Multichannel detection of acoustic emissions and localization of the source by using a hybrid programming system

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ABSTRACT

The detection of acoustic emissions with multiple channels and different kind of sensors (ultrasound electronic sensors and optical fiber sensors) is presented. The source localization based on the times of arrival is also carried out and different strategies for solving the location equations are compared. The most efficient strategy in terms of computational and complexity costs versus performance has been selected and the error propagation is analyzed. The errors of the acoustic emission source location (localization process) are evaluated from the errors of the times of arrival (detection process). For that, a hybrid programming architecture is proposed. It is formed by a virtual instrumentation system for the acquisition and the detection of multiple acoustic channels and an algorithms-oriented programming system for the implementation of the localization techniques (back-propagation and multiple-source separation algorithms could also be implemented in this system). Finally the communication between both systems is performed by a packet transfer protocol that allows remote operation (e.g. a local monitoring and a remote analysis and diagnosis).

Keywords: Acoustic Emission, Ultrasonic Detection, Source Location, Multichannel Instrumentation System, Optical Fiber Sensors, Denoising, LabVIEW, Hybrid Programming System (LabVIEW - Matlab).

1. INTRODUCTION

Acoustic Emission (AE) is the study and practical use of elastic waves generated by a material subjected to an external stress. Strictly, acoustic refers to the pressure waves detected by ear. However, the elastic waves in solids are not limited to pressure waves, since all types of vibration modes are generated by acoustic emission sources (AES). Still, the term AE has become almost universally used for the phenomena of elastic waves generated by an internal event in a medium. In this case, acoustic refers to any elastic wave generated by an AES. Therefore, AE is the generation of an elastic wave by rapid change in the stress state of a region in the material. The change of stress must be fast enough to transmit some energy to the surrounding material. The material may be a solid, liquid, gas or plasma and the external stress can be applied mechanically, thermally, magnetically, etc. A large scale example may be that of an earthquake or thunder, while small-scale breakage of crystalline microstructures (metal plates, etc.).

The elastic wave generated travels throughout the material and can be detected at considerable distances from the point of origin. Thus, the characteristics of the wave (amplitude, phase, frequency, etc.) vary due to the effect of dispersion along its acoustic path. The most important information of the AE is the time of arrival (TOA) to each sensor and its amplitude. The TOA provides information on the distance of the event and the amplitude of its magnitude. The information obtained from the wave allows calculating the location of the AES, but the detected signals at different sensors depend on each specific path and each sensor characteristics.

Leakages, friction, impact, chemical reactions, electrical discharges (e.g. partial discharges - PDs) are examples of AES. This work is based on the application of AEs from PDs in power transformers [1]. There are many other applications for which the detection and location of AEs is a useful diagnosis tool, from the structural health monitoring (metals, concrete and other composite materials) [2-3], the detection of cracks in the fuselage for the aerospace industry, the detection of leaks in the chemical industry, to the analysis of insulation failures in the electrical industry.

Regarding the detection of AE, piezoelectric sensors of Lead Zirconate Titanate (PZT) are typically used. In addition, other sensors that use optical fiber (OF) are being developed. In the case of detection of PDs in transformers, these OF sensors are very suitable because they are embedded in the insulating medium and can detect the acoustic signal directly within the transformer tank, whereas the PZT sensors are located externally on the walls.

In the field of acoustic detection, several companies offer their equipment based on proprietary systems for specific applications that solve different aspects of the detection and processing of AE signals. Main modules are for multichannel acquisition; some of them include integrated processors and others are connected to an external PC (Personal Computer). They are usually modular devices that integrate power supplies, data acquisition cards, processors and even FPGAs (Field Programmable Gate Array). Some examples are AMSY-6 of Vallen Systeme [4], LAN-XI of Brüel & Kjær [5] or PXI (Peripheral Component Interconnect (PCI) eXtensions for Instrumentation) of National Instruments [6]. The instrumentation system used in this work includes the PXI. Besides having specialized modules for acquisition and signal processing, this platform has software flexibility by virtual instrumentation.

