Design and validation of a mobile structural health monitoring system based on legged robots

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Abstract. Structural health monitoring (SHM) has been witnessing the transition from cable-based systems to wireless systems, owing to the reduced installation costs and efforts of wireless sensor nodes. However, reliable information on civil infrastructure requires dense arrays of wireless sensor nodes, which may nullify the merits of wireless SHM. This paper proposes a mobile SHM system, comprising maneuverable quadruped robots equipped with sensors for collecting, processing, and analyzing structural response data. The mobile SHM system is validated through field tests on a pedestrian bridge, proving that a minimum deployment of quadruped robots yields the same structural information as an array of wireless sensor nodes. Furthermore, the tests results are compared to results obtained from a benchmark SHM system, showcasing the accuracy of the mobile SHM system. The proposed mobile SHM system marks an advance towards employing fully autonomous robotic fleets for SHM in lieu of stationary wireless sensor nodes.

1. Introduction

In the wake of climate change, discussions on the exposure of critical infrastructure have been growing vivid around the globe, especially following catastrophic incidents of structural failures, such as the collapse of Morandi Bridge in Genoa, Italy (Rania et al., 2019). The importance of timely structural maintenance has been brought to the forefront, considering the large investments made in infrastructure (Zachariadis, 2018). In recent years, timely interventions in repairing and retrofitting aging and degrading infrastructure have been significantly aided by structural health monitoring (SHM), which traditionally has been applied via cable-based sensor networks for collecting and analyzing structural response data (Farrar and Worden, 2007). Moreover, in the last two decades, the developments in wireless communication technologies have been driving the transition from traditional cable-based SHM systems to wireless SHM systems (Lynch and Loh, 2006). Tethered sensor nodes have been replaced by wireless sensor nodes, which are easy to install and cost-efficient (typically employing low-cost sensors). In addition, the elimination of cables significantly adds to the cost-efficiency as well as to the scalability of wireless sensor networks, while offering convenient alternatives to cable-based SHM systems in case of aesthetic constraints when instrumenting structures (Smarsly and Petryna, 2014).

Notwithstanding the benefits of wireless SHM, extracting reliable information on critical infrastructure usually requires spatially dense arrays of wireless sensor nodes, thus entailing the risk of nullifying the cost-efficiency merits of wireless sensor nodes. Alternatives suggesting SHM approaches with mobile wireless sensor nodes have been introduced (Zhu et al., 2010), albeit having received scarce attention. Mobile wireless sensor nodes essentially behave as miniature robots capable of navigating and scanning large areas of civil infrastructure for collecting structural response data of high spatial density (Rubio et al., 2019). Furthermore, utilizing wireless communication, mobile wireless sensor nodes form ad-hoc wireless networks for exchanging information to collaboratively analyze structural conditions. As a result, mobile SHM systems exhibit the potential to overcome limitations of wireless SHM systems with stationary wireless sensor nodes (Smarsly, et al., 2022). In this direction, this paper introduces a mobile SHM system comprising legged robots. Representing a step towards enhancing

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previously proposed mobile SHM systems based on wheeled robots, the mobile SHM system presented herein leverages the agility of legged robots, which are capable of maneuvering and traversing locations with impediments, such as stiffener beams and secondary structures, frequently seen in civil infrastructure (Biswal and Mohanty, 2021). Specifically, a mobile SHM approach based on quadruped robots is proposed, which, compared to other types of legged robots, are ideal in terms of stability and efficiency. Maintaining levels of intelligence similar to stationary wireless SHM systems, the quadruped robots of the mobile SHM system are equipped with (i) peripherals, i.e. cameras for navigation and accelerometers for collecting acceleration response data and (ii) microcontrollers for embedding algorithms to analyze the acceleration response data. The idea behind the proposed mobile SHM system is to extract the same level of information on the structural condition with a minimal deployment of quadruped robots as with a dense array of wireless sensor nodes.

The remainder of the paper is organized as follows: Section 2 describes the design and implementation of the mobile SHM system in terms of hardware and software, followed by validation tests conducted at a pedestrian overpass bridge in Thessaloniki, Greece, which are presented in Section 3. The paper ends with a summary and conclusions as well as with a brief outlook on potential future research directions.

