

# Validation of an ultra-low-cost wireless structural health monitoring system for civil infrastructure

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## ABSTRACT

Structural health monitoring (SHM) is critical to ensure safety of civil infrastructure, such as bridges, railways, or pipelines. However, existing SHM techniques suffer from high investment, installation, and maintenance cost. This paper presents an ultra-low-cost and easy-to-use wireless SHM system for civil infrastructure, featuring real-time sensing, on-board data analysis, energy-efficient wireless communication, and Internet of Things (IoT) connectivity. To validate its performance, the proposed SHM system is installed at Itztal Bridge, Germany, for monitoring and analyzing quasi-static horizontal deck displacements in response to thermal loads. In parallel to the ultra-low-cost SHM system, a traditional tethered SHM system, also installed at the bridge, is used in this study for direct comparison and validation. As a result, the ultra-low-cost wireless SHM system is shown to be easy-to-install and sufficiently accurate for monitoring and analyzing the behavior of civil infrastructure under static loads, serving as a low-cost yet high-performance diagnostic tool with IoT connectivity.

## INTRODUCTION

Well-functioning infrastructure is a cornerstone of modern society. In many countries, infrastructure is in critical condition, and the costs of maintenance, rehabilitation, and repair exceed available budgets by far. In the United States, almost 10% of the bridges are structurally deficient, representing an estimated backlog of bridge rehabilitation needs of US\$ 123 billion [1]. In France, more than 800 road bridges are at risk of failure. Germany, with more than 2,300 bridges rated deficient, has closed many bridges on major international routes to truck traffic on a regular basis, and one third of Italian bridges require repair [2, 3]. Environmental impact and heavy traffic are the main reasons for infrastructure rapidly deteriorating worldwide. In addition, many bridges are approaching the end of their design life. For example, 40% of U.S. bridges are 50 years or older, and the majority of bridges in West Ger-

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many were built in the 1960s and 1970s and were not designed for the heavy freight traffic of today. Accurate condition assessment is critical to ensure cost-efficient operation and safety of civil infrastructure [4].

Facilitating non-destructive condition assessment of civil infrastructure based on sensor data, structural health monitoring has become a useful tool to advance maintenance, rehabilitation, and repair, thus enhancing cost-efficient operation and safety of civil infrastructure [5]. Unlike visual inspections that are performed periodically, structural health monitoring can be conducted continuously, in real time, and at locations that may be difficult to be visually inspected [6]. Based on sensors permanently installed on structures to continuously measure and analyze parameters relevant to condition assessment, structural health monitoring provides both local and global monitoring, as opposed to visual inspections that are restricted to localized areas [7].

Structural health monitoring of civil infrastructure can be further subdivided into dynamic and static monitoring [8]. Dynamic monitoring provides insight into the modal behavior and the dynamic response of structures, enabling condition assessment, system identification, and damage detection. Typically, acceleration or strain measurements serve as a basis for dynamic monitoring. Static monitoring usually employs time series collected at longer time steps to neglect effects of time-variant phenomena, such as inertial and damping forces. Deformation, tilt, or displacement measurements, along with temperature loads, are typically analyzed with respect to static behavior. Given the more extensive use of static monitoring as a common tool in infrastructure condition assessment, the remainder of this paper, and the SHM system presented herein, focuses on static monitoring using displacement and temperature measurements.

In spite of the benefits brought by SHM systems with respect to accurate condition assessment, structural health monitoring still suffers from high investment, installation, and maintenance costs that prevent owners and operators from taking full advantage of deploying SHM systems on civil infrastructure to a large extent. For example, monitoring large-scale civil infrastructure entails deploying sensors connected to data acquisition units or wireless sensor nodes with sensing, embedded computing, and communication capabilities, which may result in a total of several hundred thousand US\$ for a fully equipped SHM system. However, smaller SHM systems deployed for short-term monitoring, serving as cost-effective and easy-to-install yet accurate “quick testers” of structural condition, are often sufficient to provide a picture of the infrastructure condition.