There has been important research effort with respect to the hardware for AE monitoring, such as data acquisition, communication systems and sensor arrays [7-9]. The objective of an automatic AE monitoring system is the identification of the AES [10-11] and its localization. The localization is based on measurements of the TOAs of the AE signal to individual sensors of an array. Efforts are being made to implement faster and more efficient algorithms.

The hybrid programming system described in this paper is an evolution of previous systems in order to improve the performance. A previous approach included a single architecture based on LabVIEW [12]. It implemented a module of detection/conditioning and a module with an acoustic localization method based on lookup tables. It exhibited a resolution of *1 cm*. However, the graphical design based on LabVIEW is inefficient with other complex algorithms that are used extensively in this kind of applications [13-16], and therefore, a design based on Matlab was proposed for the localization stage.

As a result, the hybrid programming system is as follows. A first stage is programmed in LabVIEW, which is a powerful tool for managing the acquisition with multiple channels and the on-line denoising of each channel [17-18]. The second stage is programmed in Matlab, which is a tool of numerical calculation that is specialized in data processing and representation [8, 19], thus the localization algorithms and the presentation were programmed with this tool. The localization stage is based on the common technique of trilateration [20-22] and different strategies can be used [13-16]. All these methods of localization were firstly implemented in [23] with a resolution of *1 mm* and they were compared experimentally. In the present paper the hybrid programming system is described and analyzed. In addition, the error propagation is studied. The errors of the AES location (localization process) are evaluated from the errors of the TOAs (detection process).

This paper is organized as follows: the instrumentation system is described in Section 2. It was designed and implemented for the detection and location of AE based on PZT and OF sensors. The strategies for the location of the AES and their implementation are presented in Section 3. The characterization of the localization system is presented in Section 4, which includes the description of the hybrid programming system and the error propagation analysis. Finally, the conclusions are summarized in Section 5.