2. Design and implementation of a mobile SHM system based on quadruped robots

System identification strategies in traditional cable-based SHM typically have been limited by instrumentation sparsity. In particular, due to the cost of sensors and cabling as well as to the physical labor of installation, structural response data, from which information on structural conditions is extracted, has been collected from only a few locations. Instrumentation sparsity in system identification has been challenging to engineering practitioners, who have traditionally been accustomed to elaborate numerical representations of structures, used in structural design, which are able to capture detailed structural responses. System identification represents an inverse problem to structural design, and instrumentation sparsity renders this problem ill-posed.

While wireless SHM has been serving as an attractive solution in terms of cost and installation, the spatial density of wireless sensor nodes required for overcoming instrumentation sparsity may still be prohibitive from a budgetary perspective. As a result, wireless SHM stands to benefit from the proposed mobile SHM system, which integrates robotics into SHM strategies. Specifically, a minimal deployment of quadruped robots, substituting dense arrays of stationary wireless sensor nodes, could efficiently scan large areas of civil infrastructure, thus fulfilling the need for spatial density of structural response data. Moreover, the maneuverability capabilities of quadruped robots allow navigating areas that may be hard to reach physically or via wheeled robots. Finally, as will be shown in this paper, the mobile SHM system is capable of yielding information on structural conditions comparable to information obtained from a SHM system with cable-based sensors.

Drawing from the state of the art in SHM, system identification builds upon statistical processing of structural response data performed in a fully data-driven manner. System identification usually takes the form of operational modal analysis (OMA), in which vibration mode shapes are estimated from correlations between acceleration response data collected from different locations. In other words, an output-only method for extracting the mode shapes is applied in this study, which does not require to generate mechanical impulses or other strategies to induce vibration, which would fall into the category of experimental modal analysis. Consequently, conducting an OMA-based SHM strategy with the proposed mobile SHM system requires a minimal deployment of two quadruped robots equipped with accelerometers for collecting acceleration response data simultaneously. Furthermore, the quadruped robots form an intrinsically distributed SHM system, in which the processing power of the robots is leveraged to embed most tasks of the OMA-based SHM strategy, including (i) navigating across large areas of monitored structures, (ii) communicating wirelessly for exchanging information with other robots and with computer systems, and (iii) collecting, processing, and analyzing acceleration response data. The hardware and software implementation of the mobile SHM system are described below.

2.1 Hardware design and implementation

The quadruped robots used for the mobile SHM system are of type "*m*ini *i*ntelligent *do*cumentation *g*adgets" (mIDOGs). The mIDOGs offer advanced maneuverability capabilities with multi-degree-of-freedom locomotion, as well as on-board intelligence, allowing attaching sensors for collecting acceleration response data and embedding algorithms for performing SHM tasks. The hardware implemented for operating the mIDOGs within the framework of the OMA-based SHM strategy is built around a Petoi Bittle system (Petoi, Inc., 2021) and encompasses:

(i) The ***robot component***, which enables the multi-degree-of-freedom locomotion,

(ii) The dual-board ***processing component***, which includes an Arduino board dedicated to locomotion in cooperation with the robot component as well as a Raspberry Pi board that allows embedding algorithms for controlling sensors and analyzing acceleration response data, and

(iii) The ***sensing component***, which allows attaching sensors as peripherals; in this paper, an Analog Devices ADXL355 accelerometer and a Raspberry Pi v1.3 camera with an OmniVision OV5647 image sensor are attached to the sensing component (Analog Devices, 2010; Raspberry Pi Trading Ltd., 2021; OmniVision Technologies, Inc., 2009).

As mentioned previously, the OMA-based SHM strategy is designed around three SHM tasks, (i) navigation, (ii) communication, and (iii) data processing and analysis, which are allocated to the hardware components of a group of mIDOGs. The allocation of the SHM tasks is depicted in Figure 1.

As can be seen from Figure 1, *navigation* requires the cooperation of all hardware components of the mIDOGs. In particular, the robot component manages the motion of the mIDOG across all measurement points, the sensing component allows the mIDOG to identify measurement points (pinpointed with markers) via image recognition, and the processing component confirms that a measurement point has been reached using position data obtained from the sensing component. Once all mIDOGs have reached measurement points, *communication* is established among the mIDOGs, via the processing component, for confirming the status of the mIDOGs and for synchronizing internal clocks. Following the status confirmation, the mIDOGs use the robot components to assume measuring postures. Finally, the mIDOGs perform *data processing and analysis*, which is a task that also involves all three hardware components. Specifically, upon reaching a measurement point and assuming measuring posture, each mIDOG uses the robot component to attach the accelerometer to the surface of the monitored structure. For the execution of the SHM tasks, dedicated software modules are developed and embedded into the microcontrollers of the mIDOGs, which are described in the next subsection.

