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# Embedded Piezodiagnostics for Online Structural Damage Detection Based on PCA Algorithm

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**Key words:** Principal component analysis, embedded hardware, Odroid U3, Online Monitoring

## Abstract

*This work discusses a methodology used to implement a data-driven strategy for Structural Health Monitoring. First, the instrumentation of the equipment is detailed by describing the main components to be installed in the test structure in order to produce guided waves. Specifically, an active piezo active system is used for this purpose, which consists of piezoelectric devices attached to the test structure surface and an acquisition system. Then, the programming procedure to embed the damage detection algorithm is defined. In particular, the mathematical foundations and software requirements for implementing the preprocessing stage, baseline model building, and statistical index computation are specified. As a result, the Odroid-U3 computational core has the capability to perform online damage assessment. Finally, some validation tests are presented through videos and short real time demonstration. Experimental data are recorded from two test specimens:* ***i.)*** *a lab carbon steel pipe loop built to emulate leak scenarios, and* ***ii.)*** *an aluminum plate, where mass adding is used to emulate reversible damages. The results reported in this work show the high feasibility of the proposal methodology for obtaining an online embedded monitoring system with several advantages such as low cost, easy configuration, expandability and few computational resources.*

## 1 INTRODUCTION

The advantages of condition monitoring systems for structural damage diagnosis (detection, location and quantification) have been widely discussed in last years through several techniques and methods **[1]**. Therefore, challenges and perspectives have been identified in order to achieve practical implementations in complex-real structures, which are mainly related to the economic and technical benefits as well as the reliability of the system **[2]**. In this sense, dedicated solutions based on embedded hardware technology (i.e. DAQ systems, single boards and System-on-a-chip) have proven to have a high potential to provide continuous, automated and cost-effective online integrity evaluation.

To illustrate recent technical advances, Hong et al. **[3]** describe the implementation of an in situ structural integrity technique for online diagnosis of high speed trains developed on the PXI hardware platform. Thus, several working conditions (startup, acceleration, track change and emergency brake) were evaluated with the help of embedded hardware. Another example is a cost-effective vibration DAQ system for long-term continuous monitoring of a building **[4]**, where budget constraints are discussed. Similarly, Wang et al **[5]** developed a modularized system for in-situ health diagnosis of engineering structures which includes a multi-channel DAQ and software components with capacity to evaluate structural integrity in a real-time manner. Likewise, Liu and Yuan **[6]** validated damage localization algorithms implemented on a field programmable gate array (FPGA). Therefore, condition monitoring based on guided wave analysis has exhibited practical characteristics for real-world applications **[7]**: with capacity to monitor large area with only a few transducers and high sensitivity to different types of damage.

In this paper, an integrated based piezodiagnosis damage system was developed as a technological contribution of a monitoring equipment for its application in the practical engineering field and laboratory research use. The system takes advantage of feasibility and detectability of guided waves for SHM through an active piezoelectric system. By using the embedded platform Odroid-U3 as the core, the current condition (Damaged or Undamaged) of the structure is evaluated by means of statistical indexes obtained by applying principal component analysis to piezoelectric measurements. The operation of the system was verified by using two laboratory specimens: i) a carbon steel pipe loop conditioned to create leak scenarios, and ii) an aluminum plate, where mass adding is used to emulate reversible damages. The results demonstrate the feasibility of the system for online and automated structural health monitoring tasks with commendable compromise among high precision, good reliability, user-friendly results interpretation, low power requirements, easy setup, low cost, small size, expandability, hardware accessibility, as well as memory and processor adequate performance.

## 2 SYSTEM ARCHITECTURE

The system for condition monitoring developed in this paper is based on elastic wave propagation method. The concept of such system is depicted in **Fig 1**, which consists of: i) the monitored structure, ii) piezoelectric devices attached to the surface of the structure, iii) power supply and excitability elements (guided wave generation), iv) data acquisition components, v) digital signal processing core (Odroid-U3) and vi) visualization facilities.

