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Low-cost active/passive system for acoustic imaging based on large arrays of MEMS microphones

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Abstract

This work presents an acoustic signal acquisition and processing architecture that, using an extensive array of MEMS microphones and mixed processing systems with multicore processors and FPGAs, obtains high-resolution acoustic images. The system allows, by means of beamforming techniques, to know the spatial position of acoustic sources (working in passive mode, i.e. in a listening mode) and the position of objects in a surveillance space (working in active mode, i.e. in acoustic radar mode). The applications of this system are manifold, ranging from noise mapping to object localization. Additionally, the paper includes a set of case studies for the main applications of use for both modes of operation.

Keywords: active/passive, low-cost, MEMS microphone large array, acoustical imaging

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Resumen

Este trabajo presenta una arquitectura de adquisición y procesado de señales acústicas que, utilizando un array extenso de micrófonos MEMS y sistemas mixtos de procesado con procesadores multicore y FPGAs, obtiene imágenes acústicas de alta resolución. El sistema permite, mediante técnicas de beamforming, conocer la posición espacial de fuentes acústicas (trabajando en modo pasivo, es decir, en modo escucha) y la posición de los objetos en un espacio de vigilancia (trabajando en modo activo, es decir, en modo radar acústico). Las aplicaciones de este sistema son múltiples, desde la obtención de mapas de ruido, hasta la localización de objetos. Adicionalmente, el trabajo incluye un conjunto de casos de estudio para las principales aplicaciones de uso para ambos modos de funcionamiento.

Palabras clave: activo/pasivo, bajo coste, array extenso de micrófonos MEMS, imagen acústica.

Resumo

Este trabalho apresenta uma arquitetura de aquisição e processamento de sinais acústicos que, utilizando uma ampla gama de microfones MEMS e sistemas de processamento mistos com processadores multicondutores e FPGAs, obtém imagens acústicas de alta resolução. O sistema permite, por meio de técnicas de formação de feixe, conhecer a posição espacial das fontes acústicas (trabalhando em modo passivo, ou seja, em modo de escuta) e a posição dos objetos em um espaço de vigilância (trabalhando em modo ativo, ou seja, em modo radar acústico). As aplicações deste sistema são múltiplas, desde o mapeamento do ruído até a localização de objetos. Além disso, o papel inclui um conjunto de estudos de caso para as principais aplicações de uso para ambos os modos de operação.

Palavras-chave: ativo/passivo, baixo custo, matriz de microfone MEMS grande, imagem acústica.

1. INTRODUCTION

Nowadays, acoustic imaging is showing a great development. At present, acoustic images are associated with a wide variety of applications [1], such as non-destructive testing of materials, medical imaging, underwater imaging, SONAR, geophysical exploration, etc. Some of these applications are based on passive systems, which listen to the environment for sounds to be located. Other applications are based on active systems, on the basis of the SODAR (*Sound Detection and Ranging*) principle. These active systems send an acoustic signal and wait for its reflection on possible objects to be detected. Many of these systems are based on the use of arrays.

An array is an arranged set of identical sensors, excited in a specific manner [2]. By using beamforming techniques [3], the array beam pattern is electronically steered to different directions, allowing the discrimination of acoustic sources based on their position. Arrays of MEMS (*micro-electro-mechanical system*) microphones are composed of high-quality microphones with high SNR (*signal to noise ratio*), low power consumption, and high sensitivity [4]. These arrays are specially designed for acoustic source localization [5] applications, but they can also be used in DOA (*direction of arrival*) estimation [6], turbulence measurements [7], speech processing [8], identification of geometric dimensions and internal defects of structures [9], or acoustic imaging [10-11].

The authors of this paper have experience in designing [12] and developing acoustic imaging systems, based in acoustic arrays. Some of its applications are surveillance systems [13], Ambient Assisted Living [14], biometric identification systems [15], machinery fault detection [16], pedestrian detection [17], or distressed signals detection from a drone [18].

This paper presents a system that acquires and processes acoustic signals to obtain acoustic images. The acquisition task of the system can work in two modes: i) passive mode (i.e. listening mode), and ii) active mode (i.e. sodar mode). This system is based on a multi-platform framework, where each processing task can be interchanged between the different levels of the framework. Thus, the system can be adapted to different cost and mobility scenarios by means of its reconfigurable framework. As the applications of this system are manifold, this paper also includes different case studies of use for both modes of operation.