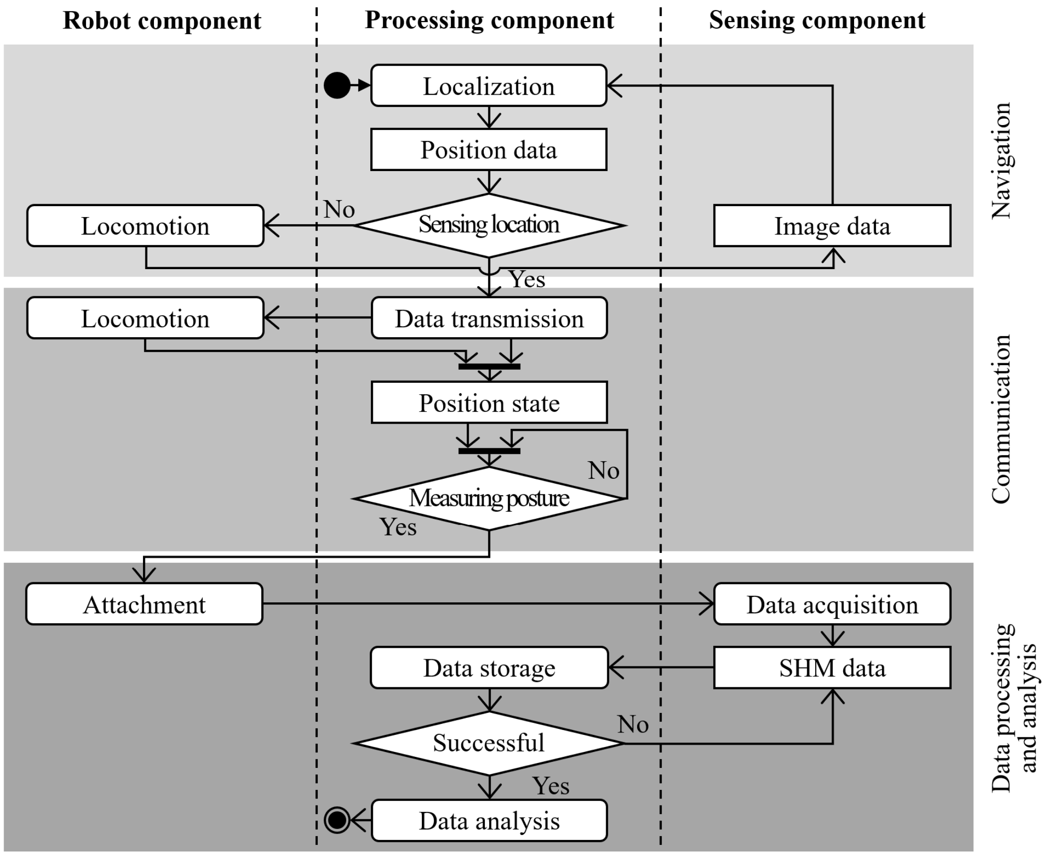

Figure 1: Flow diagram of the SHM tasks executed by the mIDOGs, divided into navigation, communication, and data processing and analysis.

2.2 Software design and implementation

The following discussion provides an overview of the embedded software modules designed and implemented in the mobile SHM system. The design rationale of the software modules follows the task allocation of the OMA-based SHM strategy to the hardware components. In this context, each SHM task is executed by a dedicated software module, i.e. the navigation module, the communication module and the data processing and analysis module, whose main classes and interfaces are shown in Figure 2. As an exception, a sensing module, which manages the accelerometer and the camera, is used as a standalone software module.

