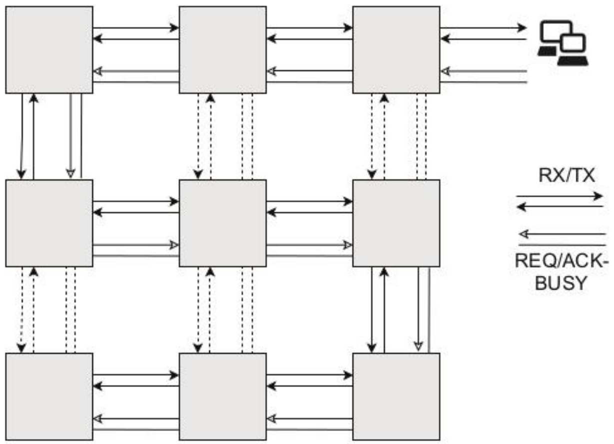
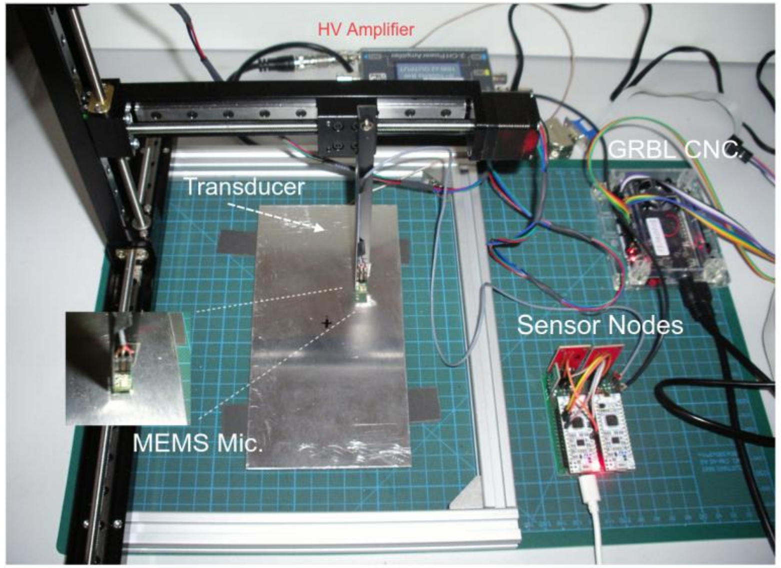
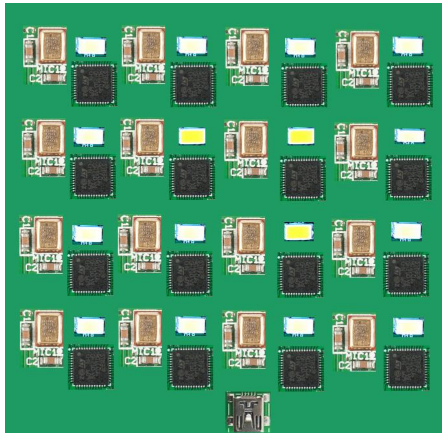
STEFAN BOSSE[1,2*]

[1] Institute of Computer Science
Researchgroup Practical Computer Science
University of Koblenz

[2] Department of Mechanical Engineering
Lehrstuhl für Materialkunde und Werkstoffprüfung
University of Siegen







TOWARDS AN AIR-COUPLED ULTRASONIC SENSOR NETWORK AND CAMERA FOR NON-DESTRUCTIVE TESTING WITH INTEGRATED MACHINE LEARNING

Stefan Bosse

Schall 2025 Conference

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CONTENT

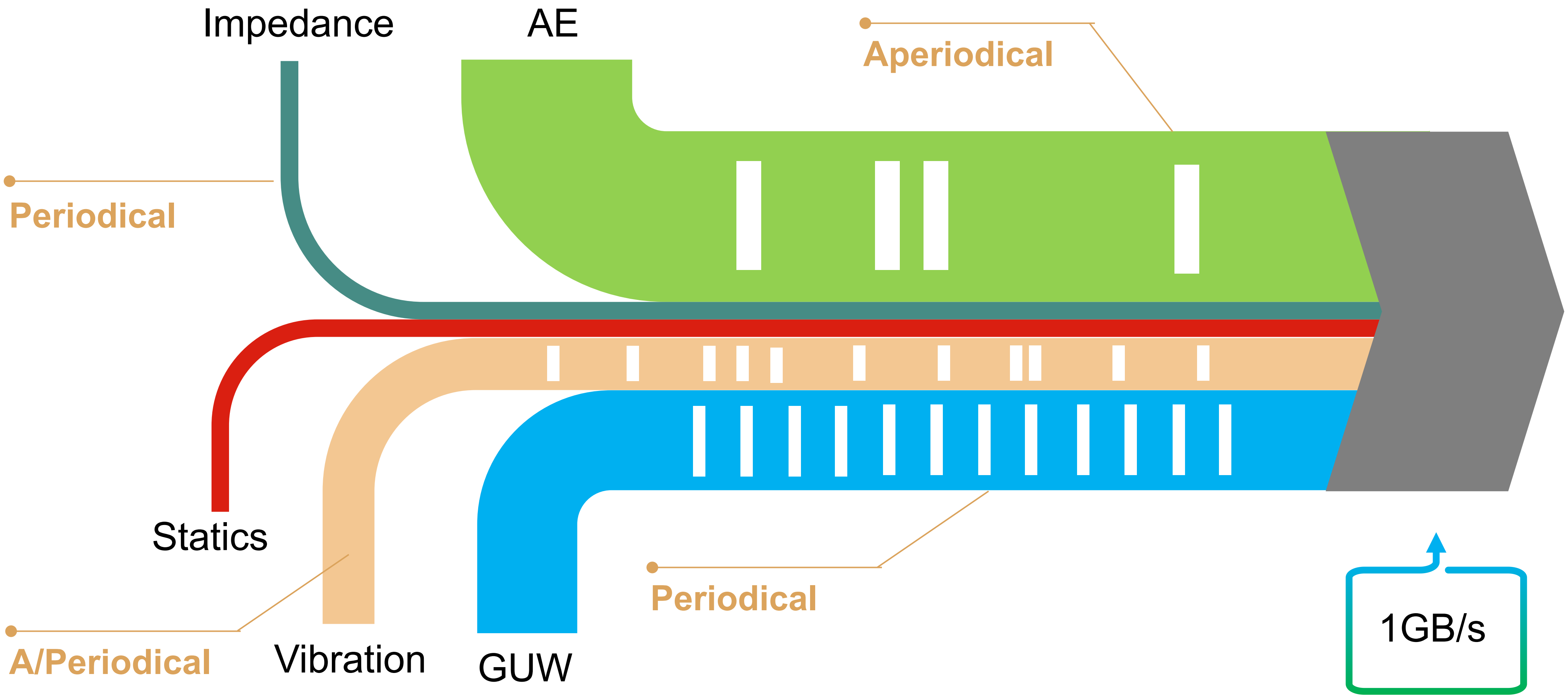
INTRODCUTION

- For non-destructive testing (NDT) of structures, various methods are usually used.
- Among other methods, acoustic emission (AE) and guided ultrasonic wave (GUW) tests are often used to assess structures and to detect damages and defects.
- Both methods are characterized by high-dimensional time-dependent data.

