

Decentralized autonomous sensor fault detection using neural networks

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The dependability and the accuracy of structural health monitoring systems can be affected by sensor faults. In this paper, the design and implementation of a wireless structural health monitoring system, capable of decentralized autonomous fault detection, are presented. For self-detecting sensor faults, each sensor node predicts expected sensor data and compares it to the measured sensor data. The predictions are computed using neural networks based on measured sensor data of adjacent sensor nodes. In laboratory experiments, devised to validate the proposed approach, several simulated sensor faults are detected. These results indicate that the use of neural networks for fault detection increases the dependability and the accuracy of structural health monitoring systems.

Dictionary

Sensorknoten (SunSPOT)	sensor node
einzelner Messsensor (Thermometer)	sensor
Knoten im neuronalen Netz	neuron
eine abgeschlossene Messungreihe	test run
gemessene Werte	sensor data
vorhergesagte Werte	predicted data
durch Vorhersage erwartete Werte	expected data
einzelner Messwert	measurement
Test	laboratory experiments
tatsächliche, nicht virtuelle Messung	actual measurement
Messaufbau	test setup

Introduction

Civil engineering structures are exposed to various external impacts during their
5 lifetime. Structural health monitoring (SHM) systems can be deployed to evaluate
the conditions and to ensure the structural stability of civil engineering structures.
Bisby [1] defines SHM as "a non-destructive *in-situ* structural evaluation method
that uses any of several sensors which are attached to, or embedded in, a structure".
The obtained sensor data is collected by sensor nodes, and then analyzed and stored
10 on a computer system over long periods of time. The analysis of the sensor data
can reveal abnormal changes in material and geometric behaviour at an early stage.

Traditionally, the sensor nodes are connected to computer systems with cables.
However, using wired SHM systems has several disadvantages, including expensive
wiring, high installation and labor costs as well as inaccessibility of optimal sensor
15 location with wires. In wireless SHM systems, the sensor nodes communicate—
through a basestation with each other and with computer systems— via wireless
transceivers, eradicating wiring-specific problems.

Over their lifetime, sensors can become inaccurate, faulty, or may even break.
A fault can be defined as a defect of a sensor that leads to an error. An error
20 is the manifestation of a fault—an incorrect system state—that may result in a
failure. To ensure the dependability and the accuracy of the SHM system, sensor
faults must be detected and isolated in real time. A well known approach to fault
detection is the installation of physically redundant sensors. Faulty sensors can be

identified through the deviation of their measurements from the measurements of
25 correlated sensors. Physical redundancy, although efficient for sensor fault detection,
causes increased installation and maintenance costs due to the multiple installation
of sensors. Representing a more efficient approach, analytical redundancy typically
uses mathematical functions mapping the characteristics of the structure and the
correlations of the installed sensors. Virtual sensor measurements are computed for
30 each sensor and then compared to the actual measurements. For example, finite
element models can be used in combination with data from adjacent sensor nodes
to calculate virtual measurements of a sensor [2].

In this study, analytical redundancy is implemented into wireless sensor nodes
based on artificial neural networks. Artificial neural networks essentially consist of
35 interconnected data processing units called neurons. The neurons are grouped in
different layers; usually one input layer, a number of hidden layers, and one output
layer. Artificial neural networks are able to learn, which is achieved by adjusting the
weights of the inter-neuron connections until a set of given input variables results
in the desired output variables; for example, a neural network can be trained to
40 approximate any mathematical functions with any level of accuracy [3].

This paper is organized as follows: First, a wireless structural health monitoring
system is designed and implemented. Next, a neural network is implemented into
each sensor node and trained to predict the sensor measurements of the specific node
for detecting sensor faults in a decentralized manner. Then, the system is tested in
45 laboratory experiments. Finally, the experimental results are discussed and future
research directions are proposed.