In order to detail the system elements in **Figure 1**, the system is differentiated into three constitutive modules: 1) Piezo-diagnostics scheme, 2) hardware realization and 3) Software design.

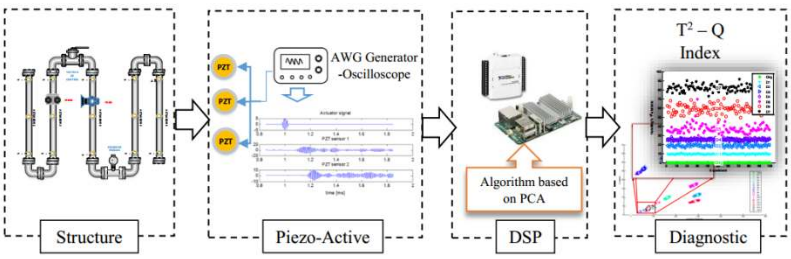


Figure 1: Diagram of the system

In **Figure 1**, piezo-diagnostics concerns to the procedure carried out to generate guided waves by using piezoelectric devices. On the other hand, hardware realization covers description about data acquisition, signal amplification, electrical coupling and the embedded platform. Finally, software design comprises the algorithm operation in order to distinguish between damage and undamaged states and how it is implemented in source code language.

## 2.1. PIEZO-DIAGNOSTICS SCHEME

The structural signature is characterized by means of piezoelectric measurements taking advantage of the piezo-diagnostics principle, where piezoelectric devices are used to produce elastic wave propagation in the structure and to analyze dynamics changes. The configuration of piezo-diagnostics scheme used in this paper is shown in **Figure 2**.

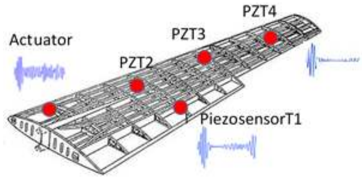


Figure 2: PiezodiagnosTiCs APPROACH

According to **Figure 2**, one of the PZT mounted on the surface structure operates as actuator. Thus, the electric energy from the voltage source is converted into mechanical one by producing guided waves along the surface structure, exploiting the inverse piezoelectric effect. On the contrary, the remaining PZTs work as sensors in a pitch–catch mode, by using the direct piezoelectric effect to measure the elastic wave propagation. So, the mechanical energy will transfer to electrical energy containing information about scattering, reflection, and mode conversion from elastic wave travelling.

Piezo-diagnostics principle has been demonstrated to be effective to detect elastic wave reflections caused by several kinds of discontinuities like boundaries, transducers and different damages **[8]**. This property is advantageous for condition monitoring algorithms. For instance, in Kolbadi et. al. **[9]**, a method to simulate cracked pipeline embedded with piezoelectric sensors and actuators utilizing bond graph approach is proposed. Another example, described in Spiegel work **[10],** is the use of piezoelectric actuators and sensors for detecting damages in a composite panel. Furthermore, it is documented that piezoelectric transducers can be used to effectively generate to guided waves **[11]**.

The main parameters considered in this paper for the process of guided wave generation are related to frequency and type of electric field excitation, coupling material for the bonding layer, and recommendations for electrical connections to piezo elements. The next concerns are included in the system design:

i. A burst type signal is used to excite the PZT actuator around its resonance frequency (~100 KHz). The burst type excitation is a finite duration signal, which mainly contains frequency components around a central band. Thus, by exciting dominant wave modes, the dispersive behavior is minimized. Also, by operating the actuator element at resonance frequency maximum amplitude is guaranteed.
ii. The coupling used in this study is adhesive cyanoacrylate, which has a better performance for repeatability of the waveform pattern and the transmitted energy. Also, the adhesive property is suitable for continuous monitoring tasks unlike other typically bonding materials used in ultrasonic tests.
iii. Key recommendations about the general soldering procedure are summarized in the

APC international supplier instructions **[12],** where equipment and materials, as well as soldering temperature among other parameters are specified. Additionally, according to tests conducted in this paper, it is recommended to use shielded and twisted pair wires in order to avoid external noise. Also, it is required to implement a signal condition circuit to interfacing piezo-devices to electronics components.