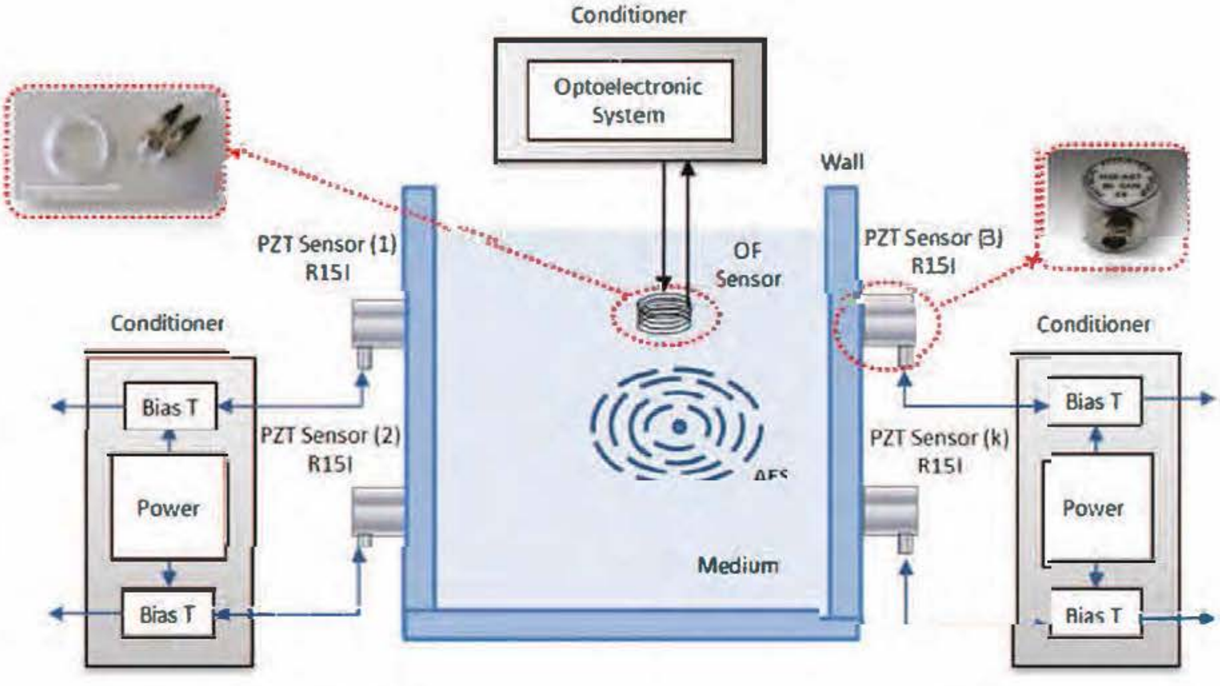


Figure 1. The instrumentation system based on OF and PZT sensing.

2. INSTRUMENTATION SYSTEM

Two types of acoustic sensors have been used: OF sensors and PZT sensors (Figure 1). OF sensors can be embedded in the insulating medium closer to the AES, which allow detecting a stronger acoustic signal. These sensors also provide a time reference in the location process. The optoelectronic conditioning scheme for the optical fiber sensor was previously designed [24]. It consists of a sensor head of single-mode optical fiber illuminated by a He-Ne laser *(633nm)* and a fiber-optic stabilized interferometer. It is sensitive to AE of *150 kHz*.

The PZT ultrasonic sensors are typically used for acoustic detection. These sensors work with ultrasonic frequencies and are mounted on metal surfaces (Figure 1), for example, on the walls of a transformer tank. The use of several sensors or a sensor array allows carrying out the AES location. The model of the PZT sensor is R15I-AST (Physical Acoustic Corporation), with the following characteristics: operating range *80-200 kHz*, resonant at *150 kHz*, low noise integrated preamplifier of *40dB*. The sensitivity of these sensors is about *1V/Pa*. Because the sensor R15I has integrated electronics but it has not separate ports for power and output, a Bias-T circuit is necessary.

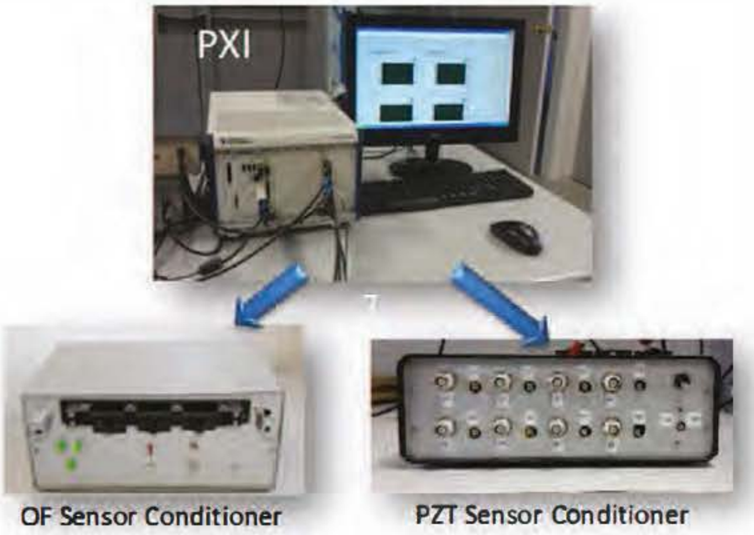


Figure 2. Multichannel acquisition and conditioning system.

An industrial PXI has been used in order to integrate into the same system different types of sensors (PZT, OF, etc.) and signal processing units. The PXI system (National Instruments) is a PC-based open platform for test, measurement and control. It includes a data acquisition module (*NI PXI-5105*) with *8 channels* of simultaneous acquisition of *12-bit* resolution, *60 MS / s* acquisition rate in real time, up to *60 MHz* bandwidth and *128 MB* onboard memory. The graphical programming tool used is *LabVIEW*.

