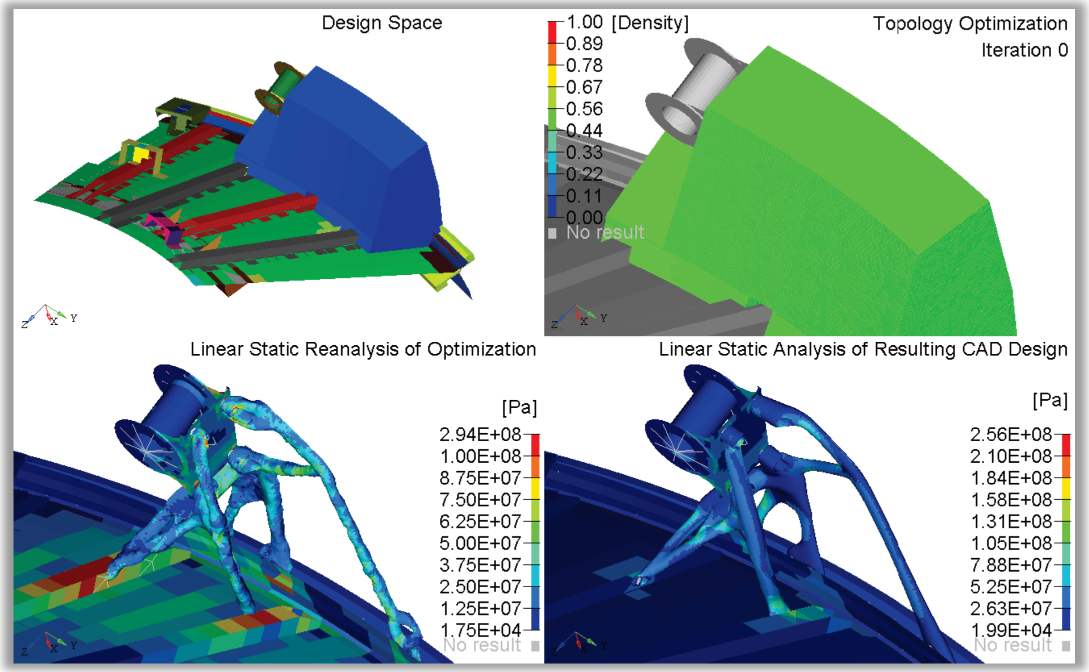
Source: McEvoy. M. A., Correll, N. Materials that combine sensing, actuation, computation and communication. Science 347 (2015) 1261689-1 bis -8 .

Introduction

Optimizing internal stiffness distributions.

Strong focus, specifically in the industrial sector, on homogeneous material/uniform composite topology optimization.

Example: Topology optimization driven design process of an additive layer Manufactured Ariane 5 bracket. (ISEMP, University of Bremen, in cooperation with Airbus Safran Launchers).

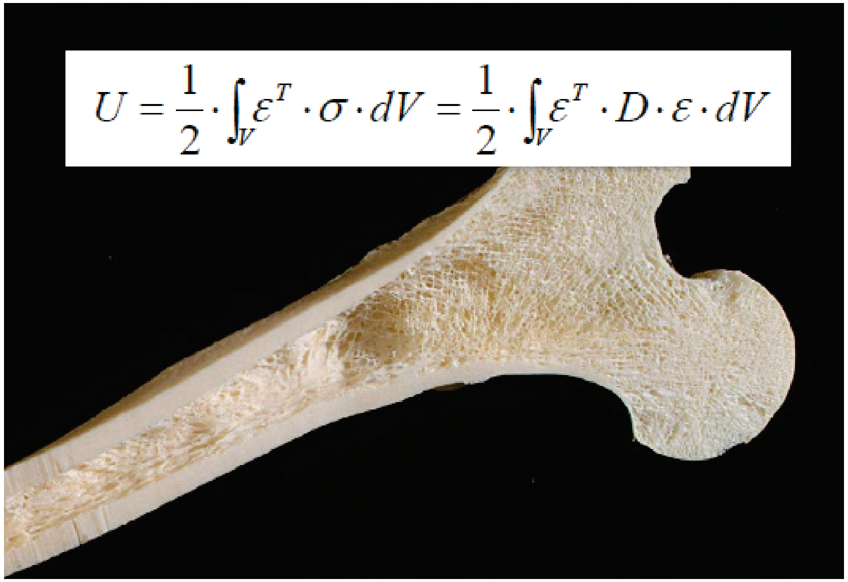


ISEMP
Airbus Endowed Chair for
Integrative Simulation and
Engineering of Materials and Processes

