Embedded models in wireless sensor networks for structural health monitoring

Kosmas Dragos

Bauhaus-Universität Weimar

Research Training Group 1462

Supported by the German Research Foundation DFG

November 11,2014

German Academic Exchange Service
Not-for-profit organization

DAAD

Bauhaus-Universität Weimar

Outline

Background

1. Structural health monitoring
2. Wireless sensor nodes in structural health monitoring
3. System identification techniques
4. Embedded computing capabilities

Theoretical approach

1. Proposed embedded software
2. Description of the decentralized condition assessment process

Experimental validation

1. Initial laboratory tests
2. Full-scale tests in small structures

Outlook

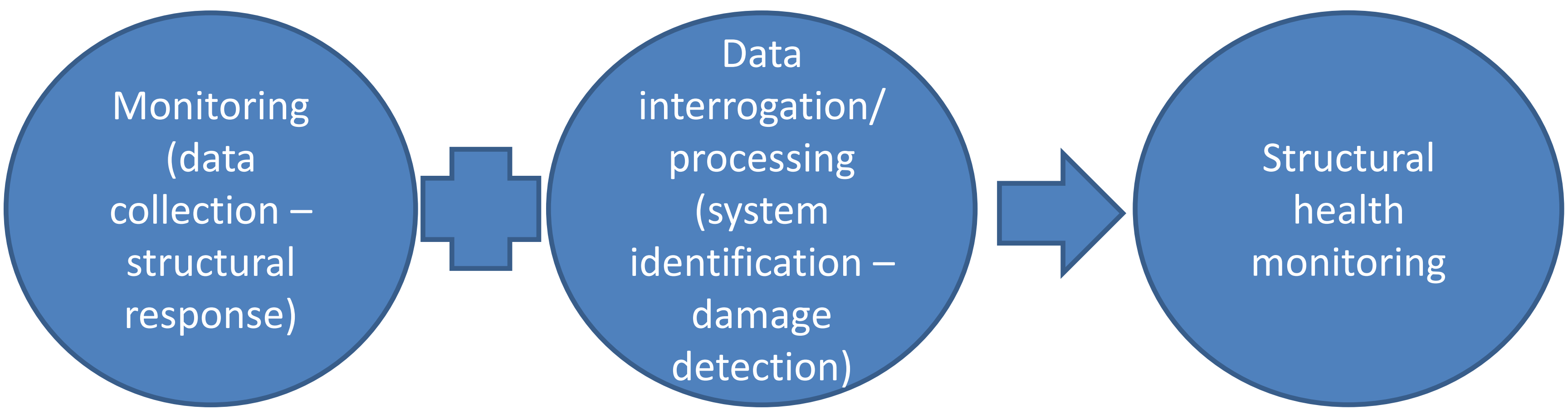
1. Further validation in larger and more complex structural systems
2. Extension to various types of structures
3. Testing of the possibility for damage localization

Background: Structural health monitoring

Review

- Despite efficient code-compliant designs, threats from ageing infrastructure and/or unanticipated loading conditions are still present
- Structural health monitoring (SHM) emerged in the past few decades drawing from the need for the safer design of sustainable structures

Assessment of the “health” of structures:



Background: Structural health monitoring

Current practice

Condition assessment of structures performed through:

Visual inspection

https://www.fhwa.dot.gov/publications/publicroads/00jan/nde.cfm

- Labor intensive
- Costly
- Hazardous
- Inconsistent

Non- destructive testing

http://www.measurement-testing.com/vibration-testing-2.html

- Time consuming
- Costly
- Accuracy restricted to the vicinity of the tested area

Destructive testing

http://www.testconsult.co.uk/item detail.aspx?id=43&dept=structural-investigation

- Labor intensive
- Costly
- Limited applicability
- Accuracy restricted to number of specimens

Background: Structural health monitoring

Tethered systems

- Initial approach in SHM
- Coaxial wires employed to ensure reliable transmission

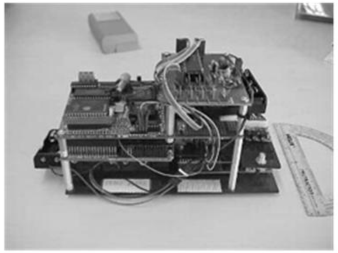
While effective for minimal configurations….