## 2.2 HARDWARE REALIZATION

The main components included in the system design comprise an embedded platform (the core of the system), data acquisition system, amplifiers signal conditioners and the visualization interface, which are described in next sections. It is remarked that details about visualization interface are not specified since any HDMI element serves for this purpose if proper screen resolution is selected.

### 2.2.1 Signal conditioning and acquisition system

As it was remarked in section 2.1, it was necessary to implement a signal conditioning circuit for the electrical coupling between PZT devices and electronics components. In this sense, a charge mode amplifier (**Figure 4**) was used to assure well operating frequency and to minimize signal loss due to the loading effect **[13]**.

The piezo-electrical response is amplified to ±10 V and recorded with a Picoscope™ series 2000 and a multiplexor board. It is possible to collect data from up to 16 channels by configuring the multiplexor in pair mode operation. Thus, actuation-sensing signal is collected simultaneously but each PZT channel is acquired with a low delay, which depends of the number of PZT installed in the structure. The PicoScope™ includes Arbitrary Wave Generation (AWG) function, which allows generate burst excitation. It is highlighted that PicoScope™ is used as DAQ/Generation system because it has desirable features for standalone and portable systems: deep memory (up to 128 MS), higher bandwidth (up to 100 MHz), faster waveform update rates, low price (From $129), and ultra-compact size.

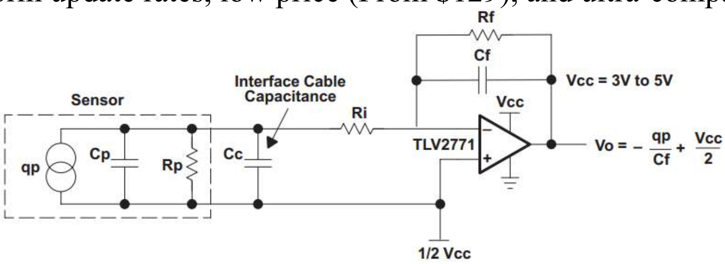


Figure 4: Charge amplifier. Extracted from [13]

### 2.2.2 Embedded platform

An embedded system or minicomputer refers to a computer system designed to perform specific functions, these systems contain embedded elements that vary according to the purpose for which it is needed, but always maintaining a number of essential elements for its operation: RAM memory, input-output peripherals and a microprocessor (CPU). The embedded platforms are generally based on ARM architectures, reducing its size and making them ideal for low power applications. One of the important features of embedded systems is its ability to process information and operation of real-time systems.

The embedded platform selected as computational core of the system developed in this paper corresponds to the Odroid-U3. Main characteristics of Odroid-U3 are summarized in **Table 1**.

| Feature | Description |
|---|---|
| **CPU** | 1.7GHz Exynos4412 Prime Cortex-A9 Quad-core processor<br>2Gbyte LPDDR2 880Mega Data Rate |
| **RAM** | 2072 [MB] |
| **Onboard Flash** | 8Gb, eMMC |
| **Power Source** | 5VDC/2A |
| **USB 2.0 Host** | 3 x USB 2.0, 1 x Micro USB |
| **Serial Port** | UART 1.8 V |
| **Ethernet** | 10/100, RJ45 |
| **Video Out** | HDMI (480p/720p/1080p) |
| **GPIO** | 5 |

Table 1: Odroid-U3 characteristics

According to **Table 1**, the Odroid-U3 has peripherals package that allows making several improvements using Ethernet communication, USB, SD, HDMI ports, video out and on board memory. It also allows execution of real time operating system such as Ubuntu 13.10, which supports the architecture of the system described in this paper.

The final component included in the hardware system design corresponds to the USB-to - IO expansion board that provides GPIO interface. It is used to implement the logical programming of the multiplexor board through the PIC18F45K50 microcontroller.