Figure 2 shows the components of the overall system: PXI based multichannel acquisition and denoising system, OF sensor conditioning system and multichannel PZT sensors conditioning system.

After comparing different techniques of denoising, a combination of wavelet techniques and digital filtering was selected [1, 12]. They can be used alone or together depending on the application.

3. LOCATION BASED ON ACOUSTIC EMISSION

The common technique for 3-D spatial location of AE is the trilateration. This technique determines the position of the AES measuring the TOAs [20-22].

The model is a 3-D space with $k+1$ acoustic sensors at specific positions (an internal OF sensor and k external PZT sensors in the surrounding of the AES). The resulting times of arrival are T from the AES to the OF sensor and T_k from the AES to the PZT_k sensor. In this case, the reference is the OF sensor.

There are several approaches to trilateration but, due to an all-acoustic instrumental scheme is employed in this work, the time-differences approach (time difference of arrival - TDOA) has been chosen (Figure 3).

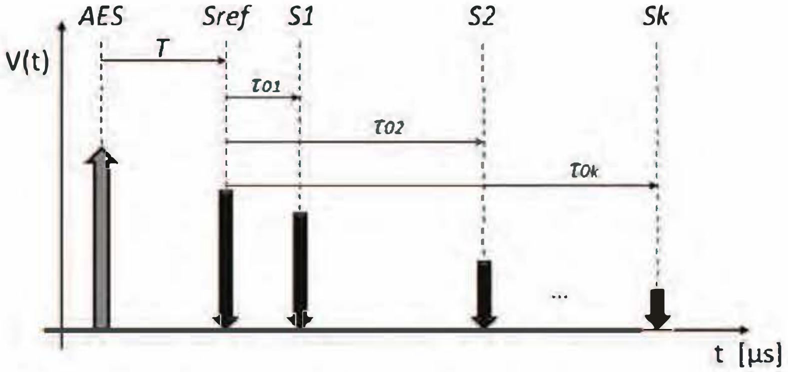


Figure 3. Schematic of time differences with unknown time reference T.

In this case, the acoustic wave reaches the nearest sensor first (straight propagation is assumed) and it triggers the process of recording the signals from all sensors simultaneously. Four time-differences (τ_{0i}) are obtained from five sensors and the reference is from the sensor closest to the AES (T). Figure 3 illustrates these time differences of the acoustic signals with an unknown timing reference.

The system of nonlinear equations of 3-D location with a time-differences approach is as follows:

$$(x - x_{Sref})^2 + (y - y_{Sref})^2 + (z - z_{Sref})^2 = (v_s \cdot T)^2 \tag{1}$$

$$(x - x_{PZTk})^2 + (y - y_{PZTk})^2 + (z - z_{PZTk})^2 = (v_s \cdot (T + \tau_{0k}))^2 \text{ , } k = 1..N \tag{2}$$

where v_s is the speed of sound in the medium, x_{OF}, y_{OF} and z_{OF} are the coordinates of the reference sensor and x_{PZTk}, y_{PZTk} and z_{PZTk} are the coordinates of the kth PZT sensor. The minimum number of sensors is 5 ($N \geq 5$). The position is determined by obtaining x, y, z, T.

In [23], different methods of localization with a resolution of *1 mm* were implemented and compared experimentally. In these solution strategies, except the PSO method [14-16], the equations system should be adapted to the matrix structure $A*X=B$. This is obtained in (3) by subtracting (1) from (2) for $k=1$ to N:

$$\begin{aligned}&2(x_{Sk}-x_{Sref})x+2(y_{Sk}-y_{Sref})y+2(z_{Sk}-z_{Sref})z+2v_s^2\tau_{0k}T=\\&=(x_{Sk}^2-x_{Sref}^2)+(y_{Sk}^2-y_{Sref}^2)+(z_{Sk}^2-z_{Sref}^2)-v_s^2\tau_{0k}^2,\ k=1..N\end{aligned} \tag{3}$$

