INTRODUCTION

Fueled by the digital transformation, the market for electronic devices is growing rapidly worldwide, generating substantial amounts of electronic waste (e-waste). Smartphones, tablets, laptops, and white goods, such as refrigerators and freezers, have a relatively short service life, which contributes to e-waste. According to the United Nations, 50 million tons of e-waste worth over $62.5 billion are produced annually (Nijman 2019). The problem also becomes apparent in the architecture, engineering, and construction (AEC) industry, which is shifting towards circular economy approaches (i.e. closed-loop production cycles) accelerated by Internet of Things (IoT) solutions (United Nations Environment Programme 2020). The AEC industry is characterized by a rapid digital transformation, materialized in terms of smart sensors installed in structures, mobile devices used in engineering practice, and robotic systems that support monitoring and inspection of structures (Smarsly et al. 2022). In particular, structural health monitoring (SHM) systems are characterized by dense arrays of sensors installed in the structures. The sensors are attached to sensor nodes, also installed in the structures, that are devised to collect, process, and analyze the sensor data as a basis to assess the structural condition (Luckey et al. 2022). SHM systems enable damage detection to facilitate maintenance and sustainable retrofitting of structures, albeit the environmental impact of the SHM systems themselves is usually neglected.

On the one hand, implementing IoT solutions within the AEC industry, such as using SHM systems for damage detection, supports circular economy approaches that extend the lifetime of structures. On the other hand, SHM systems have a noticeable environmental impact, such as increased use of toxic substances and critical raw materials, increased energy consumption for data collection and processing, as well as increasing amounts of e-waste (Ingemarsdotter et al. 2021). However, the advantages of implementing SHM systems have not outweighed the environmental impact of SHM systems, as sensors and sensor nodes in SHM systems, being prone to faults when operating over long periods of time, need to be constantly replaced. Methodologies have been proposed to perform environmental assessment of wireless sensor networks based in life-cycle energy consumption, where sensor nodes have a significant influence on the environmental impacts of wireless sensor networks (Bonvoisin et al. 2012). Hence, it is necessary to develop sustainable approaches towards designing sensor nodes to reduce the environmental impact of SHM systems.

In SHM, parameters characterizing the structure and the environment are monitored through dynamic or static monitoring approaches. Dynamic monitoring provides insights into the modal behavior and dynamic response of structures based on vibration (e.g. acceleration) measurements. Static monitoring
provides insights into slow-varying parameters that are measured as single data values, such as displacements, deformations, or environmental parameters (e.g. temperature) (Del Grosso 2012). The sensors deployed in SHM systems are selected according to the parameters to be measured (static or dynamic), resolution, accuracy, measuring range, test duration (long-term stability), and monitoring objective (Rücker et al. 2006). Sensors may be classified according to the physical property (e.g. vibration, strain/force, and temperature), power supply (active or passive), output signal (analog or digital), or functioning principle.

Based on the circular energy framework presented in (Ingemarsdotter et al. 2019), concepts that reuse and recycle resources, such as reusing sensors in SHM systems, have not yet received enough attention. Taking advantage of e-waste and the reusability of microcomputers, an additional service life may be given to e-waste sensors (i.e. sensors retrieved from disposed or outdated electronic devices) by deploying the e-waste sensors in sensor nodes for SHM systems, reducing the waste generated by SHM systems. Smartphones and tablets incorporate chips with sensors that provide data for software applications, such as accelerometers, ambient temperature sensor, gyroscopes, and magnetometer (Android Open Source Project 2022) White goods, and smart white goods in particular, use sensors to ensure efficient operation by measuring temperature, humidity, pressure, and force (EPCOS AG 2012). Sensors from white goods vary in functioning principles, input voltage and amperage, as well as output signals. To reuse e-waste sensors in SHM systems, special care must be given to select e-waste sensors that are compatible with microcomputers and that are capable of measuring the parameters relevant to SHM, such as vibration (e.g. accelerometers), strain and force (e.g. load cells), and temperature (e.g. thermistors).