Section 2 introduces the description of the developed system, showing the different hardware platforms that compose the system, and the system features. Section 3 presents the results obtained on the system tests carried out on a set of case studies based on different applications. Finally, Section 4 contains the conclusions that authors have drawn on the basis of the obtained results.

2. SYSTEM DESCRIPTION

In this section, the hardware employed in the system is defined, and the processing algorithms to obtain an acoustic image using beamforming techniques are explained.

2.1 Hardware setup

2.1.1 Processing system

A sbRIO 96xx platform [19] has been selected as the base unit for this system. This platform belongs to the Reconfigurable Input-Output (RIO) family of devices from National Instruments that is oriented to sensors with nonstandard acquisition procedures, allowing low-level programming of the acquisition routines. A commercial solution was selected in order to reduce costs, as a solution based on a specifically designed hardware would be more expensive. Specifically, the sbRIO platform is an embedded single-board controller which incorporates a Xilinx FPGA and a multicore processor. The FPGA has 96 lines of digital input/output, which are used as the connection interface with the MEMS microphones of the array and in the clock generation and synchronization.

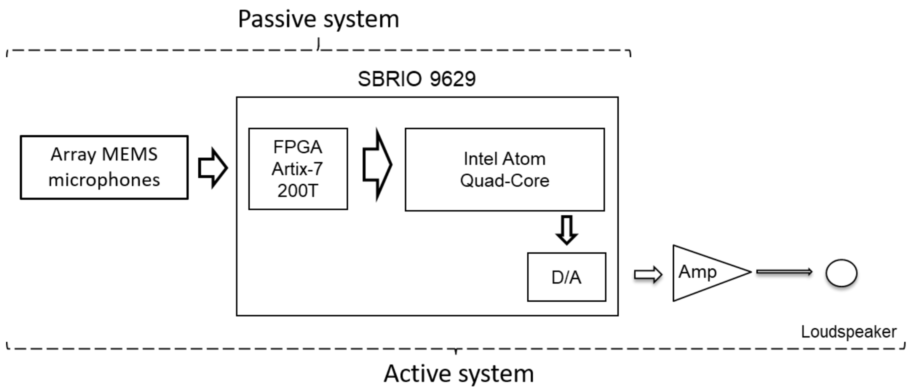


Figure 1: Hardware setup diagram.

The multicore processor is equipped with up to 2 GB of DDR3 RAM, 4G of built-in storage space, USB Host port, and Giga Ethernet port. Finally, it has sixteen 16-bit analog inputs and four 16-bit analog outputs, which are used to generate the transmitted signal used when the system works in its active mode.

The embedded processor included in a sbRIO is capable of running all the software algorithms to generate the acoustic images, so it can be used as a standalone array module formed by a sbRIO connected to a MEMS array board as shown in Figure 1.

2.1.2 MEMS array

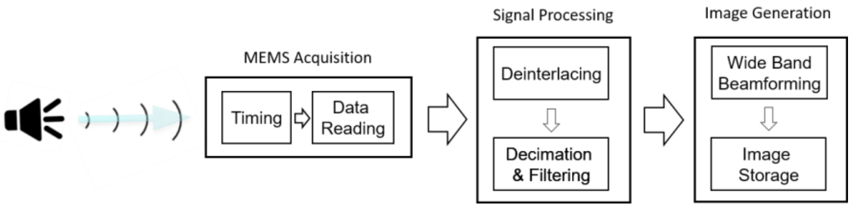
The acoustic images acquisition system presented in this paper is based on Uniform Planar Arrays (UPAs) of MEMS microphones, in order to obtain 3D position information.

In the design of a system for acquiring and processing signals from an acoustic array, costs and complexity are directly related to the number of channels/sensors of the system. A typical system to obtain acoustic images has four basic elements: sensors, signal conditioners, acquisition devices and signal processor. For the first three elements, system cost increases linearly with the number of channels, as each sensor needs a signal conditioner and an acquisition device. Digital MEMS microphones include a microphone, a signal conditioner, and an acquisition device incorporated in the chip itself. For this reason, an acquisition and processing system based on MEMS microphone arrays is reduced to two basic elements: MEMS microphones and a processing system. The integration of the microphone preamplifier and the ADC in a single chip significantly reduces costs, if compared with solutions based on analog microphones. This technology also reduces the space occupied by the system, which makes it feasible to build arrays with hundreds or even thousands of sensors.