The use of a guided wave-based approach is due to the fact that these waves can propagate over relatively long distances and interact sensitively and specifically with various types of defects.

PROBLEM: DATA STREAMS IN NDT

Central Processing not suitable

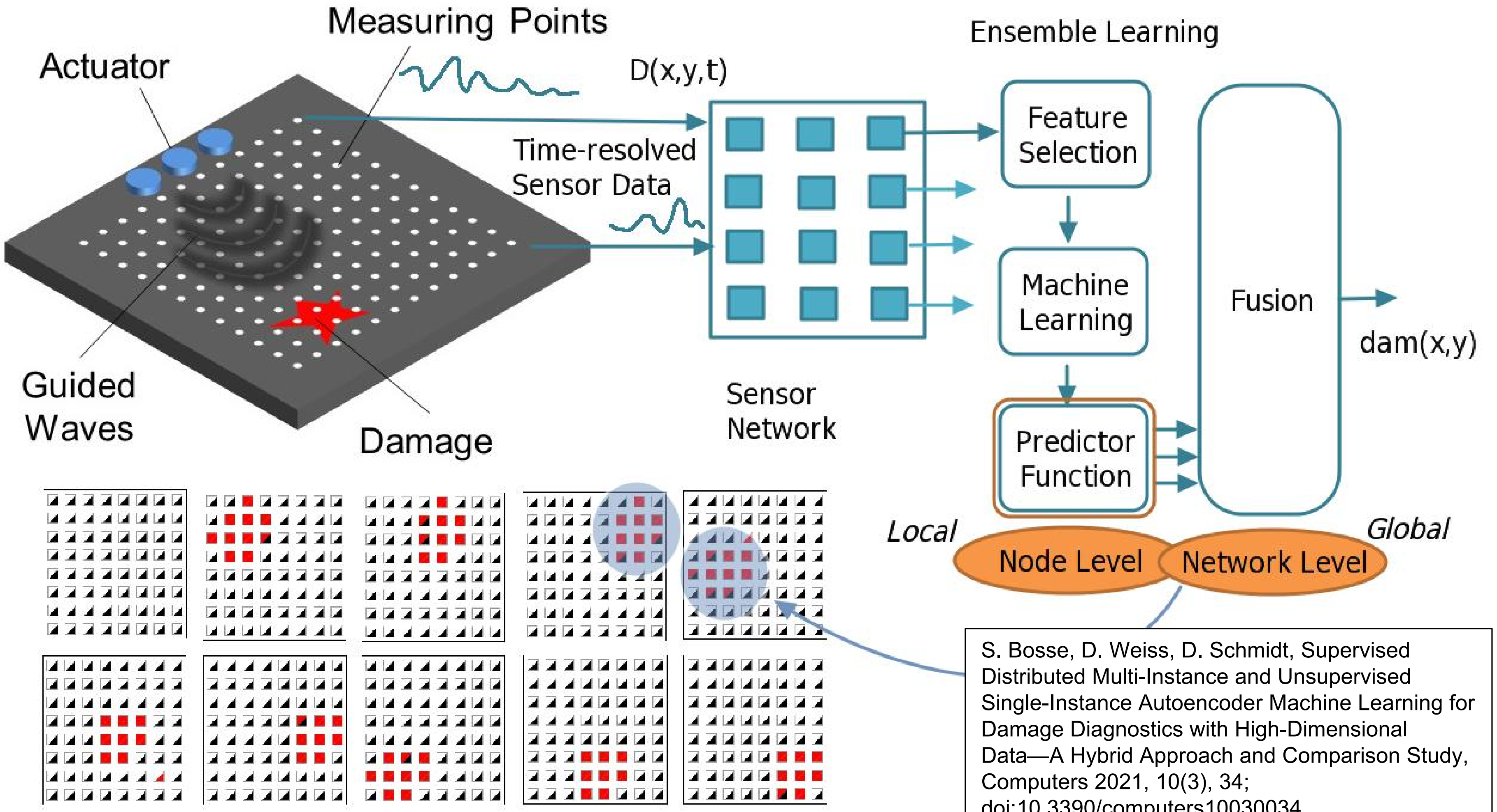


SENSORFUSION VERSA MODELFUSION IN DISTRIBUTED SENSOR NETWORKS

Distributed Spatial Sensorfusion:

Local State Estimation (Damage and Anomaly Detection)

Global Fusion (Localization and Aggregation)



S. Bosse, D. Weiss, D. Schmidt, Supervised Distributed Multi-Instance and Unsupervised Single-Instance Autoencoder Machine Learning for Damage Diagnostics with High-Dimensional Data—A Hybrid Approach and Comparison Study, Computers 2021, 10(3), 34; doi:10.3390/computers10030034