Considering the environmental impact of SHM systems, the need to develop concepts that help reduce the waste generated by SHM systems arises. In this paper, the design and implementation of a sustainable SHM system is presented. The sustainable SHM system is composed of sensor nodes assembled from e-waste sensors and recycled materials. Sensors found in smartphones and disposed refrigerators are connected to microcomputers to measure acceleration and temperature. The sustainable SHM system is validated in field tests on a pedestrian bridge and compared with a conventional SHM system serving as a benchmark system. The paper is organized as follows. First, the design and the implementation of the sustainable SHM system is described. Second, the validation of the SHM system is presented and the results are discussed. The paper concludes with a summary and potential future research directions.

2 A SUSTAINBLE SHM SYSTEM

The sustainable SHM system applies circle economy concepts to reuse and to recycle resources for hardware in SHM systems, while maintaining accuracy. The software design provides real-time sensing, embedded computing, and IoT connectivity. The sustainable SHM system is composed of two sensor nodes and a cloud server. The sensor nodes are assembled from microcomputers and e-waste sensors to measure acceleration and temperature. Both parameters, acceleration and temperature, are essential to monitor the condition of civil engineering structures.

The overall system consists of three layers, an application layer, a middleware layer, and a sensing layer (Figure 1). Users interact with the application layer by means of a live dashboard hosted in a web interface, which communicates with the middleware layer using a representational state transfer (REST) application programming interface (API). The middleware layer consists of the cloud server with a database management system (MySQL database) and a middleware application based on the Node-RED development tool. Node-RED connects to the MySQL database for data storage. A machine-to-machine application protocol (MQTT), which has authentication and encryption services, is used to communicate securely with the sensing layer. The sensing layer consists of two sensor nodes, (i) an outdated smartphone and (ii) a sensor node based on Raspberry Pi microcomputers, acting also as a gateway device. Using the outdated smartphone as a sensor node, the data of the sensors embedded into the main chip board of the smartphone can be accessed easily and transmitted via Bluetooth to the gateway device. Using the Raspberry-Pi-based sensor node, an e-waste temperature sensor from a disposed refrigerator is exemplarily attached to the Raspberry Pi microcomputer, which is capable of reading and processing sensor output signals. Algorithms are embedded into the Raspberry-Pi-based sensor node to perform on-board data analysis of the acceleration data using operational modal analysis methods, such as fast Fourier transforms (FFT) and peak picking.

To assemble the sensor nodes, concepts of reusing and recycling are considered when selecting the hardware and materials, aiming to extend the service life of e-waste sensors. Due to reusability and computing power, a Raspberry Pi 4 Model B microcomputer with 2GB RAM and 32 GB memory card is selected to control real-time sensing, to execute data analysis, and to enable communication with the middleware layer using IoT communication and application protocols. For collecting acceleration data, a Huawei P10 light with EMUI 8 operating system is deployed, as Android-based smartphones have advantages regarding custom-built applications and accessibility of open-source documentations. For collecting temperature data, a negative-temperature-coefficient (NTC)
thermistor (5 V input voltage) recovered from a disposed refrigerator is implemented, in association with a voltage divider and an analog-to-digital converter (Figure 2a). The NTC is selected because of the compatibility with the Raspberry Pi microcomputer and the known functioning principle. For supplying power to the sensor nodes, power banks (10,000 mAh) are attached to the Raspberry Pi microcomputer and the smartphone (if needed). A custom 3D-printed case, made from recycled bioderived plastic, with dimensions 140 mm × 91 mm × 45 mm (length × width × height) is used to protect the electronics of the Raspberry-Pi-based sensor node. Figure 2b shows the assembly of the sensor nodes being part of the sustainable SHM system.

The e-waste sensors are calibrated by determining the relationships between the output signal and the parameters being measured. Laboratory tests are carried out to calibrate the sensors by comparing the output signals against known values (i.e. from sensor data recorded for comparison). In the following section, the validation of the sustainable SHM system is presented.

3 VALIDATION OF THE SUSTAINABLE SHM SYSTEM

The sustainable SHM system is validated by monitoring a pedestrian bridge in a field test. The validation aims to determine the performance of the e-waste sensors by comparing the sensor data recorded by the sustainable SHM system with sensor data recorded by a benchmark SHM system. Moreover, the data analyses performed by the algorithms embedded into the sensor nodes of the sustainable SHM system are used for validation.

