A New Real-time SHM System Embedded on Raspberry Pi

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Abstract. This paper outlines the development of a real-time monitoring system, which incorporates hardware, software and database, applied to structural health monitoring (SHM). The system was conceived, designed, implemented and embedded on Raspberry Pi 3 (RP). With the need for reliability and information being provided in real time (IoT), RP has tightly integrated into the SHM field. To accomplish that, we developed an acquisition system based on Pmod IA (AD5933) along with the multiplex 4066, used to switch among the piezoelectric transducers. Furthermore, a real-time web application was developed to manage the acquisition system, integrate hardware with software and store the data collected in a dedicated NoSQL database. To perform excitation and get the structural response signals, experiments were carried out based on the electromechanical impedance technique by using three PZTs glued into an aluminium structure. Sinusoidal excitation signals, ranging from 20kHz to 30kHz with an amplitude of 2V, were applied to the host structure. Overall, the reference system presented higher sensitivity for the RMSD metric, whilst the proposed system showed more relevance for damage detection via CCDM. Despite being implemented in low-cost hardware, the developed system identified structural failures with good reliability, being advantageous from both financial and dimension standpoints.

Keywords: EMI · PZT· Database· Software-Hardware Integration · IoT.

1 Introduction

SHM (Structural Health Monitoring) systems are mainly constituted of sensors distributed throughout the structure, which acquire and send signals with structural responses to a processing centre, responsible for analysing the data and presenting a diagnosis. They seem analogue to the human nervous system, having the sensors as the nerve terminals and the processing core as the human brain, capable of interpreting these signals and presenting a solution. Considering its vast applications, NDE (Non-Destructive Evaluation) techniques play a key role for both industries and academies, encompassing numerous techniques to monitor structural integrity, such as acoustic emissions, optical fibres, comparative vacuum, wave propagation and electromechanical impedance[1].

The design of SHM systems, for real and large structures, assumes that structures will be continuously monitored during its long time in operation. To monitor large structures, such as buildings, bridges, aircraft and ships, there is a considerable demand for numerous sensors to cover the entire area of the monitored structure [2–4]. In practice, however, sensors are placed at specific points in the structure, where they would be more susceptible to collapse. These mainly occur because of the effects of excessive loading, environmental influence, impact and pressurisation. The development of SHM systems, with the perspective of embedded devices, brings many benefits to the industry that go beyond reducing costs but also increasing robustness and reliability. It is also important to mention that the connectivity arising from the use of the IoT (Internet of Things) allows to monitor remotely structures in real-time.

It is worth mentioning that the literature presents several works related to data storage, big data, IoT, compression and data analysis applied to SHM [5]. In [6] it is proposed storing and analysing large amounts of data in SHM systems to monitor old bridges. In [7] a real-time decision system for monitoring the structural integrity of bridges was also proposed. Similarly, big data analysis is employed in [8]. In the context of aircraft, the use of a database has also been of fundamental importance for storing data from sensors embedded in aircraft [9]. In [7] was proposed using cloud computing to develop a real-time monitoring system that allows users to create a 3D online structural model.

Although the literature revels several works focusing on real-time monitoring, there is a lack of proposal focusing on exploring low-cost hardware that enables to monitor structures remotely. Accordingly, this paper present the development of a low-cost real-time monitoring system, embedded on RP (Raspberry Pi), which incorporates hardware, software and database, applied to SHM.

2 Methodology

The methodology is based on the EMI (Electromechanical Impedance) technique [10]. EMI requires that the structure is excited in a frequency range through PZT (Lead Zirconate Titanate) patch glued into the monitored structure. The structure, including the PZT, is represented by an electromechanical mass-spring model with a single degree of freedom [10]. PZT transducers have proved to be a great option because of their versatility, adaptability, low energy consumption, costless and high bandwidth [1]. RMSD (Root Mean Square Deviation) and CCDM (Correlation Coefficient Deviation Metric) indices, calculated between the reference (baseline) and unknown conditions, are used to detect structural damage [11]. Having the EMI technique as the main core, the development of the proposed SHM system comprises two parts: hardware and software (Fig. 1).