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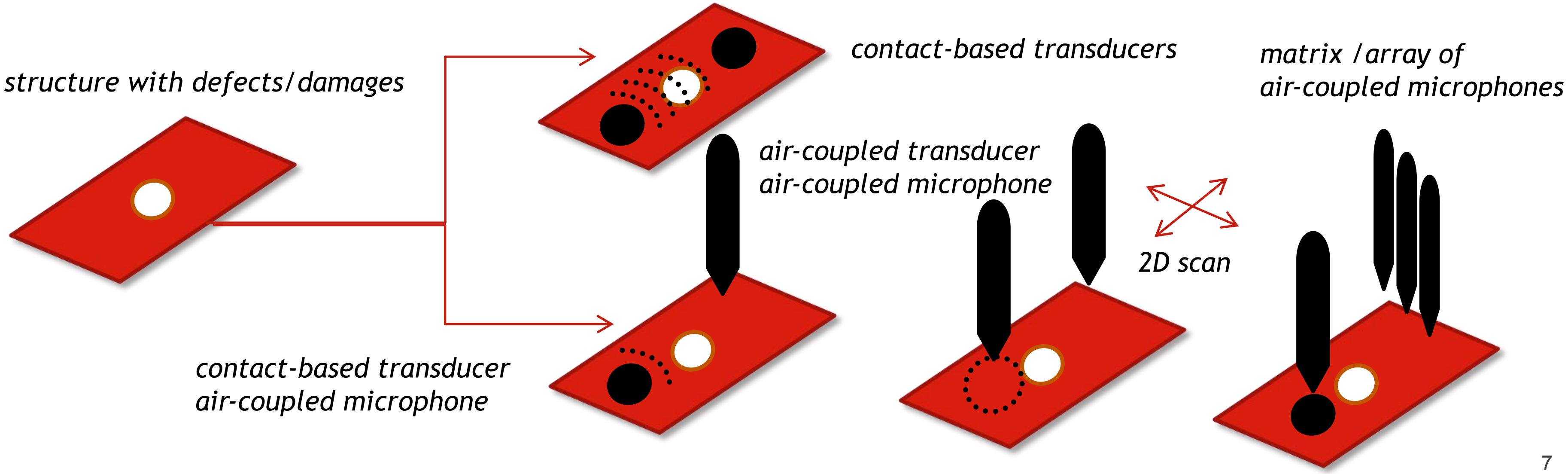
NDT MEASURING TECHNIQUES

- Suppose you have a composite material consisting of multiple layers, e.g., a sandwitch structure of alternating metal and fibre layers.
- Now suppose there is a hidden defect or a damge that we cannot see or feel from the oustide.
- How can we detect and localize these hidden defects and damages with in-field measuring techniques quickly and robustly?



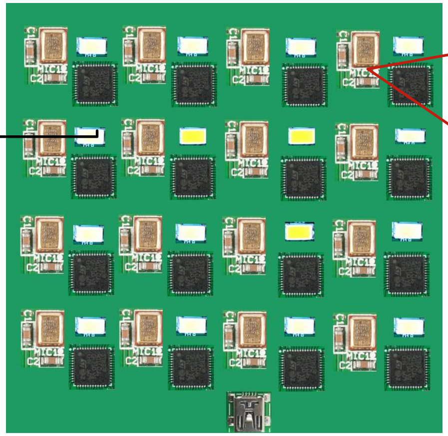
AIR-COUPLED GUW CAMERA

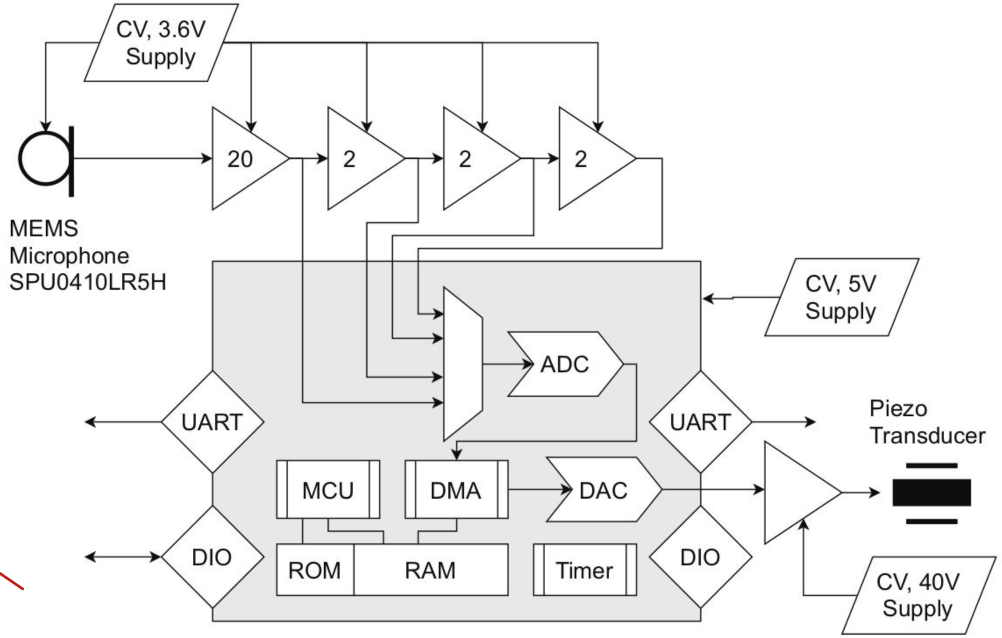
Goal: Single Board Distributed Sensor Network with multiple sensors, message- and signal-based communicating sensor nodes, and integreated spatially resolved damage and defect prediction with TinyML models and a Virtual Machine.

- This study introduces a low-cost air-coupled measuring technique using a 1$ MEMS microphone as a signal receiver and a surface-coupled transducer as a sender. Each sensor is integrated with data processing and communication (ICT), providing a "Smart Sensor Node" for signal processing, feature extraction, and Machine Learning for feature prediction. The approach provides higher freedom of design and scalability, especially for spatially large extended sensor networks.

Distributed multi-sensor acquisition of time-dependent signals require message- and signal-based synchronization; clock synchronization depends on low latency and jitter!

FULLY INTEGRATED SENSOR NODE: ARCHITECTURE





Visualization

- LEDs indicate localized state prediction

Sensor Network

- Chain or Mesh-grid
- Communication
- Network
- MEMS Microphone

Sensor Node

- Fully Integrated w. ICT
- Analog-Digital Interface
- Sensors
- Tiny ML

Analog

- Pre-Amplifier Cascade
- Bandwidth ~ 200 kHz
- ADC (12 Bits, 2 MS/s)
- DAC (12 Bits, 10 MS/s)

Digital

- STM32F303 32Bit ARM Cortex M4 + FPU
- Communication
- Embedded Basic
- Virtual Machine