## 2.3 SOFTWARE DESIGN

The algorithm for structural damage diagnosis implemented in the computational core is based on principal component analysis (PCA). It has been reported as a promising approach to detect and locate damages in structures as pipes, wind turbines, and aircraft sections, among others **[14]**, **[15]**, **[16]**. Also, the effectiveness of using PCA algorithm in combination with piezo-diagnostics principle to detect structural damages has been demonstrated in the author's previous works **[17]**, **[18]**, **[19]**. Thus, the successful application of PCA based approaches have motivated the integration of this technology with the help of embedded hardware.

In order to detect structural damages, the methodology consists firstly of obtaining a structural baseline model by applying PCA on a set of experiments at the pristine condition of the structure. Then, current condition (Damaged or Undamaged) of the structure is evaluated by comparing new measurements respect to the baseline model. Thus, the embedded structural diagnosis methodology can be runned through two stages: Modeling and Monitoring.

### 2.3.1 Modeling stage: Baseline model building

A baseline model is obtained by processing piezoelectric measurements of the structure operating on nominal or undamaged condition (no damage). These measurements are arranged in an unfolded matrix ($\mathbf{X}$), which considers noise and variance due to the stochastic nature of the process by recording $\boldsymbol{n}$ experiment trials. However, in order to eliminate noisy data trends and exclude common external signal, a preprocessing stage based on cross correlation analysis is implemented. Thus, cross-correlation between actuation and sensing piezo-signals is computed before applying PCA.

After organizing cross-correlated undamaged trials in a new data case matrix, Group-Scaling normalization procedure is used to eliminate bias and scale variance in the undamaged baseline matrix. Therefore, each data-point is scaled by considering changes between sensors. As a result of the standardization, $\boldsymbol{k}$- standard deviations and $\boldsymbol{m}$ -mean values are obtained, where $\mathbf{k}$ is the number of PZT sensors and $\boldsymbol{m}$ the total variables analyzed in PCA ($\boldsymbol{m=N*k}$). $\boldsymbol{N}$ is the number of recorded samples per sensor, which depends of the sample time. Thus, a reduced representation of undamaged state is obtained in the form of equation (1), by retaining data variation as much as possible.

$$T = \hat{X}P + E \tag{1}$$

In equation (1), $P$ is the linear transformation used to express features in the reduced spaced and it is named principal components, $E$ corresponds to the residual variance neglected by the statistical model and $T$ are scores describing the original normalized data $\hat{X}$ in the new reduced space. In order to obtain a reduced representation, only $\boldsymbol{r}$ principal components are retained to represent the original data by using a percentage of the cumulative variance.

### 2.3.2 Monitoring stage: Structural damage diagnostic

New measurements from current condition of the structure are analyzed by means of the statistical model (Eq. (1)). Thus, the piezoelectric data organized in a row vector are projected onto the reduced space by means of the linear transformation $P$. However, it is necessary, before normalization and the respective pre-processing, to consider the mean and standard deviation values, obtained in the modeling stage.

The comparison respect to undamaged baseline model is achieved by computing statistical indexes. In this sense, the squared prediction error (Q-statistics, Eq. (2)) had demonstrated to be successful in fault diagnosis systems, and it describes the residual error for each $j-th$ principal component used to reconstruct the trial experiment. The Q-statistics allows monitoring differences between baseline and current state, which are attributed to damage.

$$Q = \sum_j (e_j)^2 \tag{2}$$

Where $(e_j)$ is the residual error for each $j-th$ principal component used to reconstruct the experiment trial.

### 2.3.3 Numerical algorithm

The overall methodology, described in sections 2.3.1 and 2.3.2, was implemented in the embedded hardware by using the flowchart detailed in **Figure 5**, which allows the execution of two operation modes: offline and online. The offline mode is intended for cases when damages are studied in a controlled way and their respective labels are previously known by user, while online mode considers unknown damages and produce plots of the form index vs. time. The results in this paper are presented considering only the online option.