…. full scale implementations could be problematic!

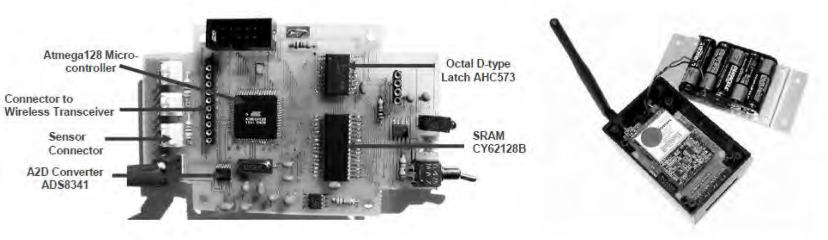
- Monitoring of large buildings with tethered systems could cost up to $ 5,000 per sensing channel [*Celebi (2002)*]
- The cost of the instrumentation of Tsing Ma bridge (Hong Kong) exceeded $ 8 million [*Farrar (2001)*] [*Lynch and Loh (2006)*]

Background: Wireless sensor nodes

Wireless sensor nodes in structural health monitoring



Prototype wireless sensor node proposed by Straser and Kiremidjian (1998)

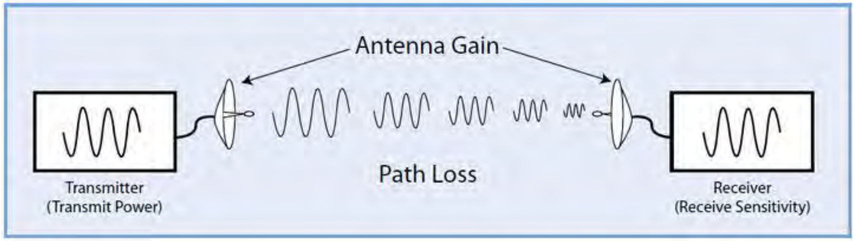


Description and packaging of the WiMMS node proposed by Lynch et al. (2003)

- Introduced in the late 1990s in structural health monitoring [*E. Straser & A. Kiremidjian (1998)*]
- Drew increased interest due to their attractive features (lower cost – reduced installation time)
- Wireless sensor nodes are essentially integrated platforms able to perform a variety of monitoring tasks

Background: Wireless sensor nodes

Wireless sensor nodes in structural health monitoring



Source: http://security-today.com/articles/2012/04/01/indoor-wireless-path-loss.aspx

- Research focuses on addressing the shortcomings of wireless sensing technology
- Two major issues:

A. Reliability of wireless communication (potential data loss/path loss)

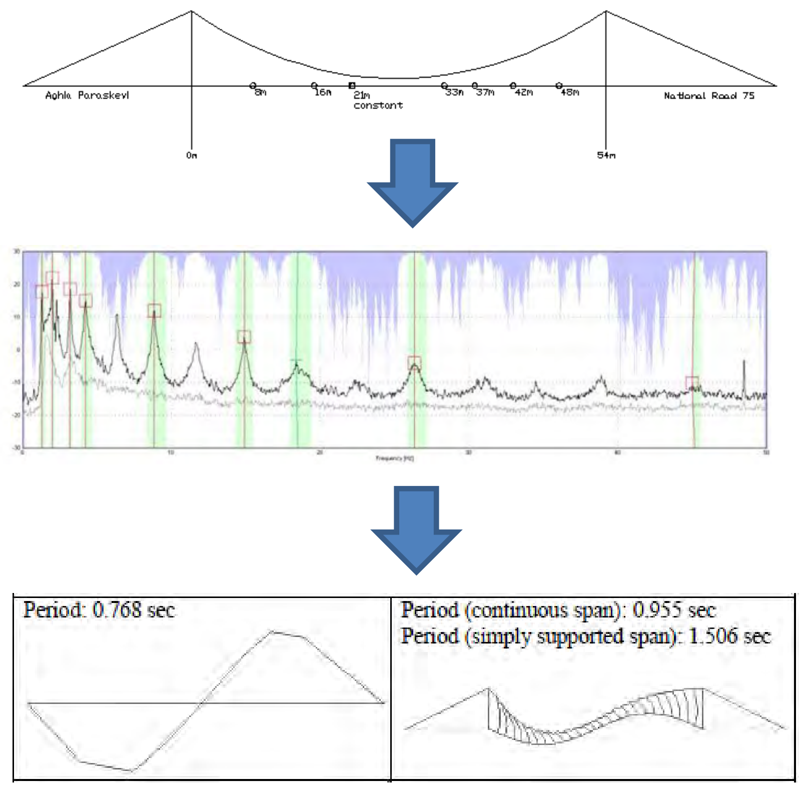
B. Power efficiency (limited resources)