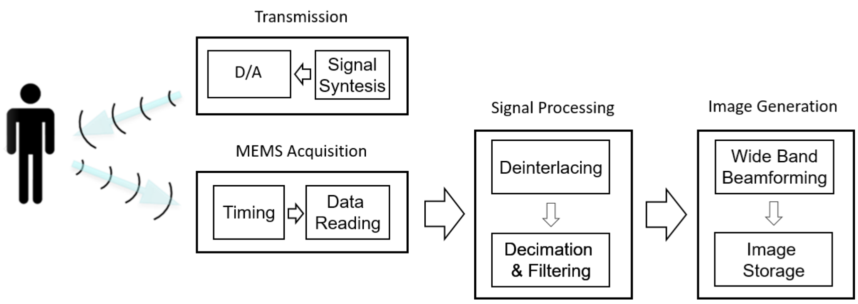
For the implementation of the arrays employed in the case studies, SPH0641LU4H-1 microphones of Knowles were chosen. They are digital MEMS microphones with a PDM (Pulse Density Modulation) interface and with a one-bit digital signal output [20]. The main features of these microphones are: high performance, low-power, omnidirectional response, 64.3 dB SNR, high sensitivity (−25 dBFS) and an almost flat frequency response (±2 dB in the range of 10kHz to 24kHz).

2.2 Software algorithms

The algorithms implemented in the system, shown in Figure 2, can be divided into four blocks: Transmission, MEMS Acquisition, Signal Processing and Image Generation. Figure 2a shows the blocks that are operative in the system's passive working mode, and Figure 2b shows the corresponding operative blocks in the system's active working mode.



(a) Passive mode.



(a) Active mode.

Figure 2: Software algorithms diagram.

The Transmission block generates a pulsed multi-tone signal through the DA converter to the signal amplifier, and from there to the loudspeaker, to transmit the signal. As can be observed in Figure 2, this block only operates if the system is working on its active mode.

In the Acquisition block, each MEMS microphone acquires the acoustic signal acquisition. As it is shown in Figure 2, if the system is working in the passive mode, the acoustic signal that the MEMS microphones acquire is generated by the environment where the system is working. Therefore, if the system is working in the active mode, the acoustic signal that the microphone acquire is the reflection of the signal transmitted by the own system. This Acquisition block is implemented in the FPGA, generating a common clock signal for all MEMS, and reading simultaneously all the sensors signals via the digital inputs of the FPGA.

In the Signal Processing block two routines are implemented:

- Deinterlacing: Through this process, one-bit signal from each MEMS microphone is extracted from each binary word.
- Decimate & Filtering: Applying downsampling techniques, based on decimation and filtering, an independent signal from each MEMS microphone are obtained and the sampling frequency is reduced.

Finally, in the Image Generation block, based on wideband beamforming, a set of N × N steering directions are defined, and the beam former output are assessed for each of these steering directions. Wideband beamforming [2] computes the FFT of the MEMS signals $x_i[n]$; multiplies, element by element, each FFT $X_i[k]$ by a phase vector, that depends on the steering direction and the sensor position; and finally takes the sum of the FFT shifted in phase, as shown in Figure 3. The images generated are then displayed and stored in the system.

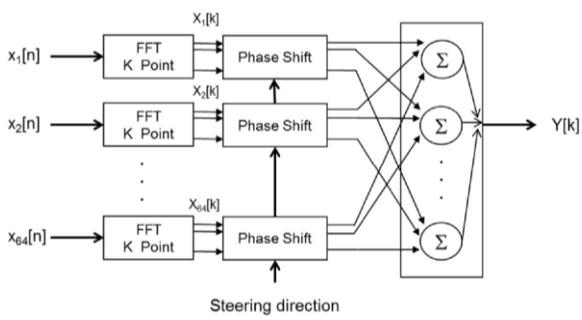


Figure 3: Wideband beamforming.

3. CASE STUDIES

This section presents two case studies using the system described on this paper. One of the cases shows the system working in its passive mode, and the other one shows an example of the system working in its active mode.

3.1 Case A: Passive mode

This case study presents the acquisition of acoustic images of a fan matrix, in order to detect if some of these fans were not working properly. These acoustic images were obtained using a planar array of MEMS microphones.