Navigation is managed by the *navigation module*. A single class, termed `Navigation-Processor`, defines motion parameters and inflicts motion on the robot component using processes encapsulated into two interfaces, designated as `Locomotor` and `Locator`. The encapsulation allows for modularity in the selection of classes for path detection. The classes used herein for path detection, implementing the `Locomotor` and `Locator` interfaces, are the `PathDetectionLocomotor` class and the `PathDetectionLocator` class, respectively. For retrieving position data with respect to the longitudinal axis of the mIDOG, which is used as reference, the `PathDetectionLocator` class uses images collected by the sensing component to follow a path using embedded image recognition. Based on the position data, the `PathDetectionLocomotor` class determines the motion parameters to reach the target, i.e. a measurement point. The motion parameters are forwarded to the `ProcessManager` class, which is also part of the navigation module, and, subsequently, to the `CommunicatonManager` class (of the communication module), which eventually passes the motion parameters to the `Arduino` class, interfaced with the Arduino microcontroller and the robot component.

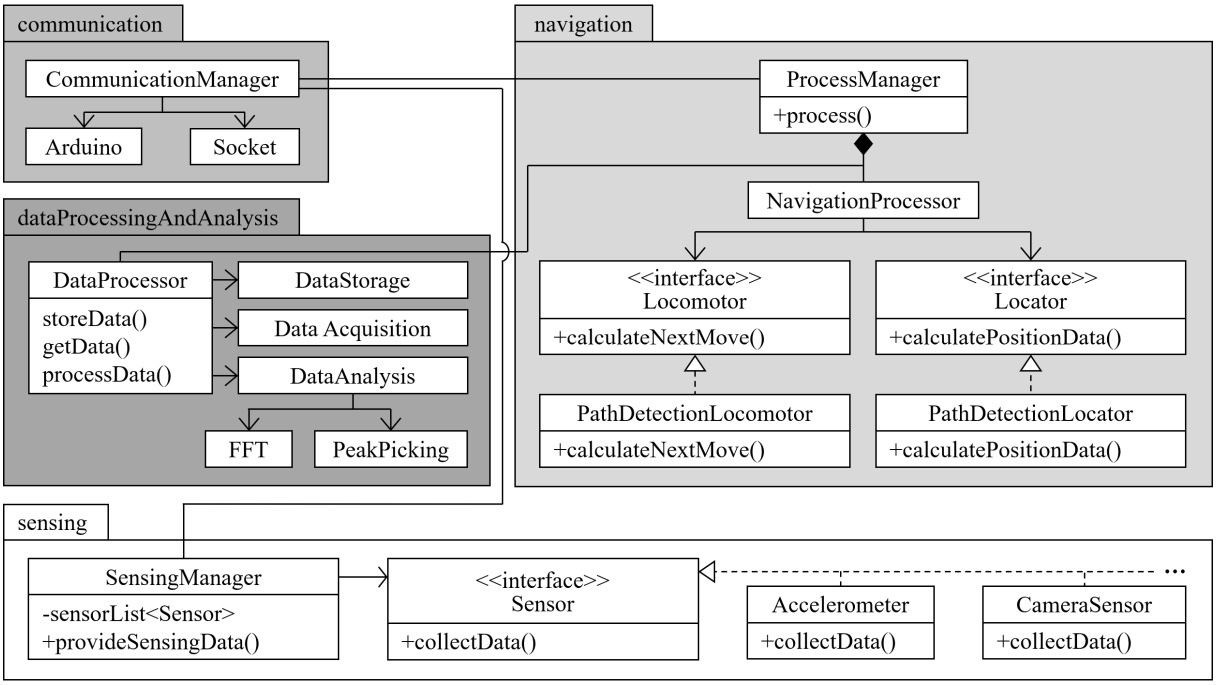

Figure 2: Embedded software modules, designed for the mobile SHM approach.

The communication task is executed by the *communication module*. The module is implemented based on sockets using the Transmission Control Protocol (TCP), which is reliable, as it ensures, through its acknowledgment mechanism, that no data gets lost and that all data received will be identical and in the same order as the data being sent. The module consists of three main classes, the `Socket` class, the `CommunicationManager` class, and the `Arduino` class. The `Socket` class is used for initializing wireless communication channels among mIDOGs, following the machine-to-machine communication paradigm. The majority of communication activities is managed by the `CommunicationManager` class, including utilization of wireless communication channels created by the `Socket` class for establishing ad-hoc wireless networks between mIDOGs and forwarding motion parameters to the `Arduino` class. The versatility of the ad-hoc wireless networks is ensured by the `CommunicationManager` class, which allows each mIDOG to establish a wireless network as a server and enable other mIDOGs to connect to its network as clients. In other words, the `CommunicationManager` class of each mIDOG is capable of recognizing if an instance of the `CommunicationManager` class of another mIDOG exists and functions as server, so as to connect as a client to the respective wireless network. The `Arduino` class, as mentioned previously, leverages the locomotion module of the Arduino microcontroller, which is used to inflict motion on the mIDOG via the robot component. Last, but not least, the `CommunicationManager` class is devised to manage the internal communication between distinct modules, such as the sensing module and the navigation module.