Background: System identification

Bauhaus-Universität Weimar
Research Training Group 1462

Methods and techniques of estimating structural properties

- Common in structural health monitoring
- Extraction of dynamic parameters (mode shapes, frequencies, damping)
- Prevalence of output-only techniques for full-scale tests (ambient vibration testing) [*Á. Cunha, E. Caetano (2006)*]
- Observed changes in global dynamic properties could be indicative of potential damage



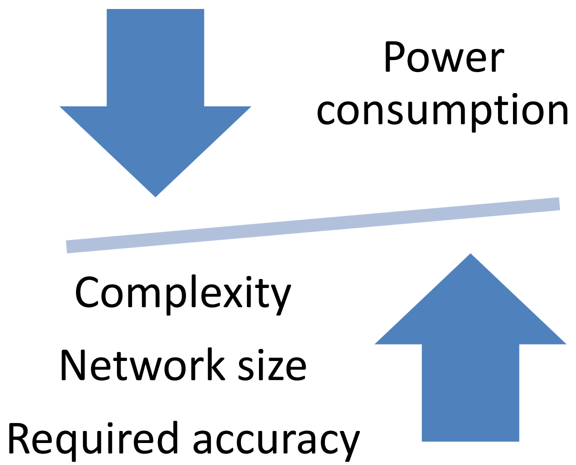
Background: Embedded computing

The embedded computing capabilities of wireless sensor nodes are a topic of ongoing research

Algorithms of different levels of complexity could be incorporated into the sensor nodes

The level of sophistication of the embedded software depends on:

- The objective of the monitoring process
- The structural characteristics
- A trade-off between power consumption and microcontroller specifications (memory, bus size, speed, etc.)