In this work, the specific MEMS array which was used was composed of 4 UPAs modules of 8×8 2.5cm-uniformly-spaced digital MEMS microphones, as shown in Figure 4. Thus, the acoustic signal acquisition is performed by a 16×16 array, i.e. by an array composed by 256 MEMS microphones. This acquisition system obtained acoustic images, in azimuth and elevation, of a 3×3 fan matrix, also shown in Figure 4. Each of the fans employed to build the fan matrix was a Foxconn D90SM-12 3-Pin with 7 blades. The fans of the matrix were controlled by a Kkmoon 8-channel relay interface board, which allowed turning on and off the fans of the matrix independently. As shown in Figure 4, for the tests, the fan matrix was placed 50cm opposite the 16×16 MEMS array, inside a 5m×3m×2.5m anechoic chamber.

In this case study, the tests simulated a faulty fan matrix with only one of the fans working each time. The acoustic images of the fan matrix working in these certain circumstances are shown in Figure 5. The acoustic images of each one of the 9 fans of the matrix running alone were obtained with using the array of MEMS microphones together with wideband beamforming techniques, using a work frequency of 1100Hz. For each fan, 1500 acoustic images were generated, in order to obtain 9 consistent averaged acoustic images, which are shown in Figure 5a. Analyzing these images, it can be observed that the center of each image seems to be placed in the same position of the matrix where the real fan is (x).

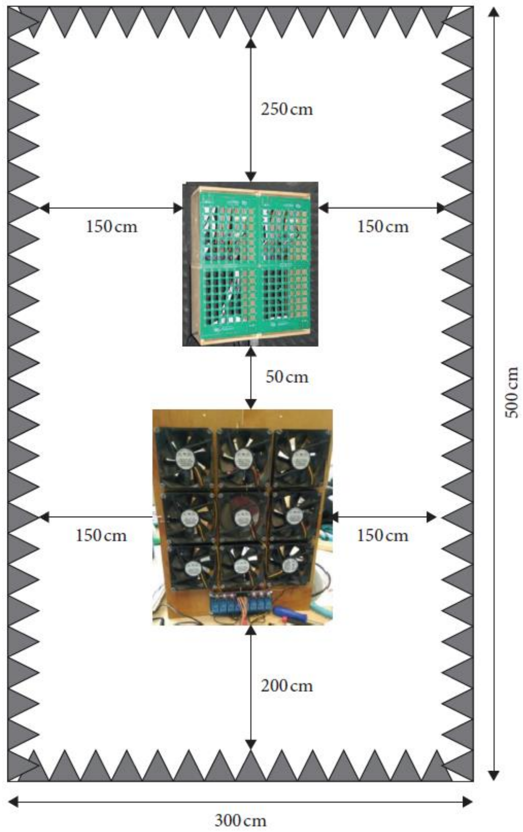
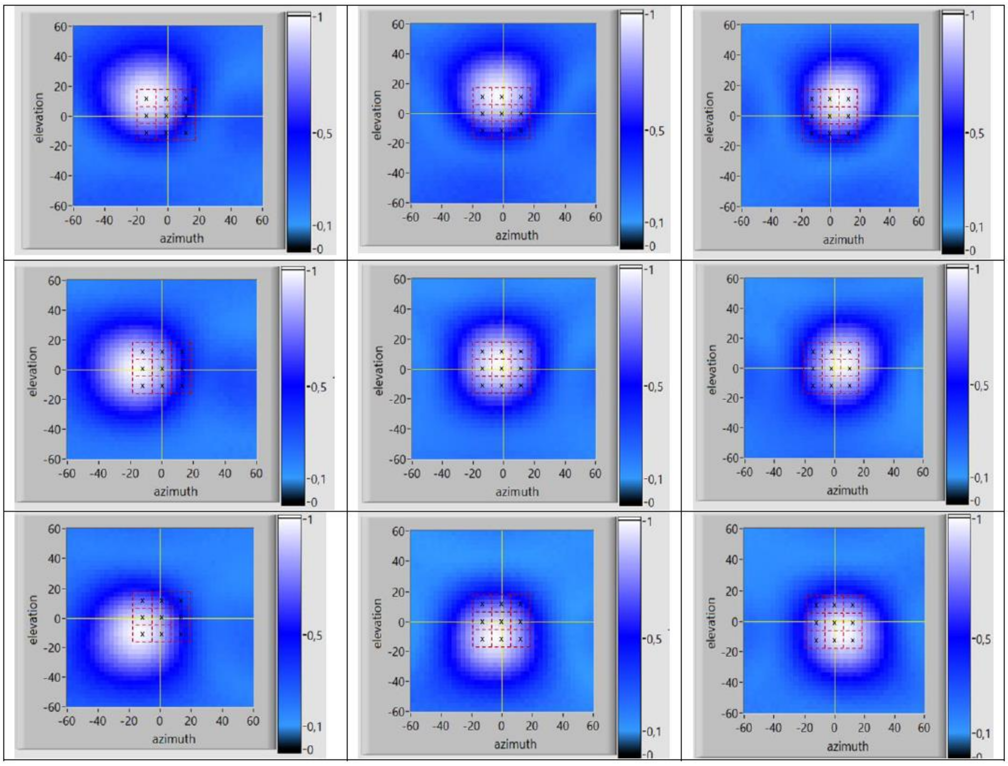