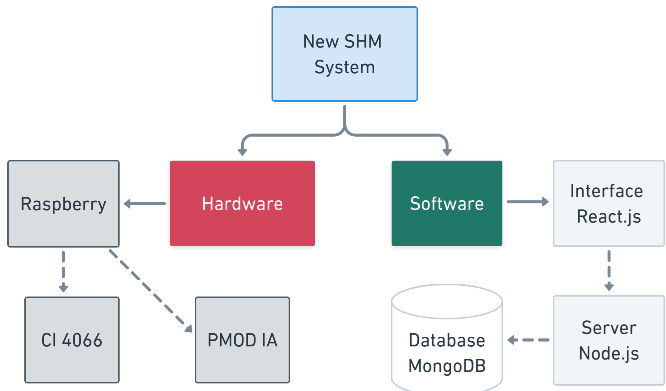

Fig. 1. Flowchart of the proposed SHM system.

2.1 Hardware

Raspberry Pi There are several options of embedded systems for processing data, such as SBC (Single Board Computers). A survey carried out by [12] analysed the main SBC available in the market, their configurations and costs. They summarised that RP presents a high cost-benefit ratio. Notwithstanding, RP could be easily used in real projects such as aircraft and bridges, for reasons of space and weight. RP also presents all requirements to work in real-time/online applications. Hence, this approach employs RP as the hardware responsible to manage the EMI measurements, running user interfaces, accessing the internet and database. The model employed here is the Raspberry Pi 3-B. The RP uses the Raspbian operating system (Linux). Python language was used to develop the application, as it presents several facilities when programming the RP.

Pmod IA The Pmod IA is designed as a complete system for impedance measurement. An ADC (Analogue to Digital Converter) is used to drive an unknown external impedance at a known frequency. Throw the ADC, frequency response samples are acquired and processed by a digital signal processor that computes the DFT (Discrete Fourier Transform). Internal registers are responsible to store both the real and imaginary parts of the impedance. Pmod IA is designed based on the AD5933. The AD5933 contain a 27-bit direct digital synthesis excitation sinusoidal voltage generator, a DAC (Digital to Analogue Converter) and a gain amplifier that determines the output voltage amplitude. Furthermore, a 12-bit

ADC and a 1024-point converter to determine the DFT and a unit multiplier accumulator. The AD5933 can measure impedance values from 100Ω to $100\mathrm{M}\Omega$, with accuracy of 0.5%. The user can also set the output voltage of the excitation sinusoidal signal (200mV, 400mV, 1V and 2V). Ultimately, the AD5933 allows the user to perform a frequency sweep (from 1kHz to 100kHz) by setting the start frequency, increment frequency, increment and number of settling cycles.

Before getting accurate impedance measurements it is needed to calibrate the AD5933 by using a known impedance (Z_k) connected into its input/output. In turn, the AD5933 returns the current I that flows through the impedance Z_k. Therefore, the calibration impedance values for the magnitude ($|Z_c|$), phase θ_c and gain factor (G_f) are calculated as follows.

$$|Z_c| = sqrt(Z_k^2 + I^2) \tag{1}$$

$$\theta_c = arctg\frac{I}{Z_k} \tag{2}$$

$$Gf = \frac{1/Z_k}{|Z_c|} \tag{3}$$

To determine an unknown impedance, the procedure is similar to the calibration one. After connecting a unknown impedance to the AD5933 pins, this returns the values for I_u and Z_u that are employed to calculate θ_u. Thereupon, to compute the final values of the impedance (Z and θ), it is needed to take into account the calibration values of G_f and θ_c (stored into the AD5933 registers) as follows.

$$\theta = \theta_u - \theta_c \tag{4}$$

$$Z = \frac{1}{|Z_u| \times Gf} \tag{5}$$

IC 4066 The IC 4066 is a two-way switch intended for multiplexing analogue or digital signals. The resistance state is constant over the entire input signal range. The 4066 device comprises four switches. In this application, therefore, the use of the 4066 is because of the PmodIA module has only one output and one input, which could lead to the analysis of only one PZT at a time. Hence, using the 4066 allows the user to analyse up to four different impedance signatures (3 PZTs and 1 calibration resistor). After it released the excitation signal, the Raspberry Pi controls which switch must close the contact, by sending a 5V signal to the 4066, which selects which PZT transducer will receive the excitation signal.

2.2 Software

This subsection presents the main aspects related to the interface and database designs for the proposed system. The acquisition system essentially can not communicate with the interface, as it only used certain REST API endpoints to persist the data read into the database, whilst simultaneously the interface pulled the data from the server using the Short Polling technique every second. The interface cannot send specific parameters to either sensor pins or structure configurations. Accordingly, the architecture developed to integrate the interface, server and acquisition system made it possible to resolve this issue.