The objective of this study, therefore, is to develop an ultra-low-cost wireless SHM system with sensing, embedded computing, and communication capabilities that is (i) cost-effective, (ii) easy-to-install, and (iii) sufficiently accurate. The system design focuses on commercial off-the-shelf components, representing prefabricated and tested hardware parts, which allow recording displacement and temperature measurements. Through a modular software design, data analysis algorithms are embedded into wireless sensor nodes, and peer-to-peer communication among the nodes and Internet of Things (IoT) connectivity is implemented. The rest of the paper is organized as follows. The design and implementation of the wireless SHM system are first presented. A field validation test at Itztal Bridge is then described. The results of this study are shown and briefly discussed. Finally, a summary and conclusions are provided.

## DESIGN AND IMPLEMENTATION OF A WIRELESS SHM SYSTEM

The hardware design of the prototype wireless SHM system aims at cost effectiveness and ease of use, integrating commercial off-the-shelf components. The software design, providing real-time sensing, on-board data analysis, energy-efficient wireless communication, and IoT connectivity, aims at accuracy with respect to data acquisition and on-board analysis of sensor data. Also, modularity and extensibility are emphasized by the system design.

On an abstract architectural software/hardware level, the overall system follows a multi-layered design approach comprising of an energy management layer, a communication layer, and an application layer. The *energy management layer*, associated with real-time sensing, node-to-node communication and IoT data communication, employs on-demand power management for regulating sensor node energy distribution. The *communication layer* manages drivers that implement wireless communication protocols, while supervising sensor data transmission throughput over the wireless sensor network. The *application layer* manages interfaces to hardware peripherals, implementing drivers for sensing and communication. The hardware components as well as the software design and implementation pursued to realize the software/hardware architecture are described in the following subsections.

### Hardware components

Enabling systematic and cost-effective (re)use of prefabricated and tested hardware parts, commercial off-the-shelf components are employed for implementing the wireless SHM system (Table 1). A 1-GHz single-board computer, type Raspberry Pi Zero W, provides the technological basis to supervise real-time sensing, to handle embedded data analyses, and, through on-board Wi-Fi communication, to manage energy-efficient wireless communication. A digital caliper with an accuracy of  $\pm 0.02$  mm is utilized for recording displacement measurements and a Pt100 temperature sensor is used for recording temperature measurements. Both sensors are interfaced with the single-board computer through an interface circuit, which comprises of two resistors and two transistors (Figure 1a). For power supply and data storage, a power bank (20,000 mAh) and a memory card (1 GB) are attached to the single-board computer. Figure 1b presents the assembly of the prototype wireless SHM system.

Table 1. Component costs and total cost of the wireless SHM system (inclusive of taxes).

Component	Cost (EUR)
Single-board computer (1-GHz CPU, on-board Wi-Fi)	10.71
Digital caliper	0.71
Temperature sensor	1.67
Memory card (1 GB)	1.00
Power bank (20,000 mAh)	9.79
Circuit board	1.84
Cables and small parts	3.43
<b>Total cost</b>	<b>EUR 29.15</b> <b>(US\$ 32.84)</b>

To protect the electronics from harsh weather and environmental impacts, the wireless SHM system is stored in a weatherproof plastic case, shown in Figure 1b. The final dimensions of the wireless system are 200 mm × 150 mm × 90 mm (length × width × height). It should be mentioned that the costs for housing and mounting are not included in Table 1.

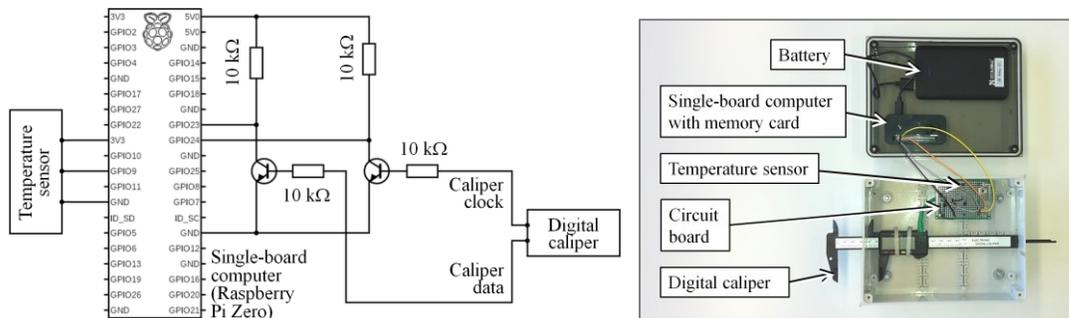


Figure 1. Wireless SHM system: (a) Electrical circuit schematic and (b) assembly of the prototype.