Design and implementation of the wireless structural health monitoring system

In the following section, the wireless structural health monitoring system is introduced and the software implementation is described. The wireless SHM system consists of wireless sensor nodes and a host computer, linked with a basestation. The sensor nodes and the basestation are of type "Oracle Sun SPOT". The Sun SPOTS are equipped with several components, see Figure 1. Among others, the sensor board includes an accelerometer and eight independent RGB-LEDs. The 3-axis digital output accelerometer with sensitivity ranging between $\pm 2g$ and $\pm 8g$ has a maximum sampling rate of 125Hz [4].

citation
BILD!

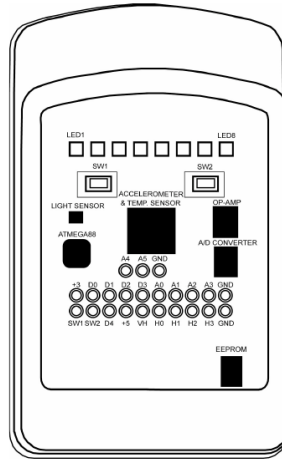


Figure 1: Layout of the Sun SPOT sensor board

The SHM system performs the following tasks: 1. data acquisition, 2. data processing, 3. data transmission, 4. data storage, 5. diagnostics and 6. information retrieval. Tasks 1 to 3 are executed by the sensor nodes: During system operation, the sensor nodes acquire acceleration measurements and perform a fast Fourier transform to determine the characteristics of the oscillation of the structure. The processed data is then transmitted via radio to the basestation and, finally, to the host computer. On the host computer, tasks 4 is conducted by storing the data in a MySQL database. Task 5 and 6—additional analysis and diagnosis—are conducted on the host computer in further steps.

neuer Absatz:

The SHM system is programmed object-oriented in Java. Object orientation uses objects, that are instanciated using classes as paradigm. A class includes methods, allowing the objects to perform actions, and attributes, specific data. Figure 2 describes the classes of the SHM system code. The SHM system consists of two packages—`sensornode` and `basestation`. A package organizes several Java classes that build a program.

The package `sensornode` consists of the classes `AccelerationSampler`, `FFT`, `Communication` and `MainSpot`, which are embedded directly into the sensor nodes. The `AccelerationSampler` class is responsible for measuring the acceleration. There are two phases: **At** first, the acceleration is measured with a low sampling rate. Once the acceleration exceeds a threshold, the **second phase is entered** by increasing the sampling rate. The measured values are stored into an array. The different phases are indicatad by lighting different LEDs. The `FFT` class performs a fast Fourier transform on the measured accelerations. With the transformed data, the magnitudes and the correlating frequencies of the measured oscillation are calculated. Finally, the natural frequency **is** determined by extracting the maximal magnitude. The `Communication` class opens a radio connection between the sensor node and the basestation to transfer data from the sensor node to the basestation. For starting the operation of **the sensor node**, the entry point of the programm is the `startApp()` method in the `MainSpot` class. Within the `MainSpot` class, instances of the `AccelerationSampler` class, the `FFT` class and the `Communication` class are created to perform the measurement.

The package `basestation` runs on the host computer and operates the basestation. It consists of the classes `DatabaseHandler` and `MainBase`. The `DatabaseHandler` class establishes a connection to a MySQL database, creates a database table, if none with the specified name is available, and inserts data into the database table. The entry point of the program is the `run()` method in the `MainBase` class. The `MainBase` class opens a radio connection between the basestation and the sensor nodes, receives data sent by the sensor nodes and creates an instance of `DatabaseHandler` to insert the data into the database.

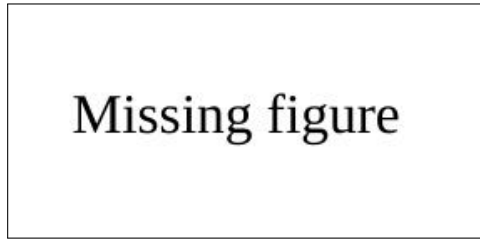


Figure 2: class diagram describing the structure of the implemented SHM system

Implementation and training of neural networks

Neural networks are implemented into the sensor nodes using SNIPE¹, a open source Java Library.