React.js JavaScript library enables the design of fast and complex user interfaces to the web, more precisely to interfaces in which data constantly change over time. React brings modern methods for dealing with the HTML DOM, organising data and treating every element of the application as individual components. As this application aims to send and present information in real-time using a package that handles bidirectional communication between client and server, the use of this library seemed appropriate and beneficial.

Node.js JavaScript comprises an environment of single-thread execution and event-oriented architecture. It was developed to build servers and web applications and has high scalability with the combination of server-side JavaScript and asynchronous programming.

MongoDB Database MongoDB is a powerful and non-relational database developed to simplify concepts that come from traditional databases and build self-scalable web applications. It is faster because of the use of document data model and query interface and it is highly used to store massive amounts of data, which is what this application proposes to store, e.g. users, multiple modules, structure configurations and numerous analyses.

3 Results

This section outlines the results obtained for the proposed SHM system. This also shows a comparison between the proposed system and a reference one [11]. Therefore, hardware, software and damage detection capabilities are compared.

The acquisition system The measurement system was built based on the concept of modules. Firstly, the PCB (Printed Circuit Board) was designed to accommodate the Pmodia IA, connectors and the IC 4066. Secondly, the measurement board was connected to RP, followed by the development of the firmware (Python language). It is important to mention that the firmware was embedded on RP, which is responsible to excite the set structure/PZT, get structural responses, calculate the impedance and communicating with the user interface/server. Fig. 2 shows the final version of the hardware developed.

Validation of the SHM system Experimental tests were carried out on an aluminium plate with dimensions of 400mm x 250mm x 5mm. During the tests,

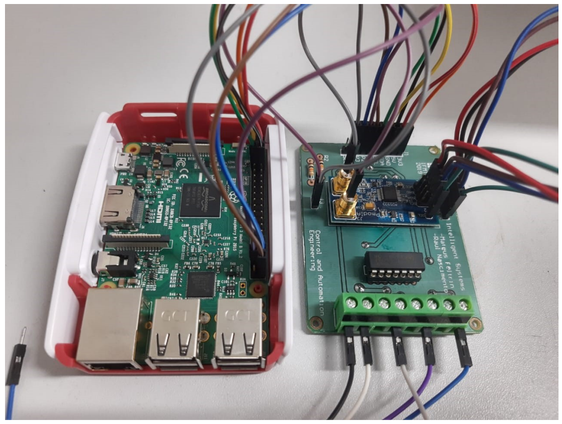

Fig. 2. The developed impedance measurement system.

the plate remained suspended in a vertical position in order to reduce the effect of boundary conditions. Three PZTs, named PZT#1, PZT#2 and PZT#3, were attached to the plate at positions (320mm,50mm), (320mm,200mm) and (80mm,50 mm). Three removable damage were separately simulated using a metallic nut weighing about 70g. Fig. 3 depicts both the PZTs and the damage locations. To simplify the analysis, the damage were named as DAMAGE#1 (close to PZT#1), DAMAGE#2 (close to PZT#2) and DAMAGE#3 (close to PZT#3). The experimental set-up is applied to the system operating in a continuous mode with a calibration resistor of 1kΩ. The interval between cycles was of 30 seconds, and the excitation signal of 2V amplitude. The range of frequency varied from 20kHz to 30kHz. Structural responses were sampled at 1MSample/s (500 samples and frequency resolution of 20Hz). The reference system [11] was similarly set, however, considering a frequency resolution of 4 Hz.

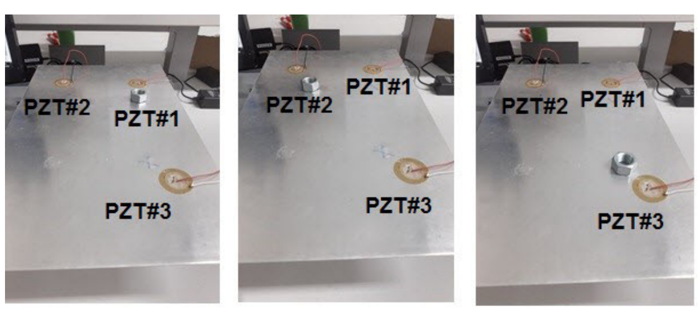

Fig. 3. Experimental setup for the SHM test.