The last task of the OMA-based SHM strategy is executed by the data processing and analysis module. The `DataProcessor` class is responsible for retrieving the acceleration response data collected by the accelerometer through the `ProcessManager` class of the navigation module. The acceleration response data is forwarded from the `SensingManager` class of the sensing module to the `CommunicationManager` class and, finally, to the `ProcessManager` class. The `DataStorage` class performs persistent storage of the acceleration response data and offers access to the data, and the `DataAcquisition` class manages data acquisition. Finally, OMA-related activities are managed by the `DataAnalysis` class, which is responsible for frequency-domain operations on the acceleration response data. More specifically, fast Fourier transform (FFT) is performed on the acceleration response data by the `FFT` class and peak picking is applied to the FFT by the `PeakPicking` class. The mobile SHM system described in this section is validated through field tests, which are presented in the next section.

3. Field validation tests at a pedestrian bridge

The mobile SHM system is validated through field tests conducted on a pedestrian bridge, as shown in Figure 3. The validation tests serve to proof the capabilities of the mobile SHM system (i) to provide spatially dense acceleration response data with a minimal deployment of quadruped robots and (ii) to extract information on the structural condition of the same level as a benchmark SHM system with cable-based sensors of higher precision than the accelerometers attached to the mIDOGs. In what follows, the pedestrian bridge and the benchmark SHM system are briefly described, the validation tests are presented, and the results are discussed.

3.1 Description of the pedestrian bridge and the benchmark SHM system

The pedestrian bridge is an overpass bridge located at Evosmos, Thessaloniki, Greece, servicing pedestrian traffic over the Inner Ring Road of Thessaloniki. The bridge was built in 2016 and its deck has a single span with a total length of 40.80 m and width of 5.35 m. The deck is made of a steel trough filled with concrete and rests on two steel girders of square hollow sections along its longitudinal edges. The girders are suspended from two skewed steel arches of the same cross section as the girders via twisted strand steel cables and are supported on each end of the bridge by cylindrical reinforced concrete columns. The girder-to-column connection is achieved through bearings allowing partial fixity. In the transversal bending direction, the deck is supported by 20 equidistant steel beams. Lateral support is provided by 10 x-braces, which are fixed to the steel beams.

Figure 3. View of the pedestrian bridge in Evosmos, Thessaloniki, Greece.

Specifically for the field validation tests conducted in this study, the bridge is instrumented with a benchmark SHM system consisting of 7 uniaxial accelerometers, placed along the middle line of the deck, as shown in Figure 4, to enable capturing translational vibration mode shapes. The accelerometers measure in the vertical (z) direction and are connected to a single data acquisition unit. The accelerometers of the benchmark SHM system are of type Syscom MS2002+, measuring at a range of ±2 g with a sensitivity of 1 V/g and at a sampling frequency of 400 Hz (Syscom, 2015).

3.2 Validation tests and results

The purpose of the validation tests is to showcase the efficiency of the mobile SHM system in obtaining the same level of information on the structural condition, in the form of vibration mode shapes, as compared to the benchmark SHM system. To this end, a minimal deployment of mIDOGs is selected to scan all measurement points of the benchmark SHM system. In particular, the mIDOGs are assigned the following tasks:

(i) Navigating the bridge deck by using its image recognition capabilities to cover all measurement points,

(ii) Collecting acceleration response data from all measurement points,

(iii) Analyzing the acceleration response data to obtain Fourier values at modal peaks for computing mode shapes.

Although the mIDOGs are capable of yielding acceleration response data of acceptable spatial density through progressively navigating the measurement points, extracting mode shapes requires synchronicity between acceleration response data from different locations. As a result, at least two mIDOGs are required to collect acceleration response data simultaneously at different measurement points. Furthermore, to extract mode shapes of the same level as the benchmark SHM system, it is necessary to scan all measurement points in overlapping pairs, the outcomes of which will be synthesized into global mode shapes. The comparison between the mode shapes extracted by the mIDOGs to the respective mode shapes of the benchmark SHM system will serve as a proof of accuracy of the proposed mobile SHM system.