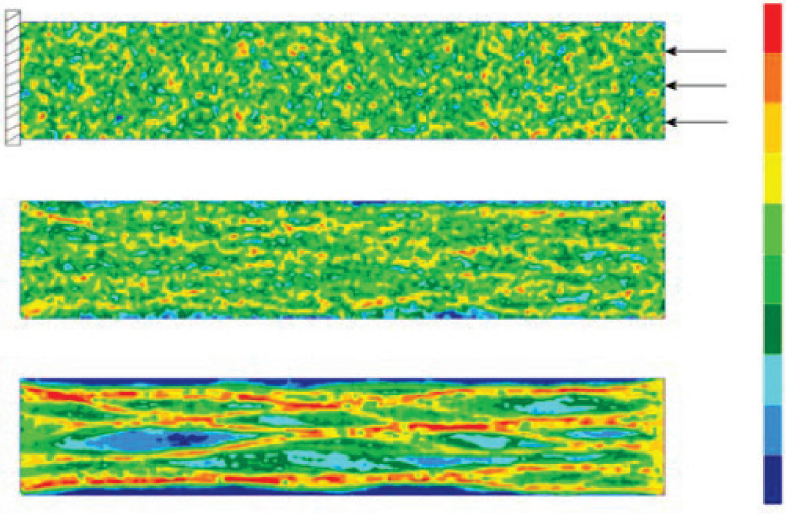
Introduction

Optimizing internal stiffness distributions.

Re-distribution of different porosity & stiffness material elements, aim: Total strain energy U mimimized through iterative, linear elastic FEM-based process.



$$U = \frac{1}{2}\cdot\int_V \varepsilon^T \cdot \sigma \cdot dV = \frac{1}{2}\cdot\int_V \varepsilon^T \cdot D \cdot \varepsilon \cdot dV$$

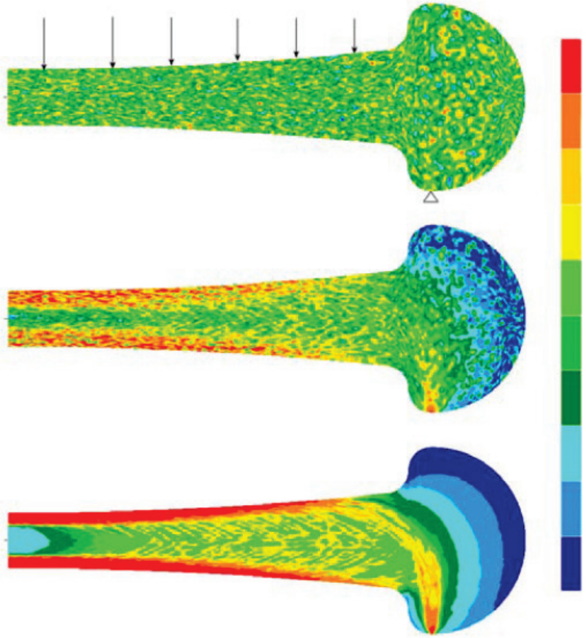


Burblies. A; Busse, M. Computer Based Porosity Design by Multi Phase Topology Optimization. Multiscale & Functionally Graded Materials Conference (FGM2006), Honolulu (USA), October 15th -18th 2006.

Introduction

Optimizing internal stiffness distributions.

Re-distribution of material ...