$$A=\begin{pmatrix}2(x_{S1}-x_{Sref}) & 2(y_{S1}-y_{Sref}) & 2(z_{S1}-z_{Sref}) & 2v_s^2\tau_{01}\\ \dots & \dots & \dots & \dots\\ 2(x_{SN}-x_{Sref}) & 2(y_{SN}-y_{Sref}) & 2(z_{SN}-z_{Sref}) & 2v_s^2\tau_{0N}\end{pmatrix}\quad X=\begin{pmatrix}x\\y\\z\\T\end{pmatrix}$$

$$B=\begin{pmatrix}(x_{S1}^2-x_{Sref}^2)+(y_{S1}^2-y_{Sref}^2)+(z_{S1}^2-z_{Sref}^2)-v_s^2\tau_{01}^2\\ \dots\\ (x_{SN}^2-x_{Sref}^2)+(y_{SN}^2-y_{Sref}^2)+(z_{SN}^2-z_{Sref}^2)-v_s^2\tau_{0N}^2\end{pmatrix}$$

TABLE I summarizes the location solution strategies.

TABLE I. LOCATION SOLUTION STRATEGIES

Type of Method	Method	Equations	Nº of Sensors	References
Direct	"Solve" (Matlab)	-	5	-
	Least Squares (LS)	$X=(A^TA)^{-1}A^TB$	5	-
	Least Norm (LN)	$X=A^T(AA^T)^{-1}B$	5	-
	Cramer	$A=[A_x\,A_y\,A_z\,A_T]\ ,\lvert A\rvert\neq 0$ $x=\frac{\lvert B\,A_y\,A_z\,A_T\rvert}{\lvert A\rvert},y=\frac{\lvert A_x\,B\,A_z\,A_T\rvert}{\lvert A\rvert},$ $z=\frac{\lvert A_x\,A_y\,B\,A_T\rvert}{\lvert A\rvert},T=\frac{\lvert A_x\,A_y\,A_z\,B\rvert}{\lvert A\rvert}$	5	-
Indirect	Non-Iterative (INI)	-	4	[13]
	Particle Swarm Optimization (PSO)	*Fitness function:* $f(p)=\sum_{j=1}^{n}\sum_{i=1}^{m}\left\lvert\left[(px_j-x_i)^2+(py_j-y_i)^2+(pz_j-z_i)^2-v_s^2(pT_j+\tau_i)^2\right]\right\rvert$ *Refinement equations:* $v_j(t+1)=w_k\cdot v_j(t)+c_1R_1[p_j^{best}(t)-p_j(t)]+c_2R_2[g^{best}(t)-p_j(t)]$ $p_j(t+1)=p_j(t)+\Upsilon\cdot v_j(t+1)$ *Inertia weight:* $w_k=w_{\max}-\frac{w_{\max}-w_{\min}}{N}k$ *Constriction coefficient:* $\Upsilon=\frac{2}{\lvert 2-\gamma-\sqrt{\gamma^2-4\gamma}\rvert},\gamma=c_1+c_2\ and\ \gamma\succ 4$	5	[14-16]

The INI and PSO methods provided the best results (the figure of merit was precision over runtime).

4. CHARACTERIZATION OF THE LOCATION SYSTEM

A. *Hybrid processing system*

An experimental platform for acoustic emission testing was used to characterize the hybrid processing system for AE multichannel detection and AES localization. The experimental platform consists mainly of a container of cubic shape and the following effective dimensions *900 mm x 550 mm x 370 mm*. The walls of the container are made of PMMA (PMMA is short of polymethylmethacrylate). A wave generator applied to a PZT ultrasonic transducer (hydrophone B&K 8103) has been employed as a source to generate ultrasonic acoustic emissions. Six PZT ultrasonic sensors have been used on the surface of a wall (R15I/AST- Physical Acoustic Corporation). In addition, an OF sensor has been used within the tank. According to the example of application, the placement of the PZT sensors follows the typical pattern of the three-phase transformers, with two sensors per phase. This platform includes only one OF sensor because of the difficulty of introducing more sensors inside the transformer tank.