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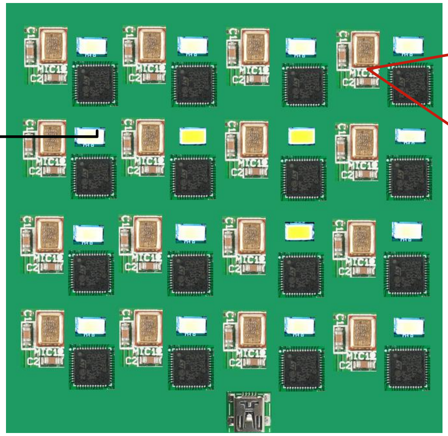
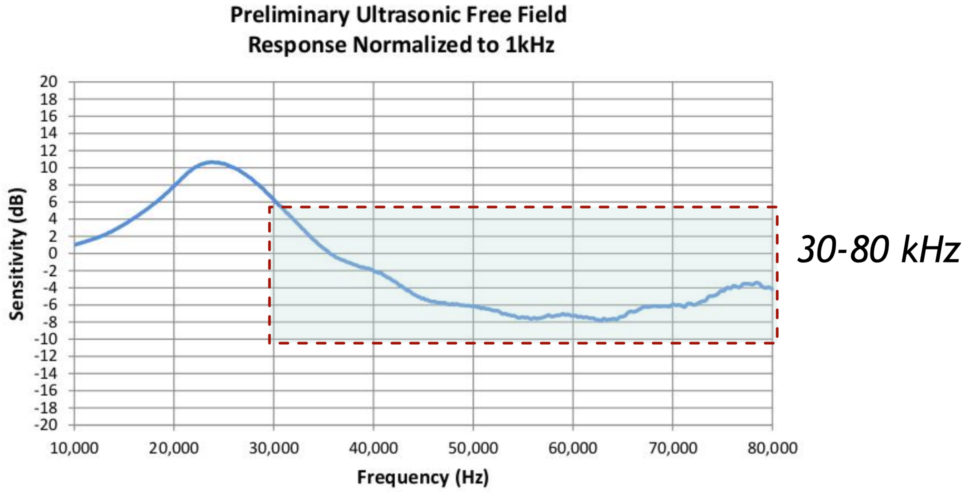
FULLY INTEGRATED SENSOR NODE: SENSOR





Visualization

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Sensor Node

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- Sensors
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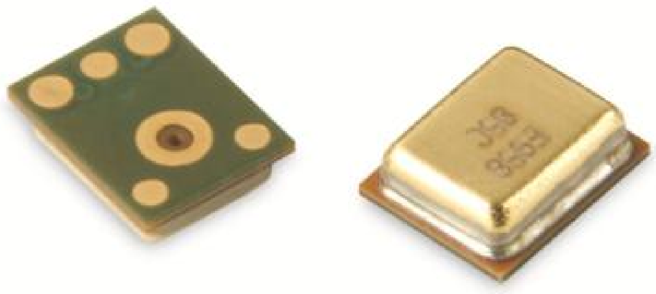
Sensor

- MEMS Zero-Height SiSonic Microphone SPU0410LR5H
- Size: 3x3.8x1mm
- Flat Frequency Response
- Omnidirectional
- Sensitivity: -38 dBV/Pa



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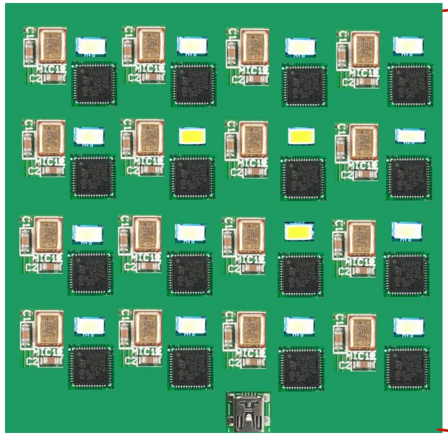
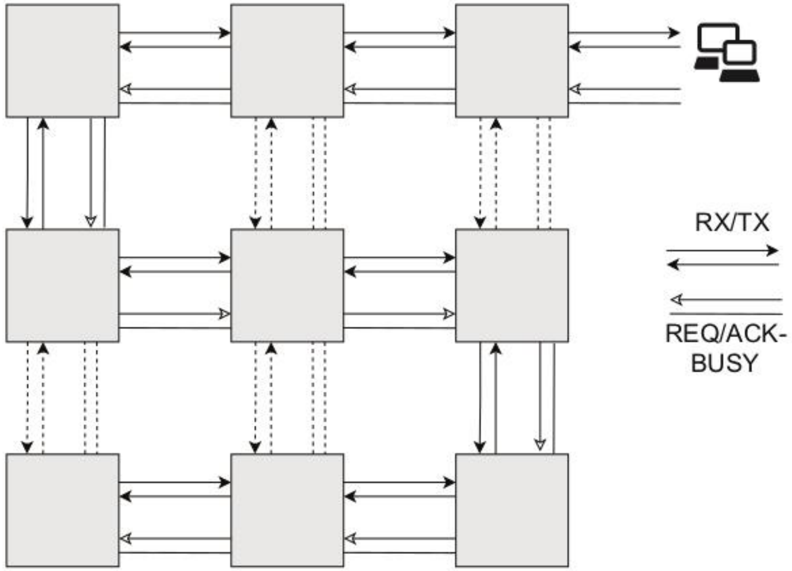
FULLY INTEGRATED SENSOR NODE: NETWORK





Sensor Network

- Chain or Mesh-grid
- Communication
- Network
- One node connected to external Computer

Sensor Node

- Fully Integrated
- Analog-Digital Interface
- Message-based Communication
- Signals

Links

- 2/3/4 bi-directional
- serial (UART/i2C) links
- up to 1 Mb/s

Signals

- Bus (OC)
- REQ: Fast hardware signal propagation
- ACK/BUSY: Message transfer control

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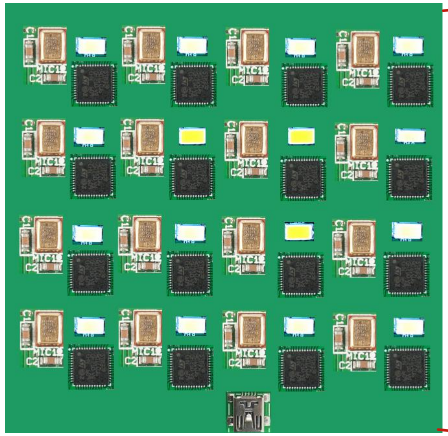
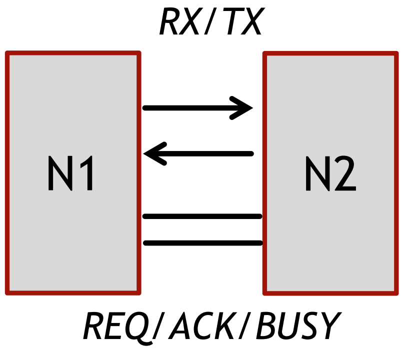
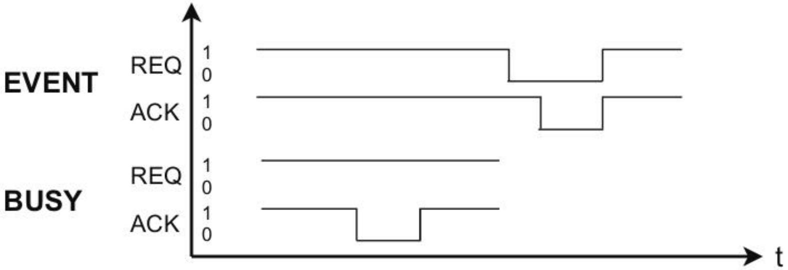
FULLY INTEGRATED SENSOR NODE: COMMUNICATION