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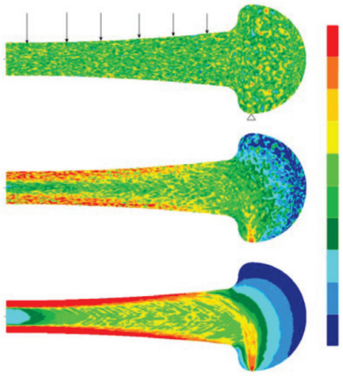
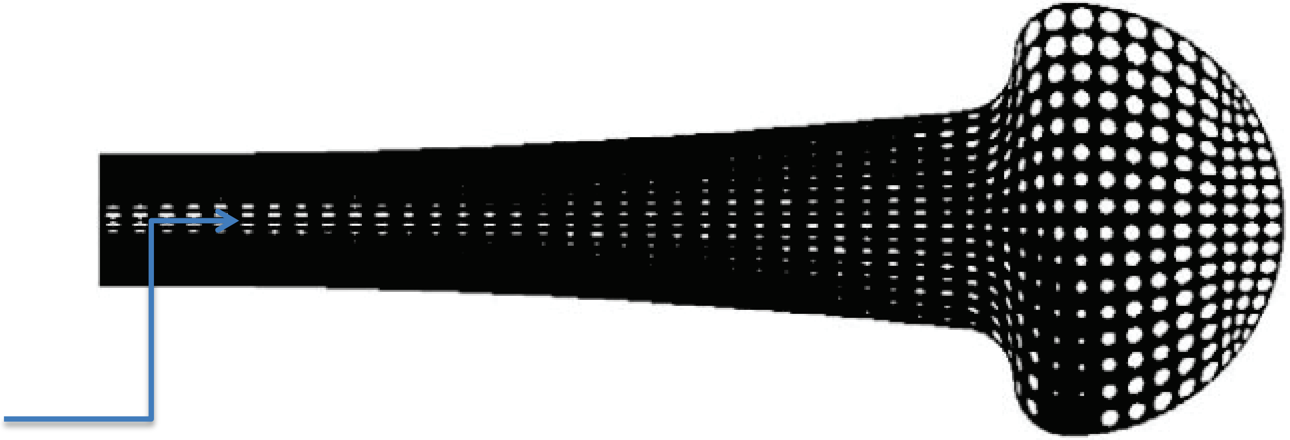
Introduction

Optimizing internal stiffness distributions.

How to reflect the optimization result in a real engineering structure?
Stochastic foams won‘t do the trick.

→ AM approach.





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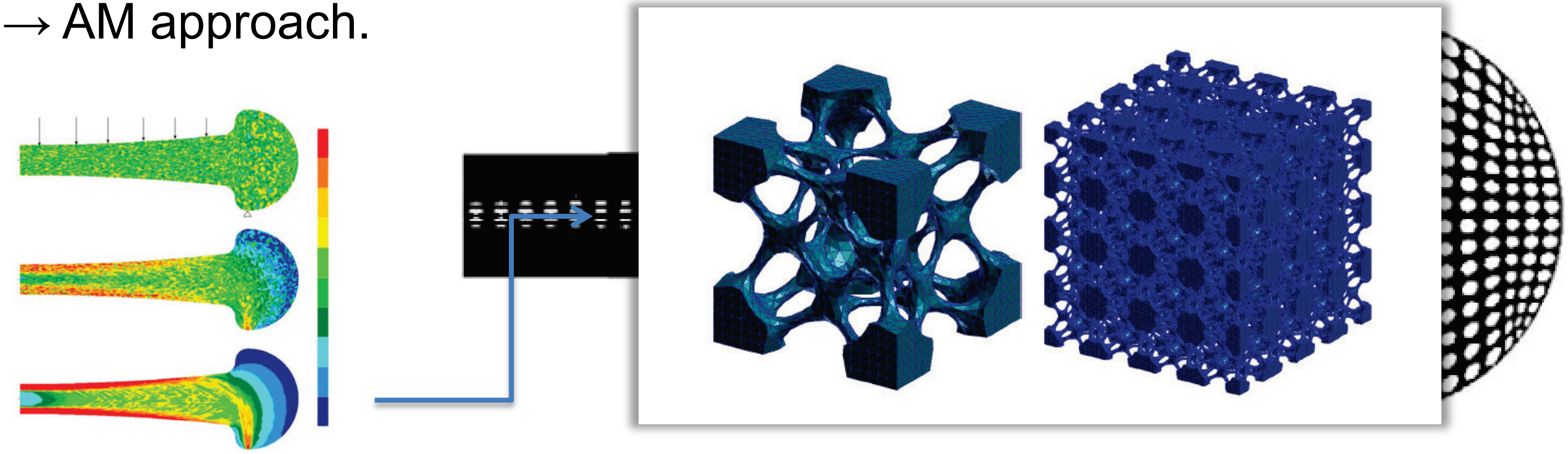