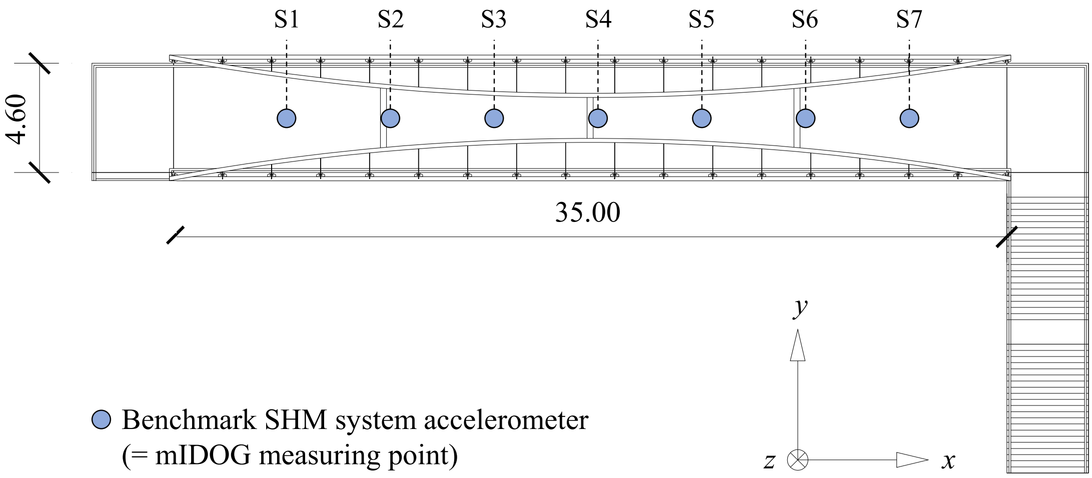

Figure 4. Benchmark SHM system installed on the pedestrian bridge and mIDOG measuring points.

At the beginning of the validation tests, the two mIDOGs are placed at one end of the bridge, serving as “deployment point”. The mIDOGs are tasked to navigate the bridge deck along a black line, leveraging image data collected by the camera and identifying measuring points, which are pinpointed by markers. The initial localization is given by the starting location and direction on the line to be followed. Upon reaching the first pair of measurement points, the mIDOGs use the communication modules to establish a wireless network with the first mIDOG functioning as a server and the second mIDOG as a client. The server and the client exchange messages to confirm the status and to synchronize the internal clocks. Synchronization is achieved using traditional concepts in wireless sensor networks, i.e. through the exchange of time-stamped messages. Next, the mIDOGs switch to a measuring posture and attach the accelerometer to the surface of the deck, using the robot component. Figure 5 shows the walking posture and the measuring posture of a mIDOG. Thereupon, each mIDOG uses its sensing component to collect acceleration response data. Once both mIDOGs have completed the acquisition of acceleration response data, the server and the client exchange messages to confirm completion of data acquisition and proceed with data processing and analysis to store and analyze the acceleration response data.

For each pair of measuring points, the acceleration response data is transformed from the time domain into the frequency domain via FFT, and the peaks corresponding to vibration modes are selected. The Fourier values of the peaks (i.e. not all Fourier values) are wirelessly transmitted to a centralized server, where local mode shapes are computed offline for the pair of measurement points by applying the frequency domain decomposition method (Brincker and Zhang, 2009). If the Fourier values at the peaks would not be sent to a centralized server, one of the dogs would have to undertake this task, but it would function itself as a centralized "hub", which would entail unnecessary over-burdening of its processing unit. Then, the mIDOGs proceed to the next pair of measurement points. After having navigated all measuring points, the mIDOGs use the local mode shapes to synthesize the global mode shape with all measuring points. The pairs of measurement points are listed in Table 1. The duration of data acquisition for each pair is set equal to t = 60 s and the sampling frequency is set equal to f_s = 125 Hz.