## Software design and implementation

The software is organized in two packages, a *sensorNode* package and a *server* package. The *sensorNode* package is embedded into every sensor node of the wireless SHM system, while the *server* package is deployed onto a remote laptop computer designated as sever. As shown in Figure 2, the *sensorNode* package executes displacement and temperature measurements based on realizations of a *Sensor* interface. The kernel of the *sensorNode* package incorporates an *Algorithm* interface. The interface is implemented by specific classes providing analysis algorithms. An algorithm is implemented to automatically analyze static behavior of bridges. Precisely, a computationally efficient linear temperature-displacement regression function is implemented to analyze horizontal deck displacement in response to thermal loads using the displacement and temperature measurements recorded through the *Sensor* interface.

The *sensorNode* package and the *server* package both implement a communication protocol that ensures a secure and reliable communication channel between *sensorNode*-based (i.e. node-to-node) wireless networks and server networks. Using a wireless local area network (WLAN) interface, the communication protocol implements decentralized peer-to-peer networking for node-to-node communication in the wireless network. One sensor node of the wireless SHM system is uniquely assigned as a gateway for propagating sensor data onto the IoT where the data is securely made ubiquitous for authorized devices. Finally, as can be seen from Figure 2, the *Server* is composed of both a *Database* interface and a *UserInterface*. While the *Database* interface enables archiving sensor data, the *UserInterface* provides user-friendly real-time data visualization and user access to the wireless SHM system.

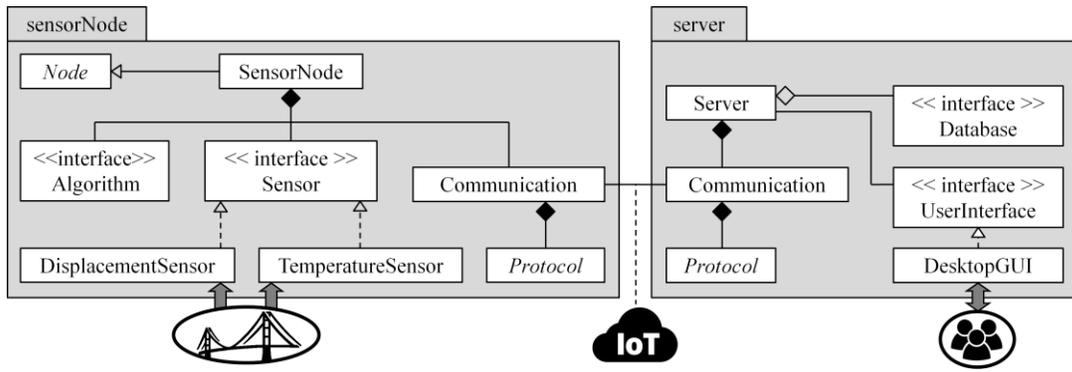


Figure 2. Software architecture of the wireless SHM system (main classes and interfaces).

## FIELD VALIDATION TESTING

To validate the ease of use and the accuracy of the wireless SHM system, a field test is conducted aiming at static monitoring of Itztal Bridge, a railway bridge located in the vicinity of Coburg, Germany. Itztal Bridge, with a total length of 868 m, is a composite concrete/steel structure spanning over 15 fields with lengths ranging between 57 m and 58 m. The total bridge height is approximately 30 m, while the deck has a height of 6.50 m (Figure 3a).

### Instrumentation and static monitoring

A large-scale tethered SHM system has been installed on the bridge prior to installing the wireless SHM system. The tethered system, designed and operated by MKP GmbH, serves as a benchmark system for validating the accuracy of the wireless system. The tethered system, originally designed for system identification and for studying the bridge response under external loading, includes a dense network of 338 sensors composed of displacement transducers and Pt100 temperature sensors. Deployed for static monitoring, the tethered system measures displacement and temperature at a sampling period of 10 minutes. For dynamic monitoring, the system may be set up to measure at sampling rates up to 10,000 Hz, triggered by trains crossing the bridge.