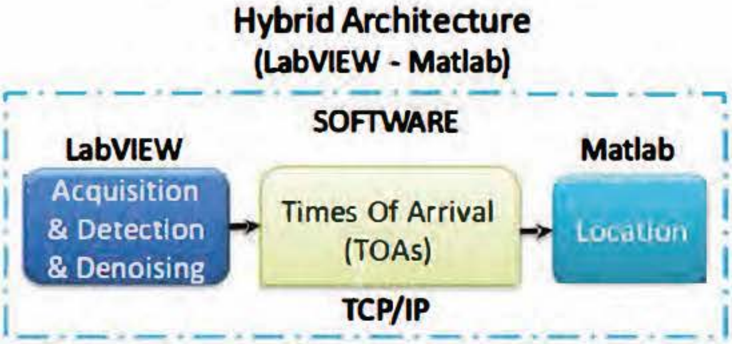


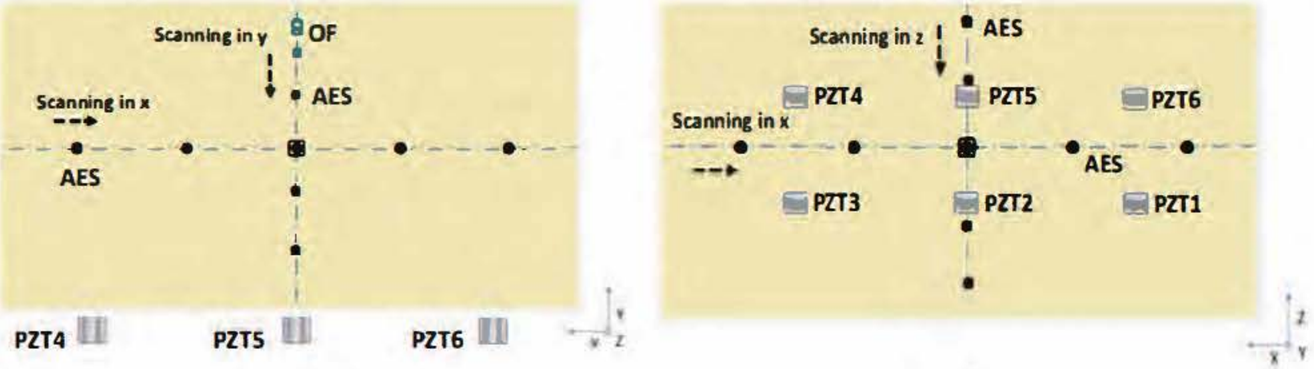
Figure 4. Hybrid processing system for detecting and locating the AES.

The multichannel instrumentation system has a specific hardware of acoustic signal conditioning and acquisition (PXI-National Instruments), and several software blocks for detecting and locating the acoustic signals. Figure 4 shows the general block diagram of the hybrid processing system for the detection of AE and the localization of the AES (hybrid architecture). It is formed by two parts; the first one is programmed in LabVIEW and it is devoted to the detection process. The acquisition of the acoustic signals is performed in all channels simultaneously and a signal processing of each channel is applied, which is based on digital filtering and Wavelet denoising [12]. As a result of the processing, the time of arrival (TOA) is obtained by the first stage for each and every channel and each acoustic emission event. Other information can be also extracted, such as the amplitude of the AE.

The second part is programmed in Matlab and it is dedicated to locating the AES. It solves the equations system of trilateration for a 3D model of localization. The communication between both parts (from LabVIEW module to Matlab module) is mainly in terms of the information contained in the TOAs. It is performed efficiently through a packet transfer protocol. Particularly, TCP/IP is used (TCP/IP is short of Transmission Control Protocol / Internet Protocol (TCP/IP). A real-time localization of the AES is obtained by these means. In addition, remote data analysis is provided by this communications protocol.