Fig. 4 presents the signatures for the real part of the impedance (PZT#3), encompassing the baseline and DAMAGE#1 for both systems. Analysing Fig. 4, it is observed that the signatures present similar resonance/anti-resonance peaks for both proposed and reference systems. However, one can note there are frequencies and amplitude shifts when comparing both systems. It is worth mentioning that that structural condition is determined via a comparison between two signatures (reference and unknown), where the differences presented here should not reflect the detection of structural damage. Therefore, under the damaged condition both reference and proposed systems have shown changes in the impedance signatures, which apparently consist of a reliable indicator to detect structural damage. The results for other PZTs and damage scenarios are similar.

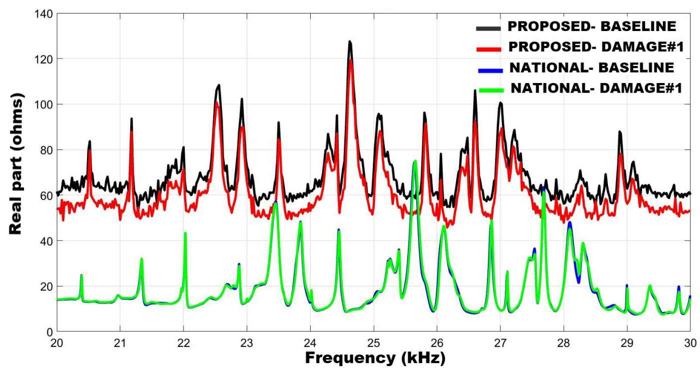

Fig. 4. Comparison between the proposed and reference [11] systems for the PZT#3.

Quantitative analyses were also performed by calculating CCDM and RMSD metrics for both systems. Accordingly, the indices were calculated between the signatures, for the real part of the EMI, in healthy (baseline) and unknown conditions. Table 1 presents a comparison between the proposed and reference [11] systems for the DAMAGE#1. Analyzing the results, it is noted that the reference system presents greater sensitivity for the RMSD, whilst the proposed system showed more relevance for damage detection via CCDM. For other damage scenarios and PZT#3, the results obtained were similar. Therefore, based on the tests presented here, it can be inferred that the developed system has identified structural failures with good reliability.

Table 1. Comparison between the proposed and reference systems for DAMAGE#1.

System	RMSD–PZT#1	CCDM –PZT#1	RMSD–PZT#2	CCDM –PZT#2
Proposed	68.0400	0.1468	49.6300	0.0987
Reference	3523.36	0.0158	735.630	0.0115

Monitoring interfaces The developed real-time interfaces enable the user to register new modules and different structures, set all configurations for the acquisition system, follow up the measurements, detect damage (CCDM and RMSD) and configure thresholds. For brevity reasons, only part of the graphics and metrics interfaces will be presented here.

After registering a given structure and setting up all measurement configurations, by clicking on the button ”Start” the server will communicate to the acquisition system local web server. The acquisition system python code (embeded on the RP) will read any detected changes on the local server then start the measurements. The measurements results are stored in a dedicated database and showed on the user screen (real-time) concurrently. Fig. 5 depicts the graphics interface during a real-time monitoring test. Wherein, it is shown the signatures for the real part of the EMI. Users can also monitor imaginary, module and phase of the EMI (they are not shown here). As all information is stored in a database, users may check anytime the graphs, verify if some damage occurred, check metrics and information related to the users and structures.

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Fig. 5. User interface developed showing EMI signature.

The metrics interface allows the user to monitor in real-time if any damage occurs. When the user clicks on the button "Monitor" the web page emits a signal to the server informing that it is ready to receive any new updates from that analysis. In turn, the server verifies into the database the information (every one second) and updates the user interface automatically. The thresholds consist of a bar chart that the user can move up and down to establish threshold levels for both CCDM and RMSD. If the metric values exceeded this set limit, a notification is issued, and a log is persisted into the database with the information of which analysis, module, PZT and date and the reached values. Fig. 6 depicts the real-time RMSD metric, including the configurable thresholds.

Fig. 6. Interface developed showing RMSD metric and adjustable threshold.

4 Conclusion

This paper presented the results of a new real-time SHM system. Based on the results obtained, we can conclude that the acquisition system presented impedance signatures very close to the reference one. Overall, the reference system presented higher sensitivity for the RMSD metric, whilst the proposed system showed more relevance for damage detection via CCDM. Moreover, the proposed system proved to be lower-cost, compact, and also uses a free software interface that allows users to access it remotely. After several rounds of tests, the system showed successfully integrated amongst hardware, software and database. The system also provides a dynamic threshold, which enables the user to have an automatic structural damage detection. Conclusively, despite being implemented in low-cost hardware, the developed system detected structural failures with good reliability, being advantageous for both financial and dimension standpoints.

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