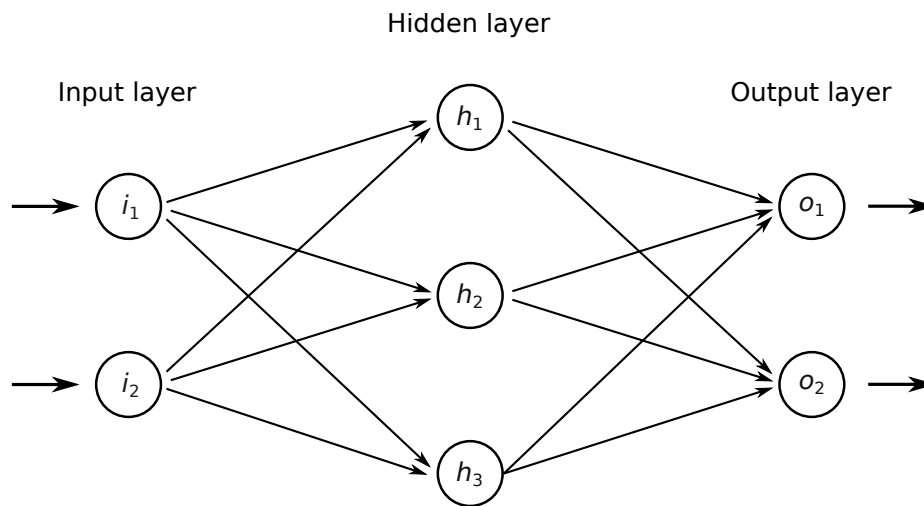


Figure 3: Schematic drawing of an artificial neural network with three layers

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Grafik wird an unser neuronales Netz angepasst

Laboratory experiments

To validate the proposed approach in laboratory experiments, the wireless SHM system is installed on a test structure. The test structure is a 4-story shear-frame consisting of four steel plates with an area of $25\text{ cm} \times 50\text{ cm}$ and a thickness of 0.8 mm. Those plates are mounted on threaded rods with a vertical clearance of 23 cm. At the bottom, the rods are fixed into a solid block of wood with an area of $40\text{ cm} \times 60\text{ cm}$ and a height of 30 cm. The SHM system is installed on the test structure by fastening wireless sensor nodes to each story. The laboratory setup is shown in Figure 4.



Bild ersetzen durch ein Bild mit den fertig installierten SPOTS

Figure 4: Laboratory setup

The structure is excited by deflecting and releasing the top of the structure. This excitation method ensures a free vibration in natural frequency with little interferences. After excitation, the sensor nodes automatically start the acceleration with a sampling rate of 40 Hz. To minimize the wireless data communication, each node performs a fast Fourier transform algorithm once sufficient acceleration measurements have been collected. The acceleration measurements are converted into the vibration frequencies and the corresponding magnitudes of the building. Each sensor node transfers only the values of the predominating frequency—i.e. the frequency with the biggest magnitude—to the basestation. The values are then stored in the MySQL database at the host computer.

Summary

This paper presents a decentralized autonomous sensor fault detection strategy for structural health monitoring systems using neural networks. We realized the autonomous sensor fault detection by implementing a neural network into each sensor node. The neural networks are trained to predict the expected sensor measurement, which is then compared to the actual measurement, revealing potential sensor faults. The SHM system has been verified with laboratory experiments, proving that sensor fault detection using neural networks can, in fact, improve the dependability and the accuracy of structural health monitoring systems.

References

- [1] LA. Bisby. *An introduction to structural health monitoring*. Department of Civil Engineering, Queen's University, Canada, 2014.
- [2] Kay Smarsly and Yuri Petryna. A decentralized approach towards autonomous fault detection in wireless structural health monitoring systems. In *EWSHM-7th European Workshop on Structural Health Monitoring*, 2014.
- [3] Jianchun Li, Ulrike Dackermann, You-Lin Xu, and Bijan Samali. Damage identification in civil engineering structures utilizing pca-compressed residual frequency response functions and neural network ensembles. *Structural Control and Health Monitoring*, 18(2):207–226, 2011.
- [4] *Sun SPOT eDEMO Technical Datasheet*. Sun Labs, Santa Clara, 8 edition, 2010.