Figure 4: Experimental setup block diagram for the passive system.

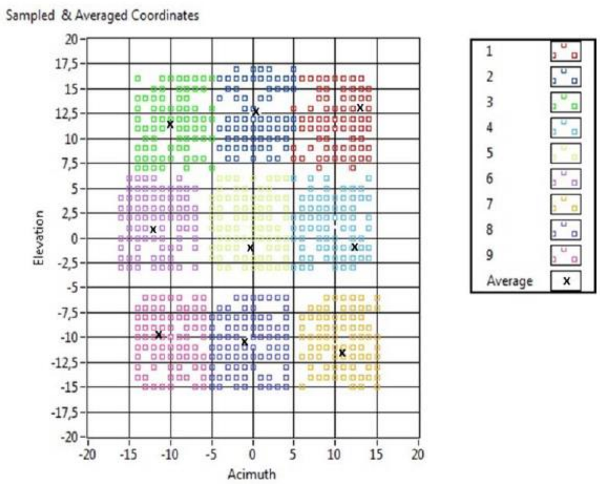
These centers are the ones of the averaged acoustic images. For each fan, the center of each of the 1500 acoustic images used to obtain the averaged one are shown in Figure 5b, where it can be observed that the centers of the acoustic images of each fan are scattered around the corresponding “averaged center”.

Thanks to the “averaged centers”, the positions of the fans in the matrix could be estimated. In Figure 7c, the “averaged centers” can be compared with the real ones. It can be observed that the estimated positions of the centers are rather near of the real ones, with errors lower than 2.5º. So, the averaged acoustic images of the fans could be used to estimate their positions.

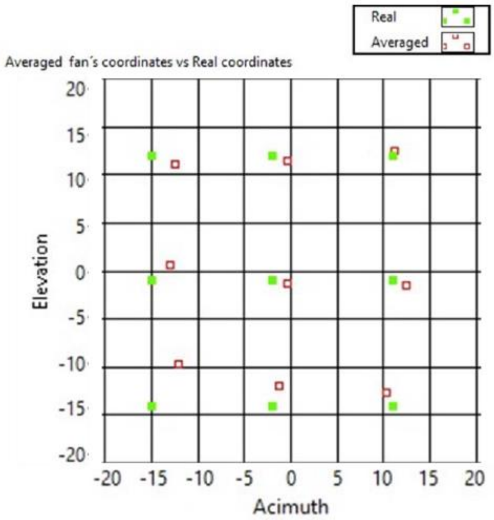
Geometrical parameters of these acoustic images for different frequencies were then used to train a machine learning algorithm, particularly a support vector machine (SVM) classifier, in order to detect the faulty fan.



(a)



(b)



(c)

Figure 5: (a) Acoustic images of the fan matrix with only each one of the fans running. (b) Calculated centers of the acoustic images of each fan of the matrix running alone. (c) Real vs. Estimated center coordinates

3.2 Case B: Active mode

This case study presents the acquisition of acoustic images of the environment in front of a vehicle, in order to detect if there are pedestrians in the vehicle path. These acoustic images were obtained using a planar array of MEMS microphones.

In this work, the specific MEMS array which was used was composed of 6 UPAs modules of 5×5 0.9cm-uniformly-spaced digital MEMS microphones, as shown in Figure 6. Thus, the acoustic signal acquisition is performed by a 5×30 array, i.e. by an array composed by 150 MEMS microphones.