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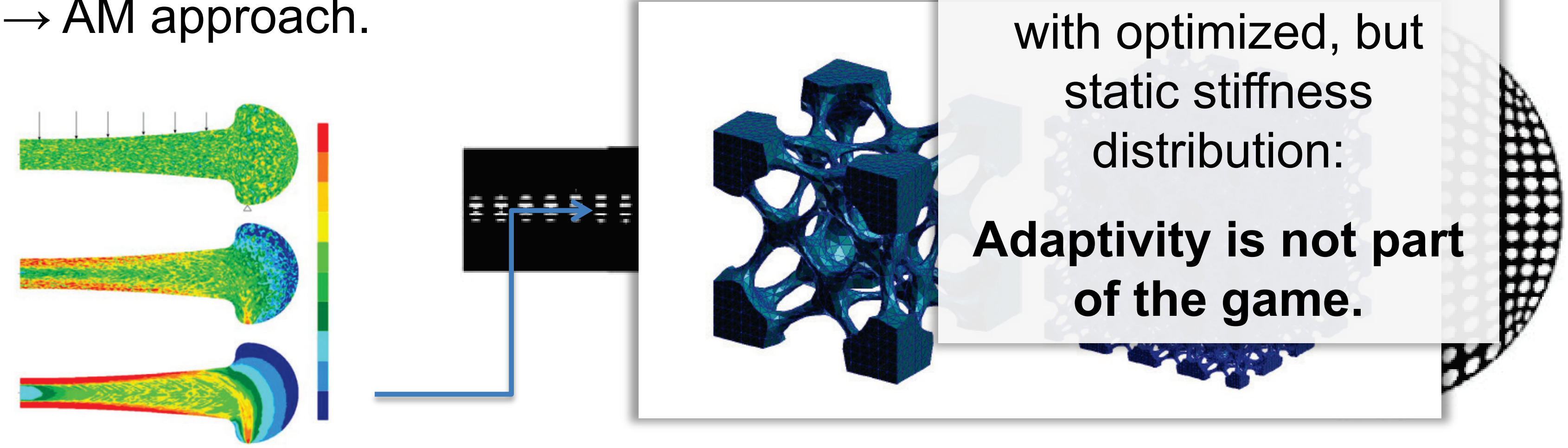


Result is a material with optimized, but static stiffness distribution:

Adaptivity is not part of the game.

Burblies. A; Busse, M. Computer Based Porosity Design by Multi Phase Topology Optimization. Multiscale & Functionally Graded Materials Conference (FGM2006), Honolulu (USA), October 15th -18th 2006.

Introduction

Now add adaptivity: Motivation.

In homogeneous materials, even simple load cases can lead to heterogeneous stress distributions:

- Uniaxial tensile/compressive load:
  Homogeneous stress distribution.
- Bending load:
  Heterogeneous stress distribution.

Introduction

Now add adaptivity: Motivation.

In heterogeneous materials, property distribution can in principle be tailored to reverse this situation:

- Uniaxial tensile/compressive load:
  Heterogeneous stress distribution due to a heterogeneous property distribution specifically focussing e. g. on the bending load case, see below.
- Bending load:
  Homogeneous stress distribution thanks to an adapted property distribution.

Introduction

Now add adaptivity: Motivation.

Achieving stress distribution homogeneity as described on the previous slight, i. e. based on a static property distribution within the material, works for a <u>single load case</u>.

Thus, think of adding <u>time</u> to the equation:

- If heterogeneity was not fixed, but variable, materials/structures could autonomously "optimize" their heterogeneity in response to recognizing a specific load case.
- This requires suitable algorithms/mechanisms for recognition of the respective load case and identification of an optimum response.
- Different optimization targets can be imagined: Homogeneous stress distribution, or limitation of maximum stress levels.

Introduction

Now add adaptivity: Motivation.

The previous slides basically refer to a “healthy” structure.

Adaptivity could also be used to better cope with incurred damage:

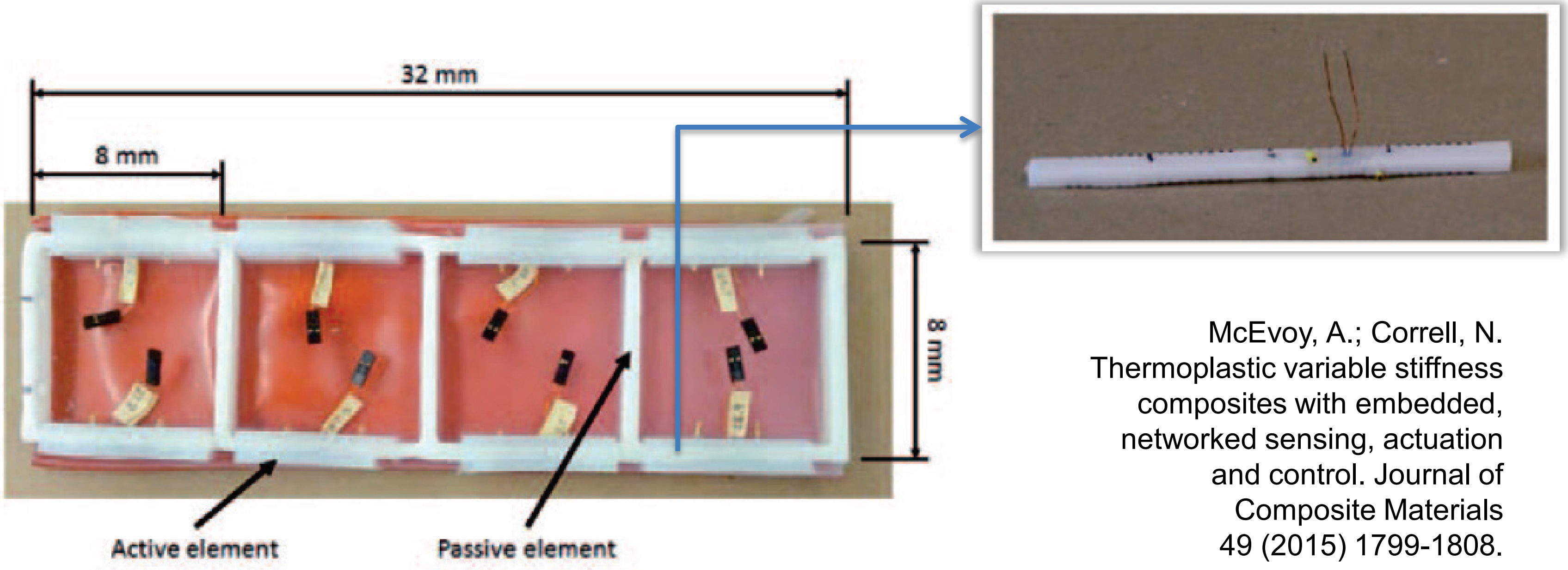
- Assuming that damage detection and localization is implemented, property adaptation could reduce stress levels in the damaged region, e.g. by creating a higher stiffness “enveloping” substructure within the material.

  This way the remaining lifetime of the structure could be extended, even if certain areas would experience higher loads than they would in an undamaged structure.

Material-level Adaptive Stiffness

Approaches for physical realization I.

Temperature-dependent stiffness macroscopic approach: Polycaprolactone structure, heating element, thermistor and microcontroller in each active element.



McEvoy, A.; Correll, N. Thermoplastic variable stiffness composites with embedded, networked sensing, actuation and control. Journal of Composite Materials 49 (2015) 1799-1808.

Material-level Adaptive Stiffness

Approaches for physical realization II.

Examples of alternative, material-level mechanisms behind adaptive stiffness:

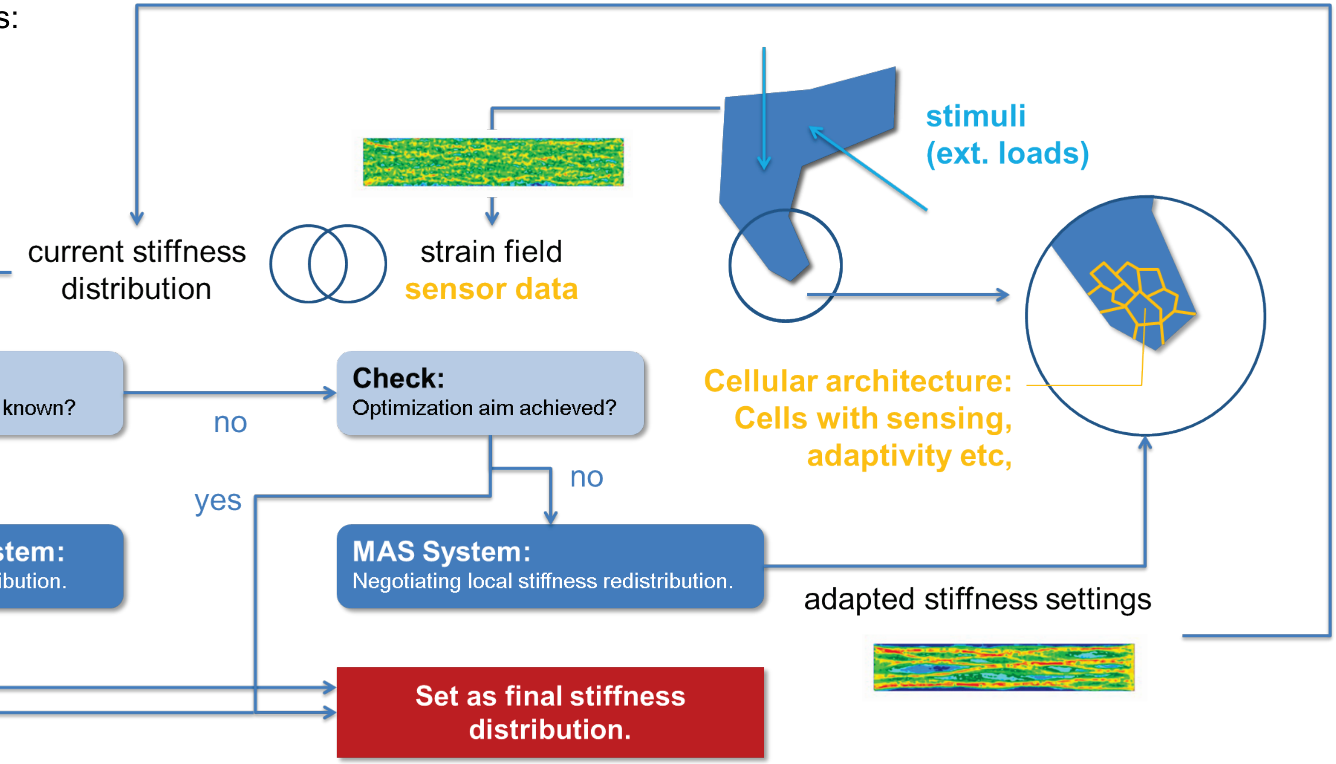
- Wood cells (driver/mechanism: Change in moisture levels)
- Polymers/spider silk etc. (temperature, stiffness change due to transgression of the glass transition temperature)
- Polymer/cellulose nanofibre composite (Chemical agent induced change of nanofibre and nanofibre-matrix interaction)
- Proteins (sacrificial bonds among molecular cross links between polymer chains)
- etc.

Based on a review by:
Saavreda Flores, E. I., Friswell, M. I., Xia, Y.
Variable stiffness biological and bio-inspired materials. Journal of Intelligent Material Systems and Structures 24 (2012) 529-540.

Decision-making in Adaptive Structures

Approaches: First, the physical structure.

Stress distribution images:
Burblies, 2006
(see slides 10-13)



stimuli
(ext. loads)

current stiffness
distribution

strain field
sensor data

Cellular architecture:
Cells with sensing,
adaptivity etc,

Check:
Strain vs. stiffness distribution known?

no

Check:
Optimization aim achieved?

yes

yes

no

Machine Learning System:
Select matching stiffness distribution.

MAS System:
Negotiating local stiffness redistribution.

adapted stiffness settings

Set as final stiffness distribution.