pseudoc.cpp

```
Read configuration parameters; /*Number of sensors, Operation mode, Folder,
                                 Sample Frecuency, Number of Experiments, etc.*/
Read actuation signal archive;
Create directory structures;
Set up Picoscope and IO USB card;
//Baseline Building
for (x=1: number of experiments:x++){
  Undamaged Data reading
  Save files
}
/*    Operation Mode Online    */
//Online Monitoring
if (operation mode == 1){
    for (k=1:indefinite number of times:k++){
        for (j=1:number of sensors:j++){
            Enable a port multiplexer;
            Enable a port of sensor;
            Generate actuation signal;
            Capture Data Stream
            Save files
        }
        //Normalization and PCA algorithm
        Data scaling
        SVD/NIPALS/POD decomposistion.
        Save Results
        Comparison and Visualization Results
    }
}
/*    Operation Mode Offline    */
//Offline Monitoring
else if (operation mode == 0){
for (i=1:number of experiments:i++){
        for (z=1:number of sensors:z++){
            Enable a port multiplexer;
            Enable a port of sensor;
            Generate actuation signal;
            Capture Data Stream
            Save files
        }
        //Normalization and PCA algorithm
        Data scaling
        SVD/NIPALS/POD decomposistion.
        Save Results
    }
    Comparison and Visualization Results
}
else { printf "Error"}
```

Figure 5: Pseudocode of piezodiagnostics algorithm in the embedded platform

As it is shown in **Figure 5**, three methods **[20]** can be used to obtain the transformation matrix *P* of the statistical model (POD, SVD and NIPALS); however, in this paper only POD method is considered as processing tool because lower memory and execution time requirements. Also, drivers to command Picoscope™ interface and scripts for saving results were developed. It is remarked that data flow communication is organized in text files in order to maintain a compromise among resources memory and time consuming.

## 3 VALIDATION TESTS AND APPLICATION

Two experiments were conducted on two structural lab specimens in order to evaluate the system performance. The first experiment corresponds to a carbon steel pipe loop with recreated leaks and the second one corresponds an aluminum plate which is configured for mass adding detection.

For both experiments a sample frequency of $T_s$=40 [ns] was used to record piezoelectric measurements, while guided waves was induced with a 5 cycles burst type pulse. The recorded measurements are processed as raw data without real units (voltage and time). In this sense, the normalization procedure eliminates scaling effects. The average time and memory resources required for the embedded platform are summarized in **Table 2**.

| *CPU %* | *Memory %* | *Runtime per experiment* | *Visualization delay* |
|---|---|---|---|
| **51.4** | **0.9** | **< 1 second** | **4 seconds** |

Table 2: ODROID-U3 Performance online structural damage detection

According to **Table 2**, a great time is required to obtain graphical results, which indicates the need for an external graphical processor unit in order to reduce the visualization costs. Also, it is noted a fast execution of PCA based algorithm taking into account that state of the structure is monitored each second.

### 3.1 CARBON STEEL PIPE LOOP EXPERIMENT

The first specimen used as test structure is a carbon-steel pipe loop which contain five sections of 1 m x 0,0254 m x 0,003 m (length, diameter, thickness). Each section has bridles at the ends and one of them has a valve which sets the air pressure from a compressor at 80 psi. In order to induce leaks, four ¼-inch holes were drilled along each pipe section wall and graduable screws are used to control where they are produced. The test structure is depicted in **Figure 6**.

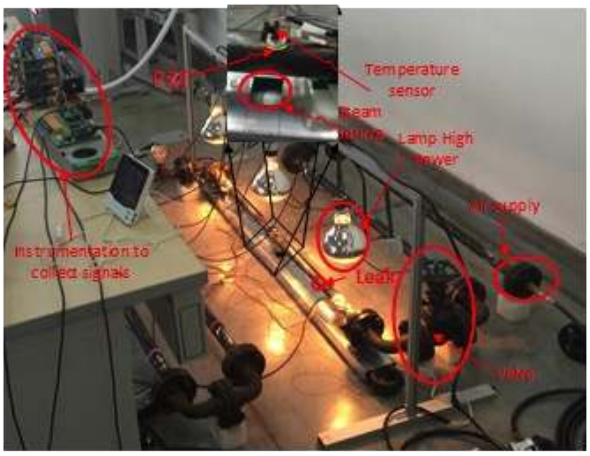

Figure 6: Pipe loop experiment

As preliminary results, a mass was added in the middle section of the pipe loop in order to evaluate response of the system for reversible damage detection. **Figure 7** shows the time evolution of Q-statistics index when damage is caused in the structure and after removing the mass. Also, repeatability of the experiment is studied by adding the mass again in a posterior time. In addition, severity of damage is considered by adding two masses as damage condition.