Serving as a proof of concept for the sensing, embedded computing, and communication capabilities of the wireless SHM system, a sensor node of the system is installed at the southernmost pier (pier 10) in tandem with a displacement transducer of the tethered system (Figures 3b and 3c). The sensor node of the wireless system is installed in a matter of a few minutes. Upon synchronizing the sensor node with the tethered system, displacement and temperature measurements are recorded at a sampling period of 10 minutes. Automated analyses of the static behavior, i.e. characterization of temperature-induced displacement response, are executed by the wireless system based on the linear temperature-displacement regression function mentioned above:

$$d = \beta_0 + \beta_1 T \quad (1)$$

where  $T$  and  $d$  are the temperature and displacement measurements, respectively. The regression coefficients  $\beta_0$  and  $\beta_1$  are obtained by

$$\beta_1 = \frac{s_{dT}}{s_{TT}} \quad \beta_0 = \bar{d} - \beta_1 \bar{T} \quad (2)$$

where  $s_{dT}$  is the covariance between the displacement and the temperature measurements, and  $s_{TT}$  is the variance of the temperature measurements. The variables  $\bar{d}$  and  $\bar{T}$  denote the means of all displacement measurements and, respectively, of all temperature measurements considered. The linear regression function calculated by the wireless SHM system, characterizing the temperature-induced displacement response at pier 10, is given in Equation 3:

$$d = -0.8362 + 0.1934T \quad (3)$$

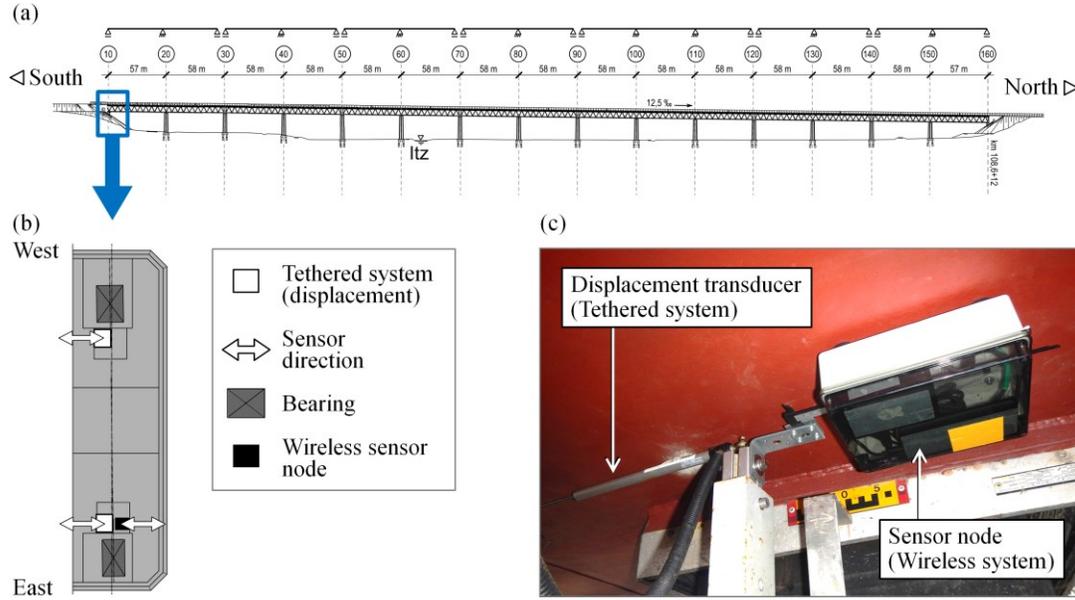


Figure 3. ItztaI Bridge: (a) elevation view of the bridge, (b) plan view of the southernmost pier, and (c) instrumentation (tethered and wireless system).