Program code	[code:code:code]⊥
Code Incremental	[[code:code:code]]⊥
Single statement	]code:code[⊥
Route-through data	!data,data,data!⊥
P2P message	$data,data,data$⊥
Routing message	$id,hops,time@⊥
Console message	text⊥



Sensor Network

- Chain or Mesh-grid
- Communication
- Network
- One node connected to external Computer

Sensor Node

- Fully Integrated
- Analog-Digital Interface
- Message-based Communication
- Signals

Software Protocol

- Code propagation (network is a SIMD computer)
- Message propagation
  - Peer-to-Peer
  - Data

Hardware Protocol

- Fast hardware event signals propagated through network
- Start of signal acquisition
- Routing control
- Clock synchronization

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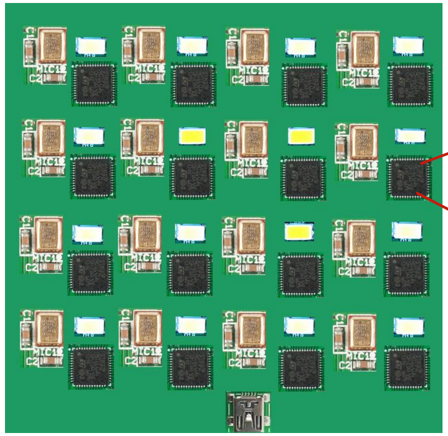
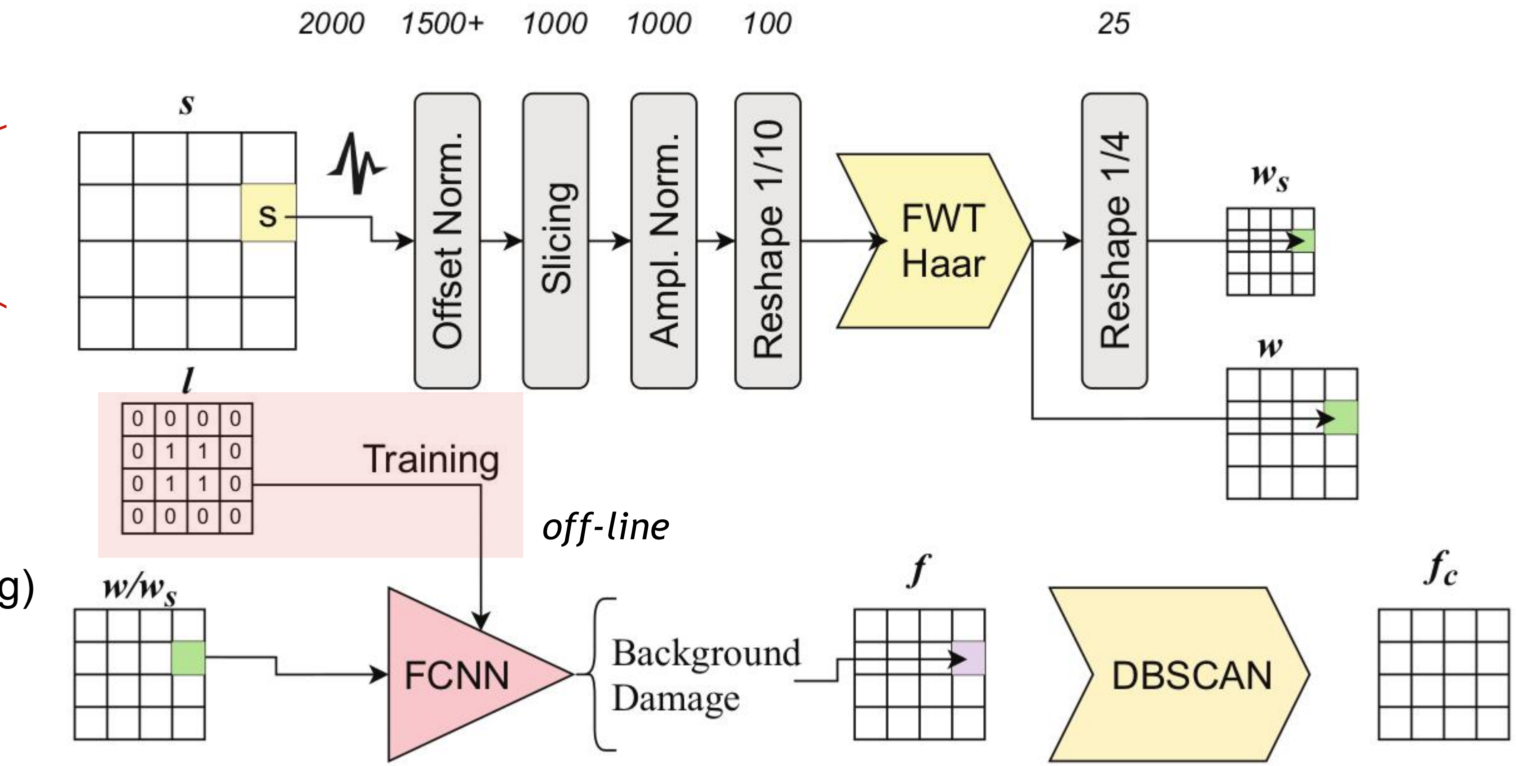
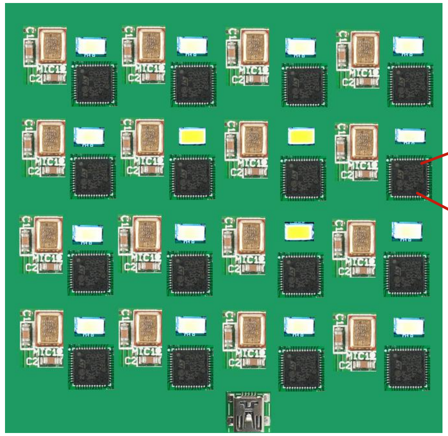
FULLY INTEGRATED SENSOR NODE: TINY ML