B. Analysis of the error propagation to the location of the AES

A simulation study was performed in order to evaluate what is the influence of the error in the TOAs on the accuracy of the location. For that, on the one hand, a sweep of the position within the tank was realized by moving the AES along the axis XYZ as shown in Figure 5. On the other hand, different percentages of error were added to the TOAs.



a)

b)

Figure 5. Sweep of the AES position within the tank, scanning XY (top view) in a) and scanning XZ (front view) in b).

The results of the PSO method are shown below, considering that it was the selected method that obtained the best response in the previous comparison [23]. For each location of the AES, *100* samples were taken. In order to present and analyze the results an offset error and a dispersion error have been defined as follows.

The offset error is the distance between the real position of the AES and the mean value of the solutions of location:

$$OffsetError = \sqrt{(x_R - x_M)^2 + (y_R - y_M)^2 + (z_R - z_M)^2} \tag{4}$$

where (x_R, y_R, z_R) are the coordinates of the real position of the AES and (x_M, y_M, z_M) are the mean value of the solutions.

The dispersion of solutions is quantified as the STD (σ) of the solutions of location:

$$\sigma^2 = \sigma_x^2 + \sigma_y^2 + \sigma_z^2 \;,\; \sigma = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{5}$$

where σ_x, σ_y and σ_z are the STD of each axis.

Both errors are presented as a ratio (percentage) to the diagonal of the tank (3-D space dimensions), which is the maximum distance between two points inside it:

$$\%_{Error} = \frac{Error}{D_{Tank}} \cdot 100 \tag{6}$$

where D_{Tank} is the diagonal:

$$D_{Tank} = \sqrt{dx^2 + dy^2 + dz^2} = 1117'766\,mm \tag{7}$$

where *(dx, dy, dz) = (900, 550, 370) mm* are the dimensions of the tank.

First, a random error up to *2%* (standard uniform distribution – *mean = 1%)* was applied to each and every TOA. The results are shown in Figure 6. The mean solution for each coordinate, the offset error, the dispersion error and the percentage of each error are represented.