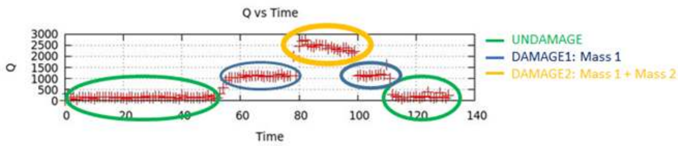

Figure 7: Mass damage detection in the loop experiment

According to results in **Figure 7**, it is observed a high sensitivity to damage detection and severity level. Moreover, the fast response of the system allows identifying transient response and the moment when damage has occurred. Similarly, in **Figure 8** presents the Q-index dybamics behavior for the leak damage experiment.

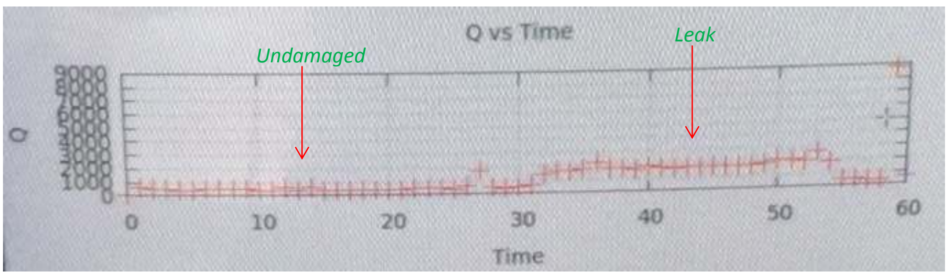

Figure 8: Leak detection in the loop experiment

The results in **Figure 8** indicate that it is possible to detect leaks by using the embedded platform. This type of damage produces variations of Q-values in the order of 1000 interval. Additionally, some atypical values are observed while the structure is manipulated to induce pipe leaks.

## 3.2 ALLUMINUM PLATE

The second test structure is a golden aluminum plate with a mass attachable to the surface. Records from two PZT (actuator-sensor) are processed in order to analyze the performance of the system. **Figure 9** depicts the behavior of Q-index and the structure used to conduct the experiment.

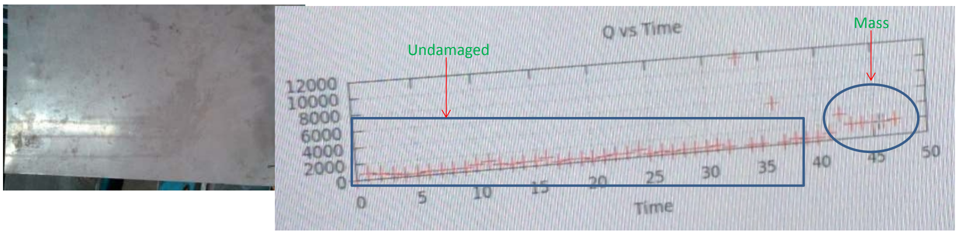


Figure 9. Plate experiment results. **Left:** Alluminum plate. **Rigth:** Q-statistics index

According to results presented in Figure 9, a clear difference between damaged an undamaged conditions is obtained.

## 4 CONCLUSION

In this paper experimental results of embedded PCA based algorithm that uses the piezo-diagnostics was presented. It was demonstrated that is it possible to use a low cost embedded platform to manage the whole sub-systems of the proposed architecture, which can be easily adapted to solve SHM tasks. Also, experimental results showed that the developed standalone system works correctly for leak and mass adding detection. In future research the focus will be on the development of application of parallel computing, wireless sensor capability and remote monitoring.

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