- Data-flow architecture implemented in each sensor node (except model training)
- Input: Time sensor signal
- Feature extraction: Fast Wavelet Transform with Haar wavelet
- Damage classifier: Fully Connectet Neural Network Classifier
- Output: Damage near by? 0/1

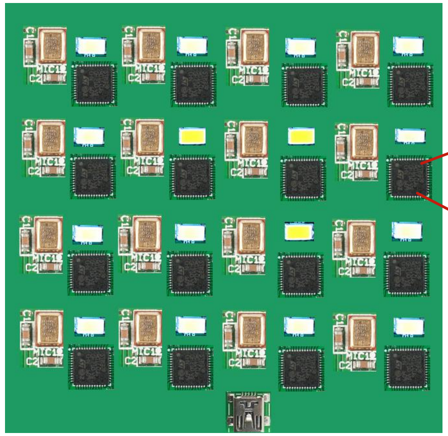
FULLY INTEGRATED SENSOR NODE: TINY ML

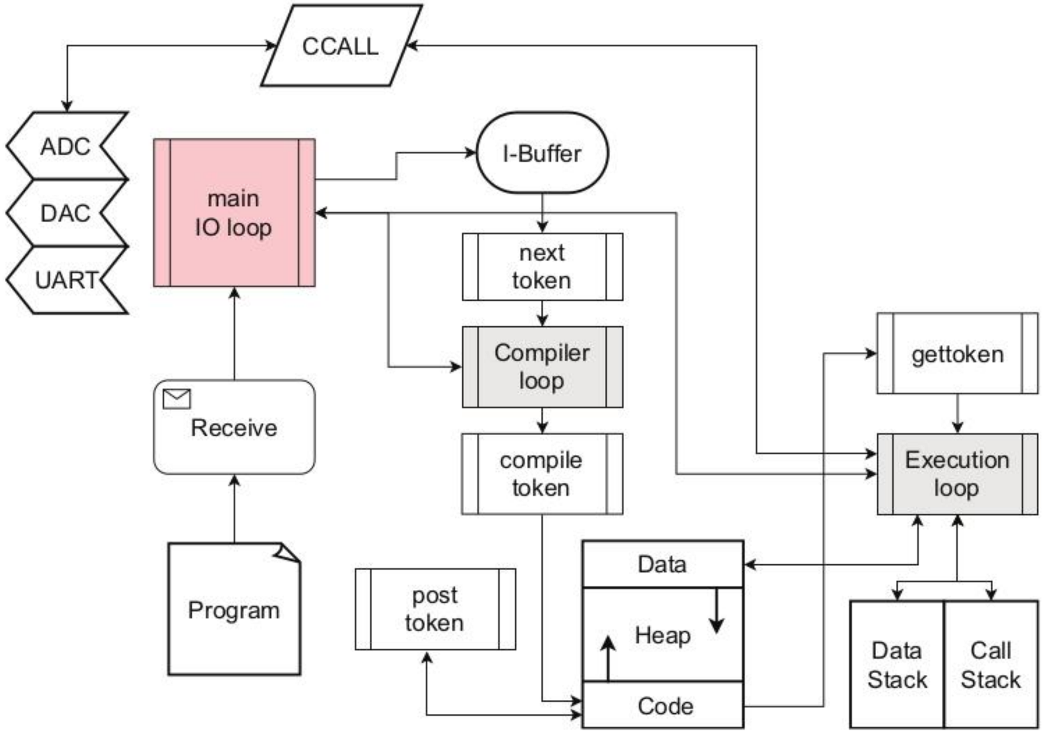


```
Fully Connected Neural Network
=========================================================
Classes:    2 {B,D}
Input:      [N,1,1]
Output:     [2]
Layers:     [L5 P9]
[1] input :              out=[N,1,1]   params=0
[2] fc :        in=[25]  out=[10]      params=N*10+10
[3] tanh :               out=[10]      params=0
[4] fc :        in=[10]  out=[10]      params=110
[5] tanh :               out=[10]      params=0
[6] fc :        in=[10]  out=[10]      params=110
[7] tanh :               out=[10]      params=0
[8] fc :        in=[10]  out=[2]       params=22
[9] softmax : in=[2]     out=[2]       params=0
-------------                          -------------------
Predictors: N                          Parameters=N*10+252
```

- Fully Connected Artificial Neural Networtk
- Input: FWT vector (Length N, Level 5)
- Output: Damage yes/no decision
- Three hidden layers + one softmax layer
- Trained with Float 32 Bits data type
- After training converted into Integer 16 Bits data type
- Int16 FCNN computed with Basic Vector Operation (STM32 microcontroller)

FULLY INTEGRATED SENSOR NODE: VIRTUAL MACHINE





- Programming Language: High-level Basic!
- Input: Text (single statements and program code)
- Fast tokenstream compiler with optimization and code compaction (two-pass compiler)
- Single-step compiler and execution loop (live in harmony with main IO loop and host appliaction)
- Event-driven preemptive processing
- Very low resource requirements: < 14 kB RAM