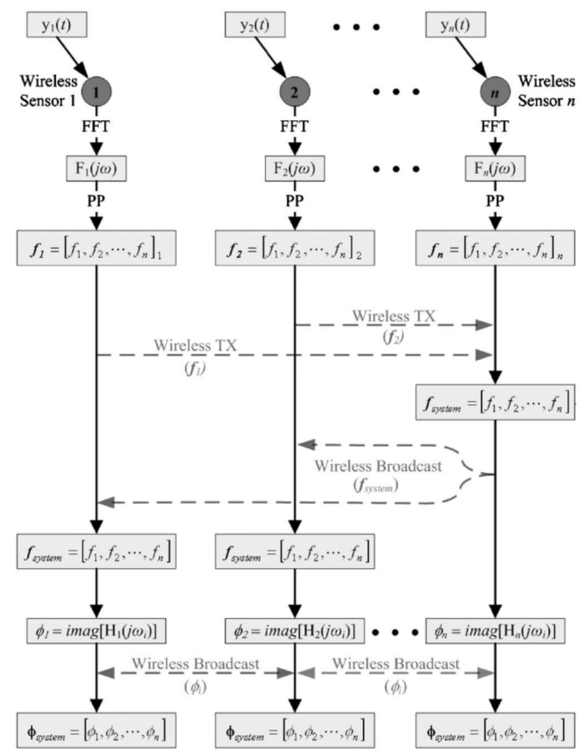


Background: Embedded computing

Bauhaus-Universität Weimar
Research Training Group 1462

Data processing

- The collection and transmission of raw time series has proven to be power consuming
- Data processing could lead to a reduction in power consumption up to 95%
- In initial data interrogation approaches AR-ARX algorithms were used for damage detection [*J. Lynch et al. (2001)*]
- Data processing algorithms of increasing complexity (FFT, PP, FDD, SSI, ERA) have been integrated following the developments in the fields of electronics, electrical engineering and computer science [*Y. Wang et al. (2005)*] [*J. Rice et al. (2010)*] [*Zimmermann et al. (2008)*]



Representation of the embedded peak picking algorithm presented by Zimmerman et al. (2008)

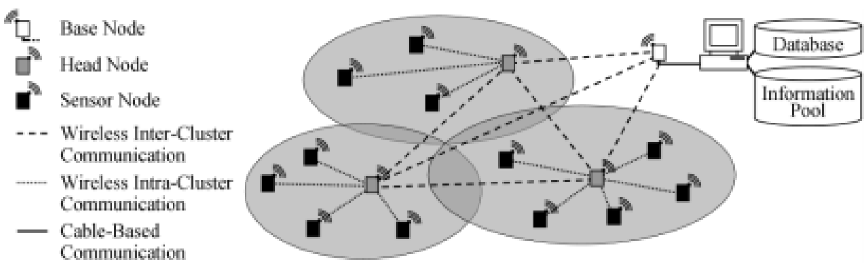
Background: Embedded computing

Networking

Utilization of the embedded computing capabilities of the sensor nodes to enhance the interaction among network components

Various approaches:

- Programmable networks with more than one tiers (clusters of sensor nodes assigned with different tasks) [*Paek et al (2006)*]
- Middleware services dealing with communication reliability, synchronization and data aggregation [*Nagayama et al. (2008)*]
- Code "migration" using software modules ("agents") that could migrate on demand to sensor nodes for further analysis [*K. Smarsly and K. Law (2013)*]



Theoretical approach: Embedded software

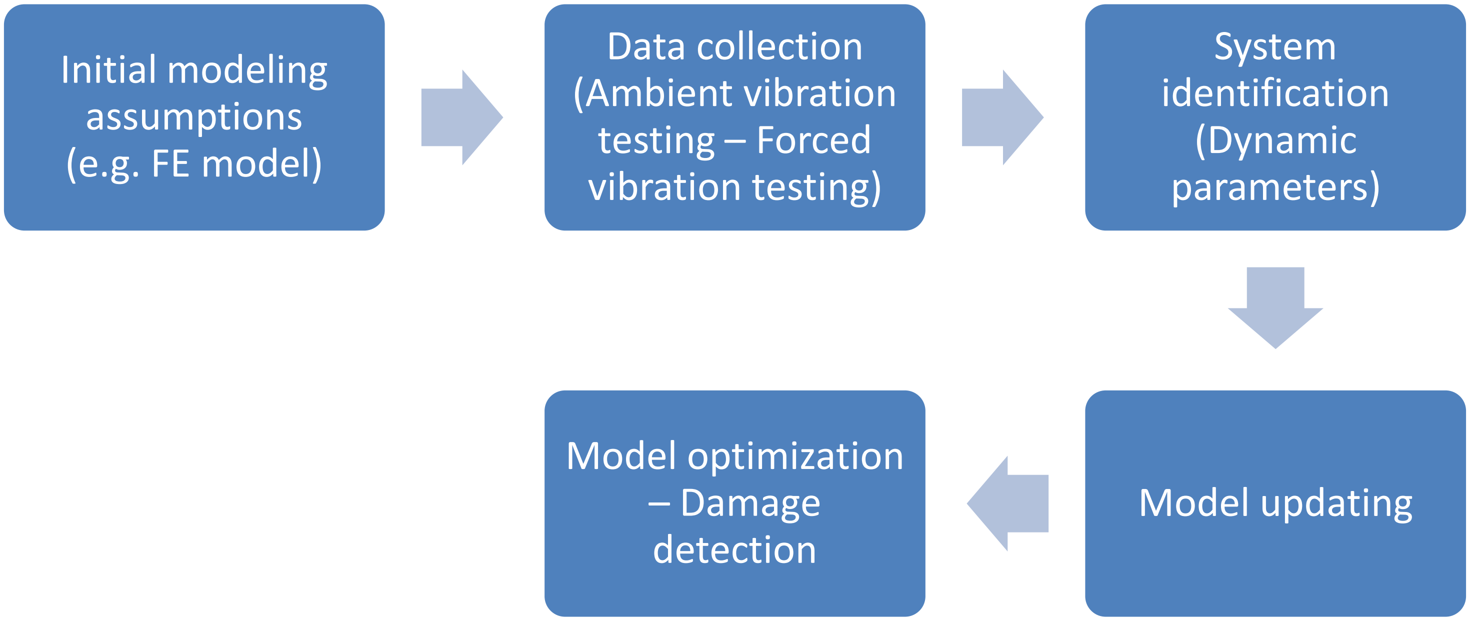
Advances in wireless sensing technologies have enhanced their embedded computing capabilities and have allowed the incorporation of more sophisticated algorithms