## Experimental results and discussion

To determine the accuracy of the wireless SHM system, the displacement time histories recorded by the tethered system and by the wireless system at pier 10 are statistically compared. As shown in Figure 4, the 24-hour time histories of the horizontal deck displacement in response to thermal loads are plotted for both the tethered and the wireless system. To compare both time histories, i.e. to indicate the accuracy of the wireless SHM system, the Euclidean norm is used, captured by the formula

$$\|\mathbf{p} - \mathbf{q}\|_2 = \sqrt{\sum_{k=1}^n (p_k - q_k)^2} \quad (4)$$

where  $\mathbf{p}$  is the time history vector of the tethered SHM system,  $\mathbf{q}$  is the time history vector of the wireless SHM system,  $n$  is the number of measurements, and  $\|\mathbf{p} - \mathbf{q}\|_2$  is the Euclidean norm. The validation test yields the absolute error

$$\|\mathbf{p} - \mathbf{q}\|_2 = 0.7768 \quad (5)$$

over 24 hours with  $n = 144$  measurements recorded by each SHM system. The relative error is calculated as follows:

$$\frac{\|\mathbf{p} - \mathbf{q}\|_2}{\|\mathbf{p}\|_2} \times 100\% = 0.46\% \quad (6)$$

As a result, the Euclidean-norm-based comparison establishes a displacement measurement discrepancy of 0.46% between both SHM systems, indicating sufficient accuracy of the wireless SHM system.

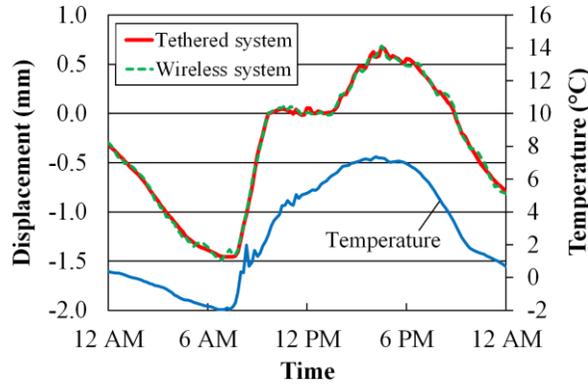


Figure 4. Displacement and temperature time histories recorded during the validation test.

Prior to implementing the wireless SHM system, different hardware components have been considered in the design phase. Of these, the Arduino Uno R3, another popular single-board computer, represents a more cost-effective and more energy-efficient solution than the Raspberry Pi Zero W used in this study. Ultimately, the Raspberry Pi Zero W, providing complex peripheral interfaces that encompass wireless communication and flash storage is opted for, in contrast to the Arduino Uno R3, which does not facilitate complex peripheral interfacing on board. Furthermore, while an Arduino-based solution stands to provide significantly lower power consumption together with a reliable dedicated thread for data sampling, multi-threading on the Raspberry Pi Zero W supports real-time data processing and wireless communication. For wireless communication, the proposed wireless SHM system implements the IEEE 802.11g (Wi-Fi) standard, which has a maximum bit rate of 54 Mbit/s and a relatively high power consumption. For future improvements, the IEEE 802.15.4 (Zigbee) standard may be considered, which has a maximum bit rate of 250 kbit/s and a relatively low power consumption. The overall power consumption of the wireless SHM system is proportional to the data sampling rate, the embedded computing, and the frequency and extent of communication. Contingent upon the 10-minute sampling periods devised in this study, the wireless SHM system with the 20,000 mAh power bank remains sufficiently powered for approximately 10 days.

## SUMMARY AND CONCLUSIONS

In this paper, an ultra-low-cost and easy-to-install wireless structural health monitoring system has been presented. A prototype wireless SHM system, composed

of commercial off-the-shelf components of less than EUR 30 in total, has been designed and implemented. The software architecture of the wireless SHM system follows a modular and extensible design, enabling real-time sensing, on-board data analysis, energy-efficient wireless communication, and IoT connectivity. A validation test has been conducted on a railway bridge in Germany. For validation, the wireless SHM system has been installed at a pier of the bridge to monitor quasi-static horizontal deck displacements in response to thermal loads. When mounting the wireless SHM system on the bridge, the system has shown to be easy to install. The accuracy of the wireless SHM system has been proven through the Euclidean norm, calculated from the displacement measurements recorded by the wireless SHM system and from displacement measurements recorded by a commercial tethered SHM system that is installed in parallel. Furthermore, automated analyses of the static behavior of the railway bridge (i.e. temperature-induced displacement response) have been achieved using a linear temperature-displacement regression function embedded into the wireless SHM system. As a result, the wireless SHM system is shown to be ultra-low cost, easy-to-install, and sufficiently accurate, serving as a “quick tester” for analyzing the behavior of civil infrastructure within short-term, static monitoring campaigns.

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