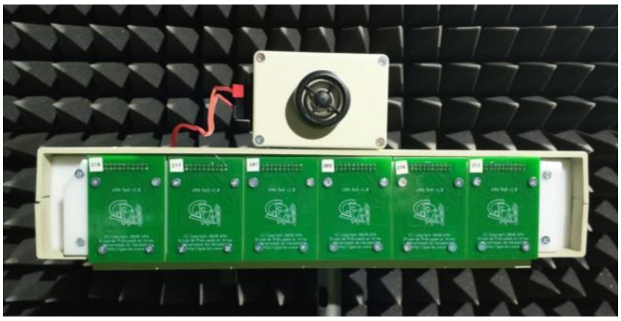


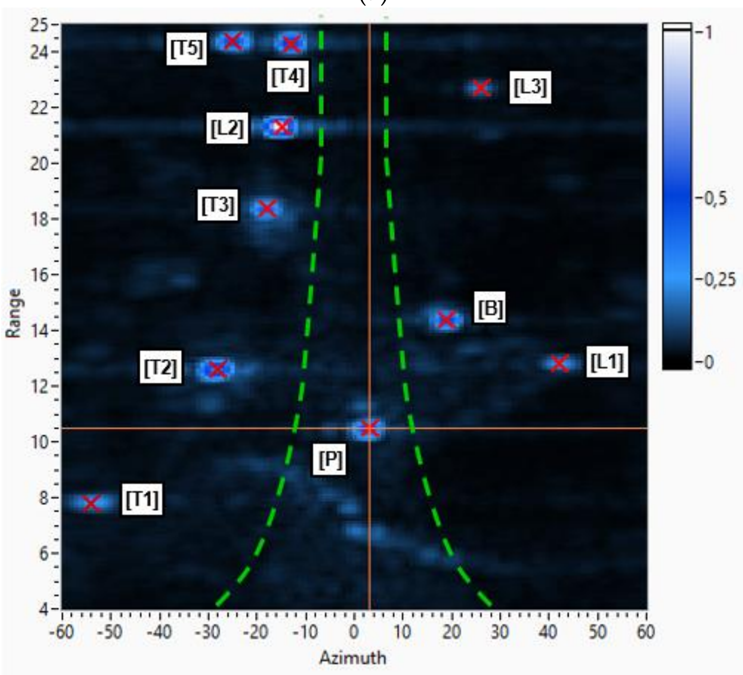
Figure 6: Active system MEMS array.

The transmitted signal was a 3ms pulse of 20kHz. It was generated with the tweeter loudspeaker, which is also shown in Figure 6.

In this case study, the horizontal dimension of the array was greater than the vertical one, since the coordinates of interest of the pedestrian's position were azimuth and range. In this case, elevation information, was not relevant.

For the tests, a compact vehicle was assumed, on a normal 4m-wide road, with street lamps and trees along its edges, as shown in Table 1. In the test scenario, a person was also placed 10m away from the acquisition system, as can be observed in Figure 7a

(**a**)



(**b**)

Figure 7: (a) Test scenario. (b) Acoustic image with detected targets.

Table 1: Position of the targets on the test scenario.

ID	Target	Range [m]	Azimuth [º]
T1	Tree	7.8	-51
P	Pedestrian	10.5	3
T2	Tree	12.6	-28
L1	Lamppost	12.8	42
B	Bin	14.4	19
T3	Tree	18.3	-18
L2	Lamppost	21.3	-15
L3	Lamppost	22.7	26
T4	Tree	24.3	-13
T5	Tree	24.4	-25

Figure 7b represents an example of the obtained acoustic images in azimuth/range space. In the image, the red crosses represent the detected targets. It is clear that the system detected both the person, placed at around 10m, and other objects in front of it, such as the lampposts and the trees on the roadside.

In Figure 7b, it can also be visualized the lane boundaries, represented by a dashed green line. Most of the detected targets were outside the road lane and should therefore not be taken into consideration in subsequent detection work. In this case, only the pedestrian would remain as a detected target.

4. CONCLUSIONS

This work presents an acoustic signal acquisition and processing system which obtains high resolution acoustic images using beamforming techniques.

The acoustic acquisition system is based on large arrays of MEMS microphones. On the other hand, the processing part of the system, on the other hand, is based in multicore processors and FPGAs.

With some examples it has been shown that the system can work both in a passive or in an active mode. The system is able to obtain the spatial position of acoustic sources when it is working in passive mode, and the objects position in a surveillance space if it is working in active mode.

5. ACKNOWLEDGEMENTS

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