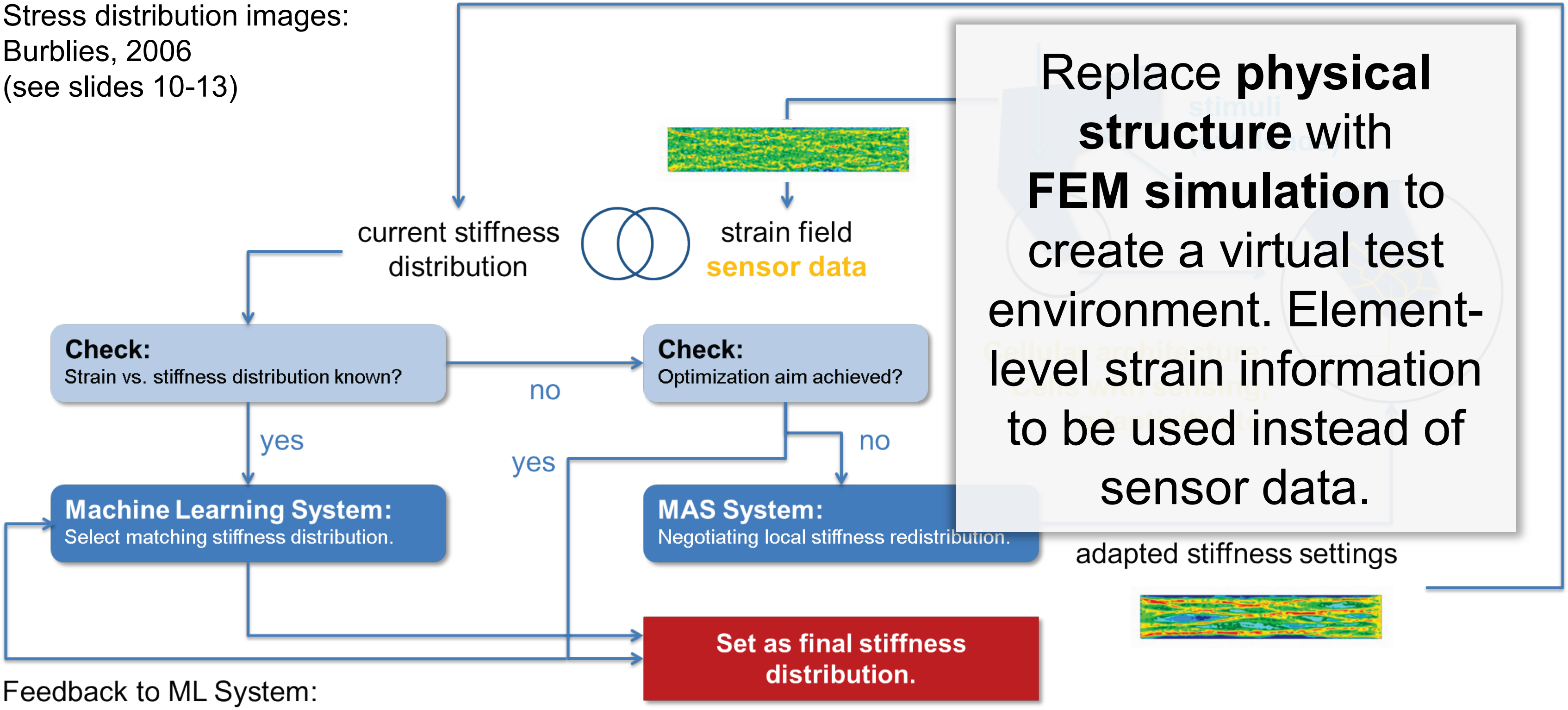
Feedback to ML System:

Optimized stiffness distribution linked to load description(s),
i. e. strain field/stiffness setting combined datasets.

Decision-making in Adaptive Structures

Second, a virtual evaluation environment.

Stress distribution images:
Burblies, 2006
(see slides 10-13)



Replace **physical structure** with **FEM simulation** to create a virtual test environment. Element-level strain information to be used instead of sensor data.

Feedback to ML System:

Optimized stiffness distribution linked to load description(s), i. e. strain field/stiffness setting combined datasets.

Decision-making in Adaptive Structures

MAS/ML System Cooperation.

The Multi-Agent System (MAS) is active if a load case - described by current stiffness distribution and associated structural response (e.g. strain fields) - is "unknown" to the Machine Learning (ML) System.