The field test is conducted at Citadel Bridge (“Zitadellen-Brücke”), a pedestrian bridge over the Lotse canal located at Harburg Inland Port, Hamburg, Germany, to validate the sustainable SHM system. The Citadel Bridge, completed in 2016, is a swing bridge of 45.5 m length, comprising a movable section and a fixed section (Figure 3a). The bridge superstructure consists of a welded-steel hollow-box girder of varying width and height with transverse bulkheads and a reinforced concrete deck. The bridge is instrumented with the sustainable SHM system and the benchmark SHM system for comparison. The
benchmark SHM systems follows the same system architecture as the sustainable SHM system. The benchmark SHM system consists of two Raspberry-Pi-based sensor nodes attached to accelerometers of type Analog Devices 3-axial ADXL355, measuring vibration, and to environmental sensors of type Adafruit BME280, measuring temperature and humidity.

In the field test, the structural response of the bridge (i.e. vibration) under pedestrian traffic is monitored to perform an operational modal analysis, including environmental conditions. The SHM systems are placed on the middle span, where the maximum displacement due to loading is expected (Figure 3b). For the sustainable SHM system, the smartphone sensor node (labeled “SS1”) is placed at the mid span measuring acceleration, while the Raspberry-Pi-based sensor node (“SS2”) is placed at the fixed support measuring temperature. For the benchmark SHM system, the sensor nodes “SB1” and “SB2” are placed equidistantly at 8 m from the midspan, measuring acceleration and temperature. For the field test, a measuring time of 250 s and a sampling frequency of 200 Hz for the accelerometers and of 11 Hz for the temperature sensors are defined.

Acceleration data is acquired, analyzed, and transmitted to the cloud server. The raw acceleration data is processed and analyzed by the sensor nodes. First, the raw acceleration data is processed by removing the gravity effect and noise. Second, the acceleration data is analyzed, transforming the acceleration data from the time domain into the frequency domain via FFT, resulting in frequency spectra. In the frequency spectra, peaks corresponding to the vibration modes are identified.

The results of the field test are presented in Figure 4. The acceleration data and the corresponding frequency spectra obtained by the sustainable SHM system and by the benchmark SHM system are plotted side by side. From the frequencies of the vibration modes identified in the frequency spectra, the accuracy of the sustainable SHM system can be evaluated. The frequencies of the vibration modes are in accordance with the benchmark SHM system with a difference of 0.049 Hz for the first vibration mode ($f_1$) and of 0.147 Hz for the second vibration mode ($f_2$).

Furthermore, the temperature data is compared using the cosine similarity coefficient, defined as

$$\text{similarity}(A,B) = \frac{A \cdot B}{\|A\| \cdot \|B\|} = \frac{\sum_{i=1}^{n} A_i \times B_i}{\sqrt{\sum_{i=1}^{n} A_i^2} \times \sqrt{\sum_{i=1}^{n} B_i^2}}.$$

In Equation 1, $A$ represents the n-size series of temperature data collected by the sensor nodes of the benchmark SHM system and $B$ represents the temperature data collected by the sustainable SHM system. The similarity coefficient ranges between $-1$ and $1$, where $-1$ indicates absolute dissimilarity and $1$ indicates absolute similarity. The temperature data yields a similarity coefficient of 0.999 with a maximum difference of 0.77 °C, indicating high similarity between the two SHM systems.

4 SUMMARY AND CONCLUSIONS

A concept to reduce the waste generated by SHM systems has been proposed, addressing the environmental impact of SHM systems. A sustainable SHM system, composed of wireless sensor nodes and a cloud server, has been developed using e-waste and recycled materials. Sensor nodes have been assembled using Raspberry Pi microcomputers, connected with e-waste sensors found in smartphones and disposed refrigerators to measure acceleration and temperature. Furthermore, recycled materials from bioderived plastic have been used for casing. The sustainable SHM system has been calibrated in laboratory tests and validated in a field test on a pedestrian bridge, showing results comparable to conventional SHM systems.
Developing sensor nodes using e-waste components and recycled materials is a viable alternative to implement sustainable SHM systems. The reusability of e-waste components is limited by the accessibility, the functioning principles, and the compatibility with microcomputers (e.g. regarding input voltage, amperage, and output signals). Furthermore, e-waste components must be properly calibrated to obtain accurate results. By reusing e-waste sensors, the service life of sensors and devices may be extended, reducing waste and contributing to minimize the environmental impact of SHM systems. In future research, a modular approach towards sustainable SHM systems may be explored.

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6 REFERENCES