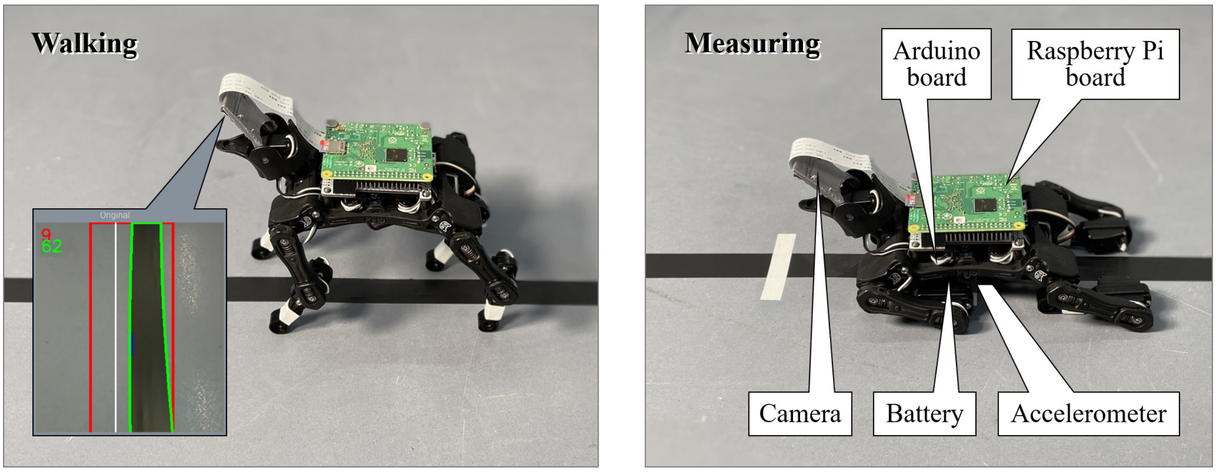

Figure 5: Field of view, walking posture, and measuring posture of a mIDOG.

Table 1: Overview of the pairs of measurement points.

Setup	mIDOG 1			mIDOG 2		
	Measurement position	f_s **(Hz)**	t **(s)**	**Measurement position**	f_s **(Hz)**	t **(s)**
1	S1	125	60	S2	125	60
2	S2	125	60	S3	125	60
3	S3	125	60	S4	125	60
4	S4	125	60	S5	125	60
5	S5	125	60	S6	125	60
7	S6	125	60	S7	125	60

Six mode shapes are synthesized from the outcomes of the mobile SHM system and are plotted in Figure 6, next to the mode shapes computed from the benchmark SHM system for comparison purposes. To quantify the similarity between the mode shapes, the modal assurance criterion (MAC) is employed, which is a well-established measure of similarity between vectors

(Allemang, 2003). Indicated by MAC values shown in Figure 7, it is evident that the majority of mode shapes extracted with the mobile SHM system and the mode shapes computed with the benchmark SHM system exhibit high similarity. The similarity serves as proof that the mobile SHM system proposed in this paper is capable of yielding information on the structural condition with accuracy comparable to a traditional cable-based SHM system. Moreover, the minimal deployment of quadruped robots has not compromised the spatial density of the SHM outcomes. Rather, the agility of the quadruped robots has enabled efficient scanning of all measuring points, thus eliminating the labor and cost of extensive installations. The results of this study clearly demonstrate that quadruped robots can be efficiently used for SHM in lieu of traditional cable-based SHM systems as well as of stationary wireless SHM systems.