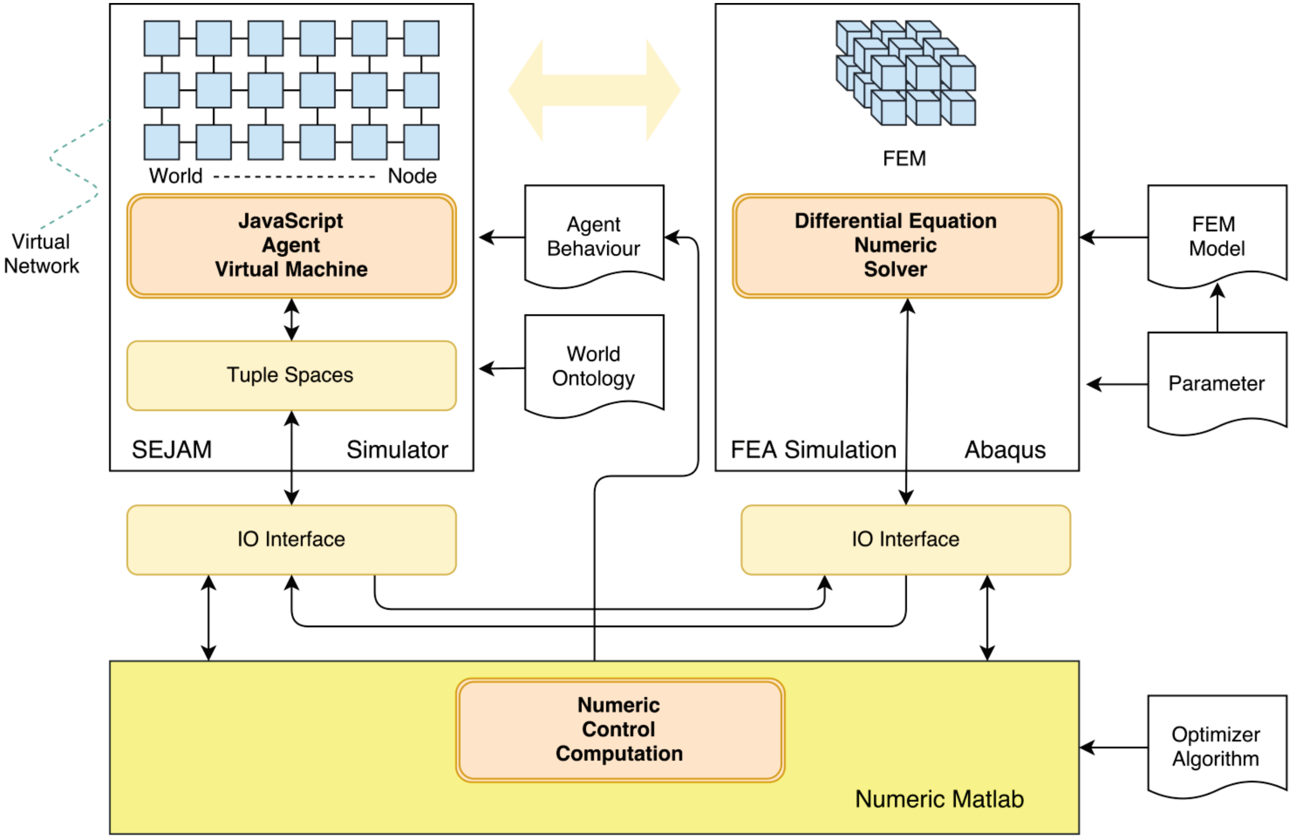
In this case, a new stiffness distribution is negotiated based on clearly defined optimization criteria the fulfillment of which can be derived from sensor data.

Once an optimum solution has been identified, information on (a) load case (b) optimization target and (c) stiffness distribution found is provided as new training data set to the ML system.

Otherwise, i. e. in case of a "known" load case, the ML system will directly select a matching stiffness distribution.

Decision-making in Adaptive Structures

MA/FEM System Cooperation and Modules.



Decision-making in Adaptive Structures

MAS System: Optimization aims.

Optimization can target different aims. Possibility of a situation-dependent switch may be studied (i. e. dependent on health of structure).

- Limit maximum stress/strain levels.
- Limit global deformation.
- Maximize lifetime of structure.
- Control damage propagation/growth.

Potential conflicts between targets of global character and local nature of the MAS based optimization approach must be considered.

Decision-making in Adaptive Structures

Global aims vs. local range.

A major challenge for the MAS system is the fulfillment of global optimization aims based on local optimization

A main research target will be to test MAS-based optimization algorithms that meet this aim and evaluate their performance in this respect.

Potentially, a multi-layer approach is needed which combines coarse and fine-grained approaches.

A major asset is the fact that thanks to its adaptivity, the envisaged material/structure is in principle capable of self-evaluation.

Conclusion, Outlook.

Adaptive Materials – Challenges & Promises.

- A cellular adaptive material architecture may raise additional potentials in lightweight design.
- Adaptivity can focus on different timescales: First, momentary loads can be addressed throughout a part. Second, based on typical use patterns, prediction-based limits to life cycle loads are possible.
- Adaptivity can be used to increase remaining lifetime of damaged structures by limiting loads in areas with known damage. To achieve this, a coupling between adaptivity control and SHM approaches for detection and localization of damage is necessary.
- In the latter role, adaptivity may contribute to safety as well as longevity of load-bearing structures.

Many thanks for your attention …

Where to find us:

Find my work on
RESEARCHGATE

www.researchgate.net/profile/Dirk_Lehmhus/

… soon including this presentation, too!

Dr.-Ing. Dirk Lehmhus

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