Programming Features

- Event handler
- Error handler
- Extended I/O
- Math

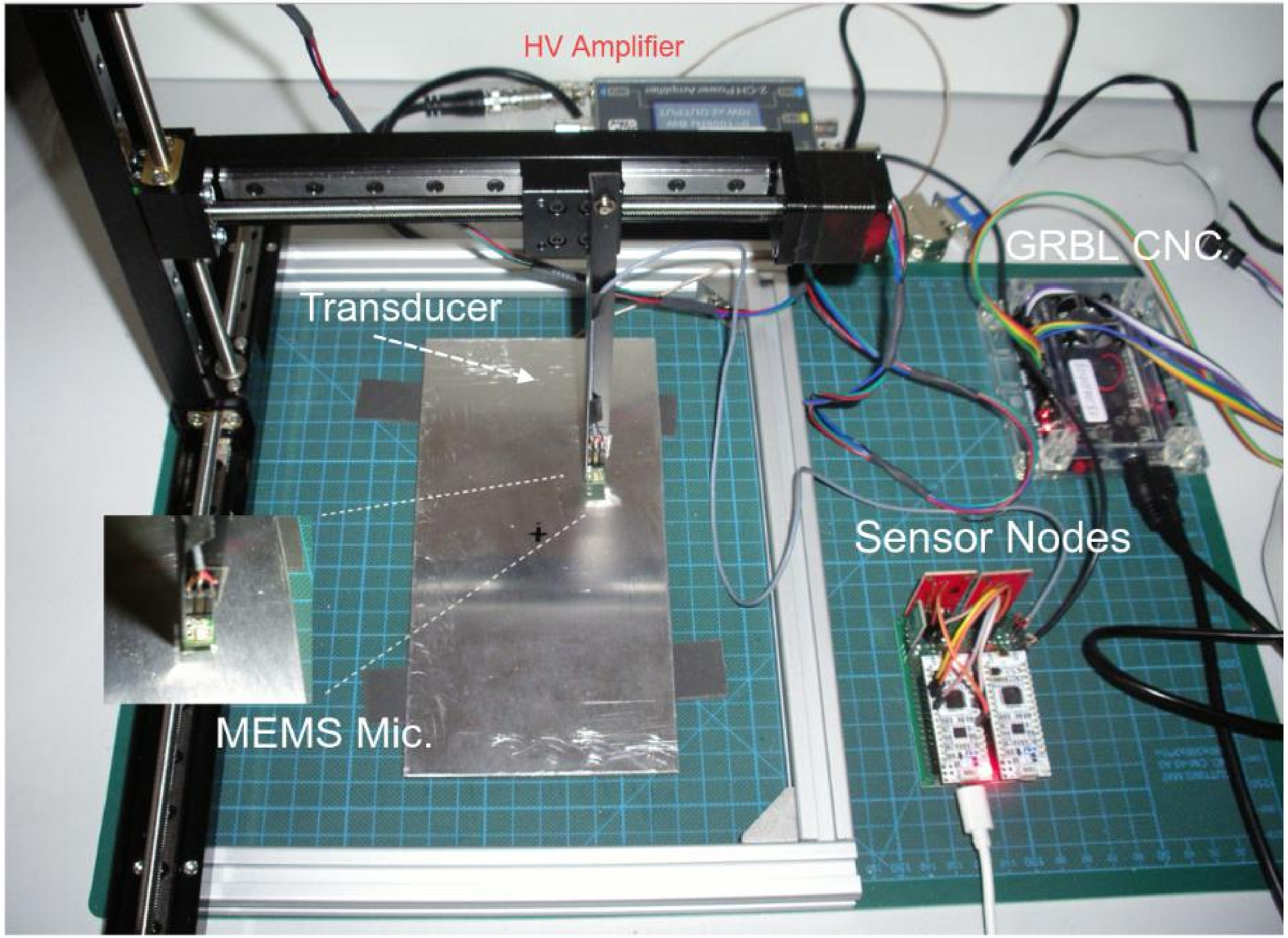
- Vector operations for Tiny ML
- 16 Bits data width (Int 16)
- can be easily extended
- C Call API

AIR-COUPLED SCAN TECHNIQUE

- Proof-of-concpet: Experimental data acquisition to evaluate the damage prediction model (ML)

- The experimental prototype: The 3-dim. portal arm device with a mounted MEMS microphone and the test plate.

- On the lower right side there is an experimental demonstrator consisting of two sensor nodes and the amplifier cascade circuit.
- On the upper right side there is the GRBL CNC controller driving the portal arm machine
- The transducer is mounted on the down side of the plate and driven by a high-voltage amplifier (V_{max} =40 V_{pp}, f_{-3dB} =100 kHz, G=20 dB)



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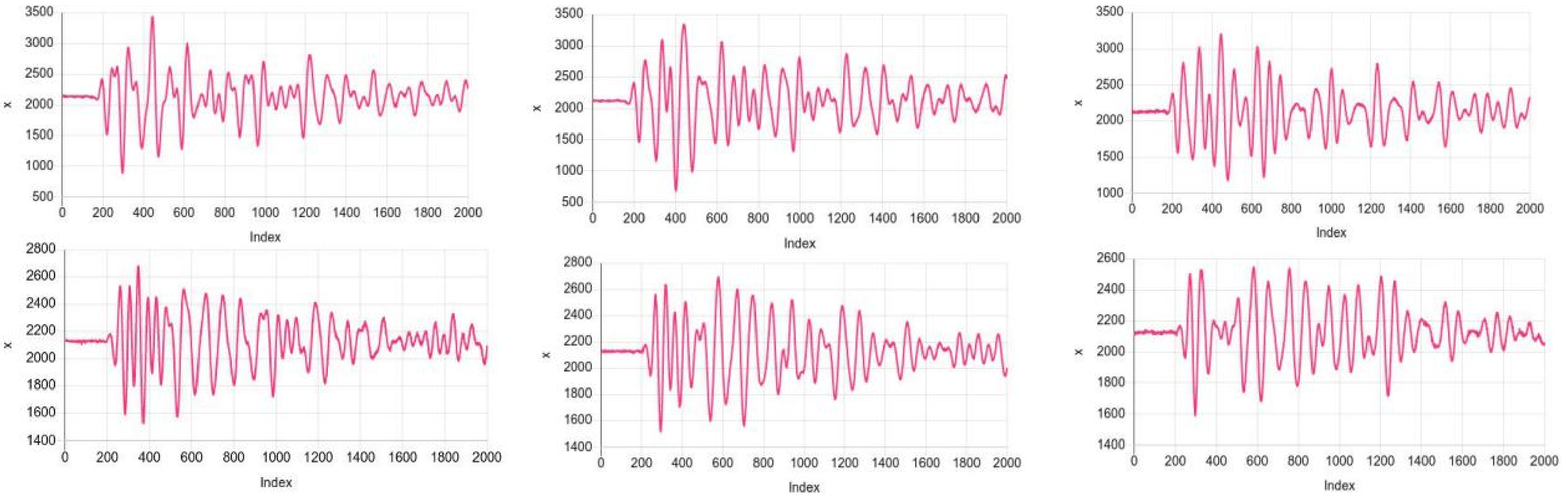
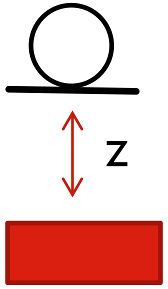
AIR-COUPLED SCAN TECHNIQUE