Proposed approach:

- Development of partial models to be embedded in the wireless sensor nodes
- Coupling of the partial models in order to obtain a global updated model
- The coupling of the partial models is performed by making use of both the computational power and the wireless communication of the sensor node
- Assessment of model qualities as well as of the coupling process

Theoretical approach: Process description

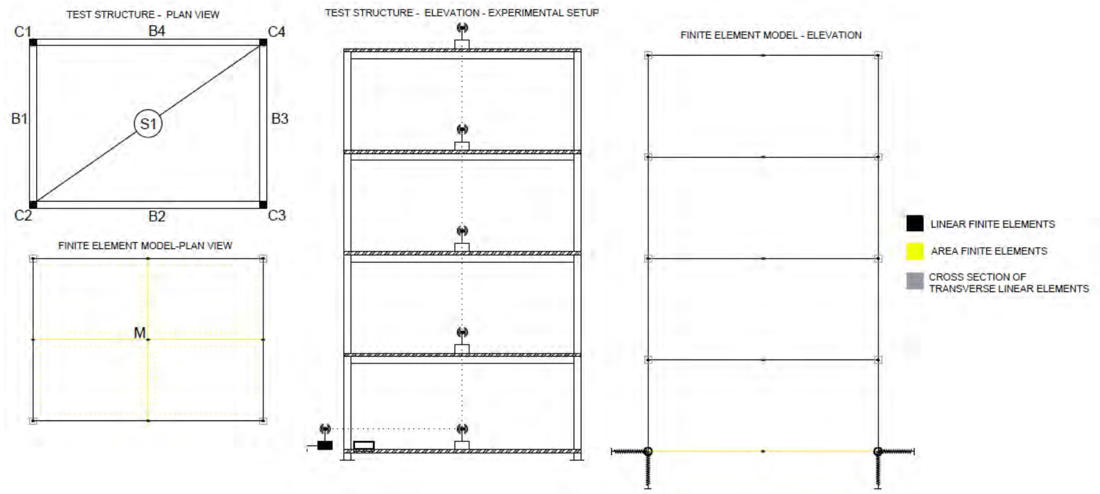
Bauhaus-Universität Weimar
Research Training Group 1462



- Integration of a model into the nodes in order to decentralize the process of condition assessment (by enhancing the level of intelligence of smart wireless sensor nodes)
- Java code developed to perform on-board model analysis (e.g. FEA, dynamic analysis, etc.)