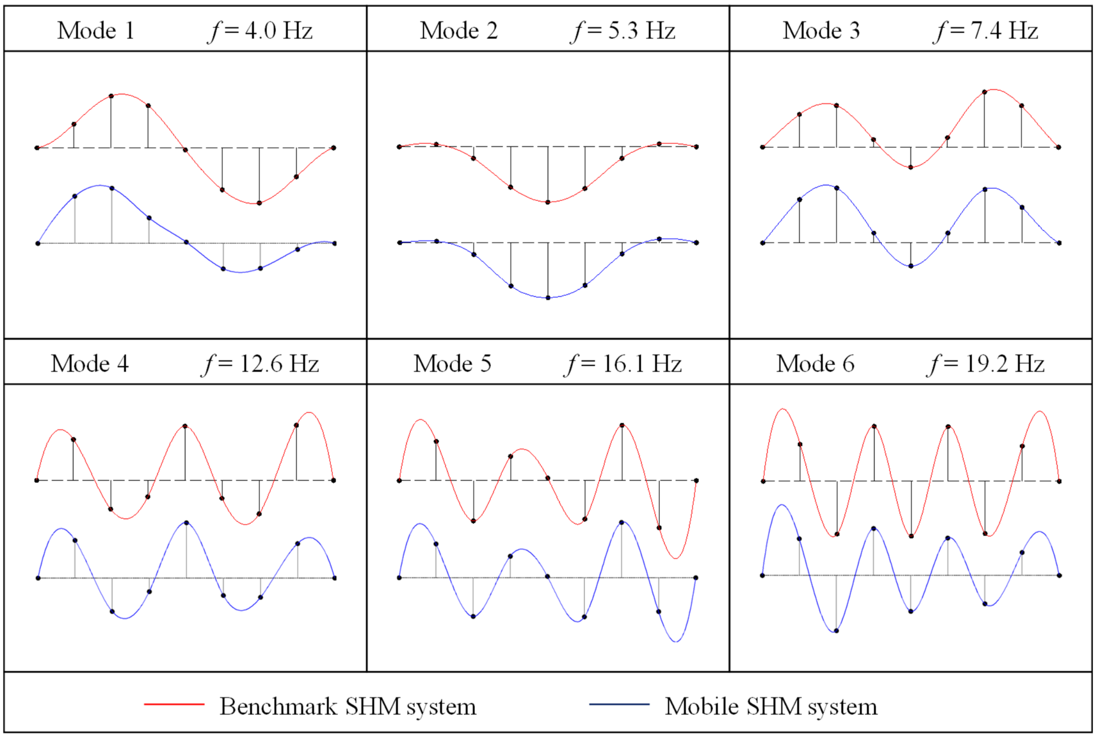

Figure 6: Mode shapes from the mobile SHM system (L) and from the benchmark SHM system (R).

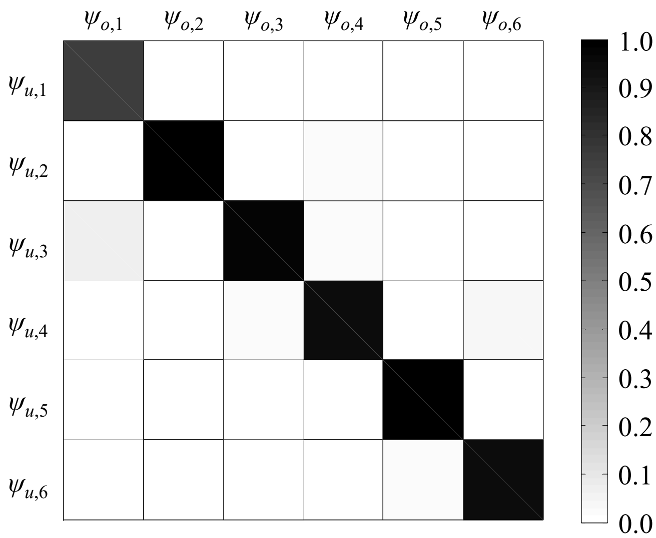

Figure 7: MAC matrix computed from the results of the validation tests.

4. Summary and conclusions

Wireless sensor networks offer promising opportunities towards enhanced flexibility and scalability, as compared to cable-based SHM systems. However, wireless sensor nodes are installed at fixed locations and, causing high installation costs, need to be employed at high density to reliably monitor large infrastructure. This study has proposed legged robots for wireless SHM of civil infrastructure, leveraging advantages regarding cost-efficiency and maneuverability. The legged robots implemented herein are equipped with sensors to collect acceleration data relevant to SHM of civil infrastructure, with cameras for navigation, and with embedded algorithms, facilitating autonomous data processing, analysis, and communication. The accuracy of the legged robots has been validated on a pedestrian bridge by comparing the outcomes of an operational modal analysis SHM strategy (conducted by the robots) with the respective outcomes achieved from a dense array of cable-based sensors (implemented as a benchmark SHM system). The results confirm that the legged robots, as compared to stationary wireless sensor nodes, require a smaller number of nodes to achieve the same information on the structural condition, entailing more cost-efficient SHM. As compared to wheeled robots, the legged robots offer better maneuverability, as critical parts of civil infrastructure may be hard to reach by wheeled robots. Future work may include further steps towards fully autonomous SHM based on robotic fleets, which requires autonomous capabilities regarding localization and communication, representing upcoming research endeavors.

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