z=4 mm | z=5 mm | z=6 mm

X=30 mm
Y=30 mm
Damage

X=2 mm
Y=2 mm
No Damage



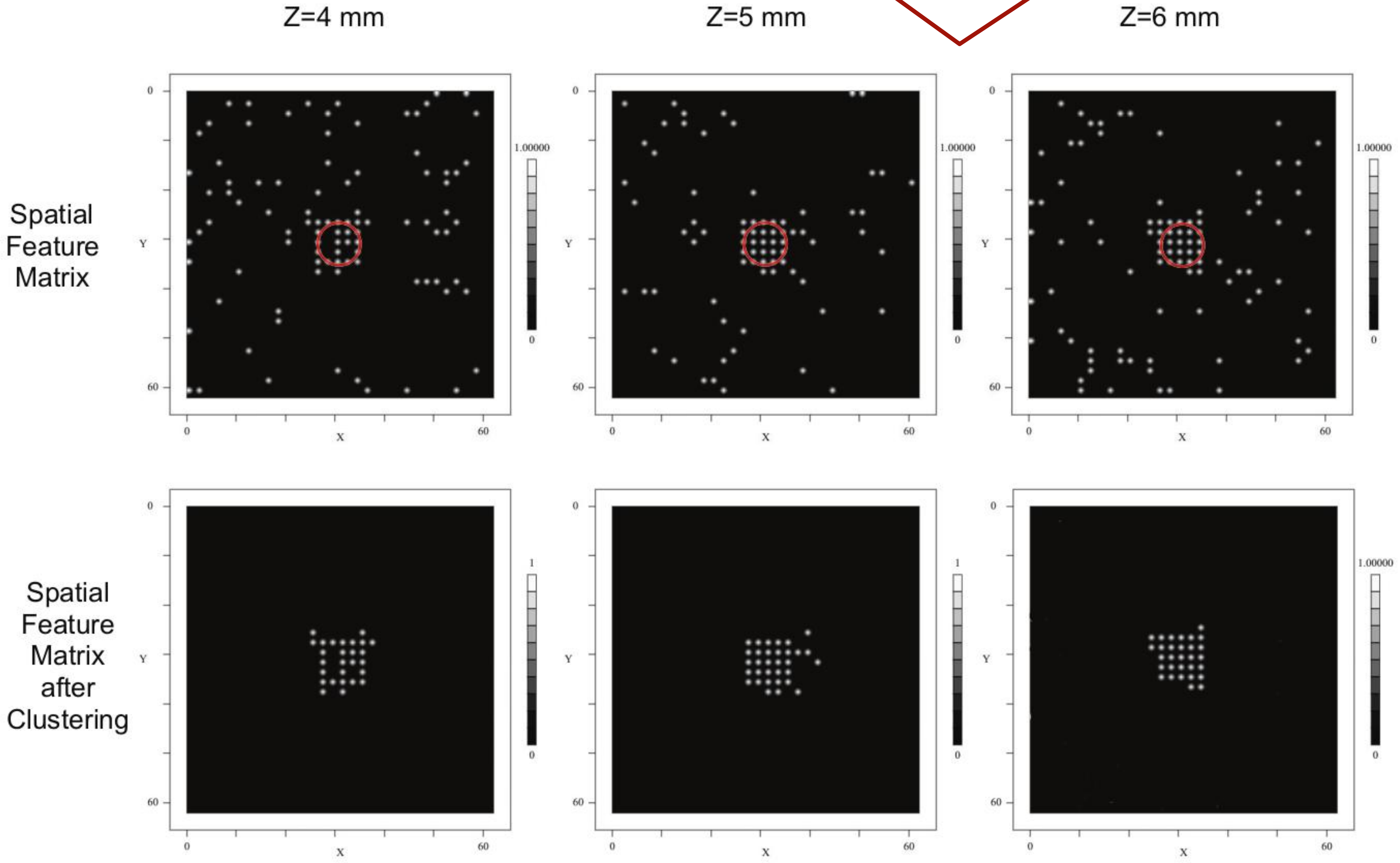


Sensor signals are significantly dependent on the distance from the material surface to the microphone (microphone height z)!

EXPERIMENTAL RESULTS

- Input data: GUW sensor signal matrix from **air-scan** with 31 x 31 (x,y) positions (2 mm distance) and different microphone heights (z)
- Input feature vector: FWT (25/100)
- Predictor model FCNN (Float32) was **trained** with labeled sensor data (all heights z)
- Predictor model FCNN and feature extraction were applied to 31 x 31 signals for different microphone heights (z), resulting in **feature images** (top)
- **Density-based clustering** was applied to the feature image (bottom) removing noise (false-positive predictions): **Model Fusion**

- But wait, there is a lot of noise!



FWT: L5-N100 FCNNF32 L3[10-10-10]:tanh

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EXPERIMENTAL RESULTS

	Error	F1 Score	False Positive	False Negative	Localization
FWT=100 DT=Float32	8.3%	0.89	10%	0%	±5 mm
FWT=25 DT=Float32	6.8%	0.90	10%	4%	±6 mm
FWT=100 DT=Int16	8.3%	0.90	12%	2%	±6 mm
FWT=25 DT=Int16	6.6%	0.89	10%	2.6%	±6 mm

	Average	Variance
Hardware Signal Propagation (Node-to-Node)	3μs	<100 ns
VM Execution Time (1 Token==VMachine Instr.)	2μs	<1μs
FCNN Computation (STM32)	<100 ms	-
Signal Recording	12 Bits, 2MS/s, 2000 points (1ms)	-

Ressources:
STM32 F303
64 MHz Clock
50/64 kB ROM
14/14 kB RAM

Only proof-of-concept study!

CONCLUSIONS

Air-coupled MEMS Microphone and GUW

- Contactless GUW monitoring
  - Small size
  - Easy integration, high miniaturizatiob
- **Ultrasonic frequency response 30-80 kHz**
- **High sensor density**
- 1-Sensor 2D-scan or Distributed N sensor network
- **Signal is z-dependent** and damage/defect information is time- and location dependent

Distributed Sensornetwork

- Fully Integrated Sensor Node with low-resource microcontroller (STM32): Less than 64kB ROM and 20 kB RAM
- Chain- or mesh-grid network
- **Synchronization** is performed via hardware signals and messages
- A **Virtual Machine** provides a Basic scripting engine, event-driven preemptive processing, signal processing (e.g. FWT) and TinyML (vector operations)
- VM supports single-step (single-token) compilation and execution

Distributed ML

- Each sensor node records a GUW signal, performs a Wavelet transformation, and predicts the local state using a simple FCNN model trained off-line
- False-positive rate is increased - therefore no robust local damage or defect prediction is possible
- But clustering and global model fusion (or within a given range) improves damage predicition and localization significantly
- Instead gloabl density-based clustering a local neighboring approach can be used

THANK YOU

Stefan Bosse

sbosse@uni-koblenz.de

www.edu-9.de

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Praktische Informatik