Experimental validation: Lab tests

Bauhaus-Universität Weimar
Research Training Group 1462



- Performance of initial ("pilot") envisaged laboratory tests on a multi-story shear frame
- Each node will be placed at the mass center of each floor
- The frame will be subjected to various vibration time-histories on a shake table
- A tethered system will also be used for comparison purposes
- Comparison between model analysis results and test results

Experimental validation: Nodes

Sensor nodes

The Oracle SunSPOT sensor nodes will be used for the initial validation tests

Technical specifications:

Microcontroller:

• Speed:	32 bit
• Flash memory:	1 MB
• RAM:	512 kB

Sensor board:

- Three-axial accelerometer (MMA7455L), temperature sensors
- 10 bit ADC

Experimental validation: Lab tests

Scope of the test

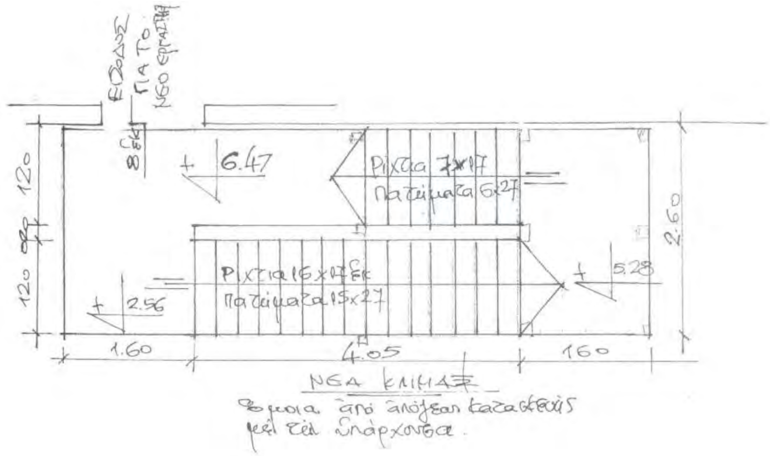
- Begin the process by performing model analysis using initial assumptions
- Perform various types of tests to derive partial models of the structure from extracted parameters
- Combine the partial models to derive an updated model
- Use an objective function to obtain optimized values for key model parameters with high uncertainty (e.g. boundary conditions)

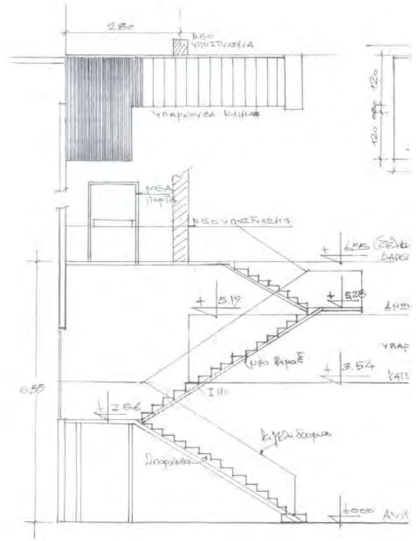
Further step…

- Correlate damage scenarios with different mode shape patterns

Experimental validation: Field tests

- Full-scale implementation of the method in a steel multi-story stairway (test devised to be conducted at Aristotle University of Thessaloniki (A.U.Th.)
- Further comparison with data collected by tethered system (performed by A.U.Th.)





Outlook

Further experimental validation

- Possibility of conducting full-scale experiments in larger and more complex structures
- Testing of a steel pedestrian bridge in collaboration with A.U.Th.
- Application of the proposed methodology to the reference test objects within the framework of the GRK 1462 (telecommunication tower and railway poles)
- Use of data from previous measurements on those reference objects for comparison

Outlook

Next steps

- Extend the proposed methodology to various types of structures (e.g. concrete, masonry, etc.)
- Definition of data structures and database schema for automated database access
- Address modeling uncertainty issues for each type of structure
- Assess the quality of partial models and model couplings (as well as of the modeling techniques used)
- Derive optimized parameters and provide alternative modeling suggestions
- Test the ability of the proposed methodology to localize damage in different types of structural systems

Thank you for your attention!