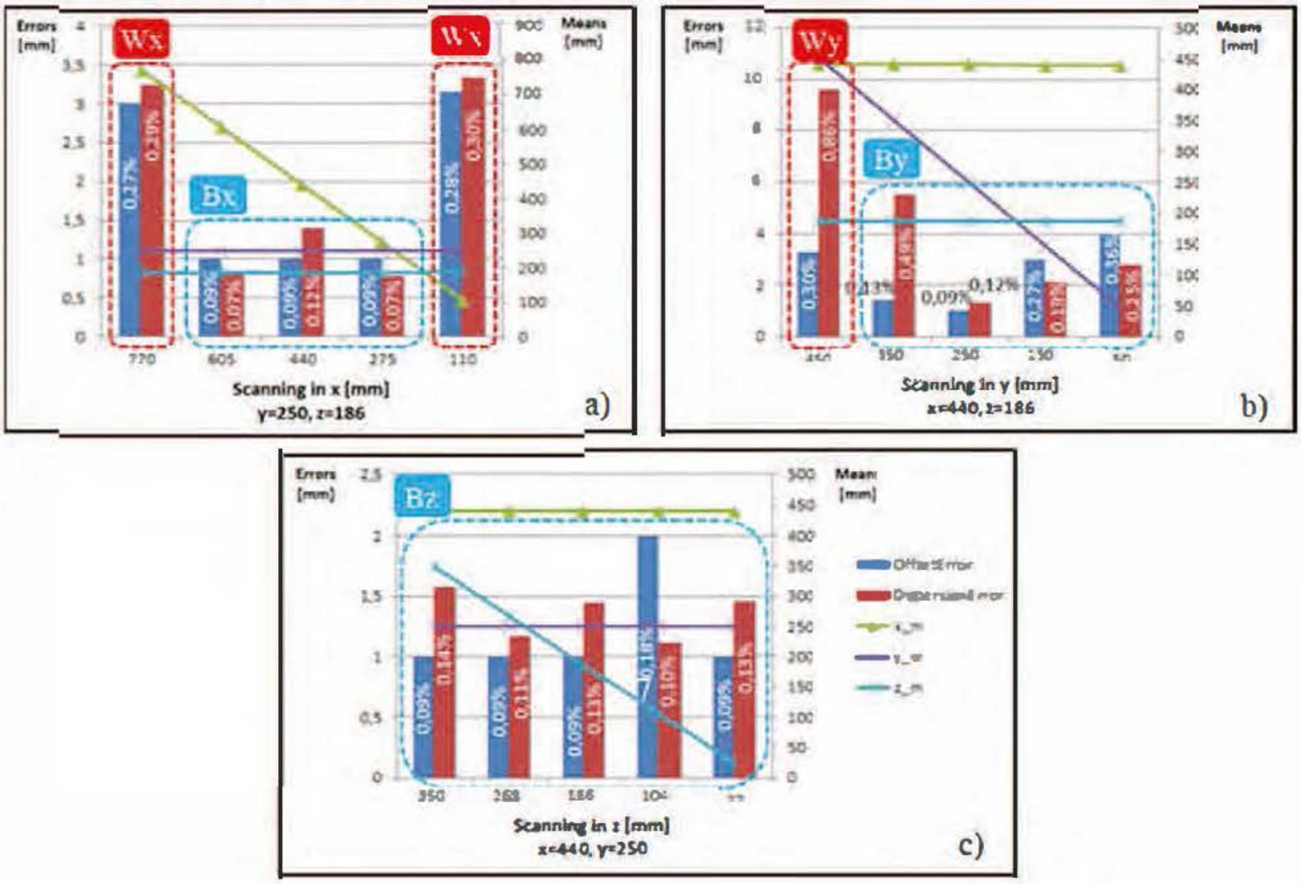


Figure 6. Results (2%) of the scanning X in a) , the scanning Y in b) and the scanning Z in c).

These results show different axis-dependent zones. The *Bk* areas are zones with small limited stable error and the *Wk* areas are zones in the borders that exhibit higher errors. Edge and depth effects are observed in the zone *Wx* and *Wy*, respectively. In this case, the maximum dispersion error is *9.5 mm* and the maximum offset error is *4 mm* (less than *1%* in both cases).

Second, a more intense error source (up to *10%* – standard uniform distribution – *mean = 5%)* was applied. The results are similar to the previous case except of the scale. The results of 10% follow the same pattern as 2% with a factor of about *5*. However, in the second case, the effect of the proximity to the PZT sensors is more pronounced (*Wy* area). The maximum dispersion error is *4.5 cm* and the maximum offset error is *3.5 cm* (less than *5%* in both cases).

5. CONCLUSIONS

The detection of acoustic emissions with multiple channels and different kind of sensors (ultrasound electronic sensors and optical fiber sensors) has been implemented in a modular configuration, thus it is easily adapted to different applications. The source localization based on times of arrival was also implemented and analyzed, by comparing different strategies for solving the location equations. For that, a hybrid programming architecture has been proposed and demonstrated. It is composed by a virtual instrumentation system for the acquisition and detection of multiple acoustic channels, an algorithms-oriented programming system for the implementation of localization techniques and a communication module between them that is performed by a packet transfer protocol that allows remote operation.

The Particle Swarm Optimization strategy of localization was demonstrated as the most efficient in terms of computational and complexity costs versus performance. In addition, an analysis of the error propagation from the times of arrival to the results of location was applied to this strategy under different conditions of error magnitude and positions of the acoustic source. The edge, depth and proximity effects were clearly identified during the analysis of the location results. Even so, the maximum relative errors of location (offset and dispersion) are limited to less than the TOA relative mean errors. Results of location better that *1 cm* in *1 m* were obtained with TOA uniform (0% - 2%) error distribution.

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