APPLYING PDC FOR THE RECOGNITION OF FIREARM'S CALIBRE

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Abstract— Nowadays, there has been an enormous increase in audio recordings, some of these of the interest of audio forensics. Audio forensics has been used in many different ways for recognising firearm's calibres. In this work, we use Partial Directed Coherence (PDC) on recordings of capsules hitting the ground to recognise the firearm's calibre. Six different calibres were recorded in a controlled environment, and these audios were cut to have the same size. These audios were analysed using PDC. The results show that the audios of the calibres are orthogonal; thus, for this experiment being impossible to get a false positive while using the proposed methodology.

Keywords— Calibre, Recognition, PDC

1 Introduction

Nowadays, handheld devices capable of multimedia recording are everywhere, above all in the form of smartphones. That quasi ubiquity comes generating a significant amount of audio recordings, some of them inevitably of forensic interesting - for example, an unpretentious audio recording that timely registers a pistol shot followed by a tinkling in the floor of the ejected cartridge.

Audio forensics refers to the analysis, acquisition and evaluation of audio recordings admissible to a court of law as forensic evidence. It is typically used to verify the authenticity and integrity of audio evidence, enhancement of audio recording improving speech intelligibility and audibility of low-level sounds, and speaker identification (Khan et al., 2018; Zakariah et al., 2018).

Despite the fact that these are the primary uses of audio forensics, with the increase of use of firearms in crimes (Manley et al., 2019; Maher, 2007) (in Brazil the increase was of 27.4% from 2006 to 2016 (Ipea, 2018)) and in the military in the last few years combined with the increase of audio recordings with crimes (Larrain et al., 2015) the techniques of audio forensics adapted to new types of scenarios. Thus, recently, several acoustical detection, location and classification systems for gunshot sounds (Maher, 2007) have been developed. These systems usually use the muzzle blast, or the acoustical shock wave or both (Thumwarin et al., 2014; Mäkinen e Pertilä, 2010; Maher, 2006) as the basis of its analysis. One example of these systems is presented in the work of Thuwarin et al. (2014), where they use the gunshot blast to identify the calibre of the firearm by recognising the gum. A different example would be the work of Mäkinen and Pertilä (2010) in which they use the firing sound and the shock wave to estimate the shooter location and the bullet trajectory, calibre and speed.

Going through the road not taken, Larrain et al. (2015) created a system to identify the firearm calibre using the acoustical signature of the ejected cartridge case inspired by acoustic physics concepts, such as resonance of the capsule. They applied their system to audios of four different calibres in a controlled environment and 339 gunshots recordings extracted from YouTube and obtained a 75% rate of precision of identification. Following their lead, in this work, the Partial Directed Coherence (PDC) was used to recognise the calibre of the firearm by its capsule sound on hitting the ground.

This paper is organised as follows, in Section 2 the theory behind our method is presented, in Section 3 the procedure of the analysis and the signal acquirement is described in detail, in Section 4 the results are shown and discussed and, finally, in Section 5 the conclusions are presented.

2 Theory

In this section, the theory behind this work is approached on the following subsections.

2.1 Partial Directed Coherence (PDC)

Partial Directed Coherence is a frequency-domain approach to describe the direction of information flow between multivariate time signals using the decomposition of multivariate partial coherences computed from autoregressive models (Baccalá e Sameshima, 2001). This concept is a frequency-domain approach of Granger Causality.

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Given a set of N signals $\mathbf{X}[n] = [\mathbf{x}_1[n], x_2[n], \ldots, x_N[n]]$, the AR representation is

$$\mathbf{X}[n] = \sum_{r=1}^{p} \mathbf{A}_r \mathbf{X}[n-r] + \mathbf{E}[n], \quad (1)$$

being p the order of autoregressive equation, A_r representing the coefficients matrix and $E[n]$ the noise matrix. The a_{ij} elements of $\mathbf{A_r}$ represents the linear interaction effect of $x_j(n-r)$ towards $x_i(n)$.

The coefficients matrix $\mathbf{A_r}$ is transformed into $\mathbf{A}(f)$ by

$$\mathbf{A}(f) = \sum_{r=1}^{p} \mathbf{A_r} e^{-ir2\pi f}, \quad (2)$$

and the joint spectral density is obtained by

$$\overline{\mathbf{A}}^{-1}(f) = (\mathbf{I} - \mathbf{A}(f))^{-1} \quad (3)$$

The PDC from j to i is given by

$$\overline{\pi}_{ij}(f) = \frac{\overline{A}_{ij}(f)}{\sqrt{\overline{\mathbf{a}}_j^H(f)\overline{\mathbf{a}}_j(f)}}, \quad (4)$$

where $\overline{A}_{ij}(f)$ is the i, jth element of $\overline{\mathbf{A}}(f)$. Equation 4 represents the relative interaction strengths between signals if adopting the following normalization properties hold:

$$0 \le |\overline{\pi}_{ij}(f)|^2 \le 1 \quad (5)$$

and

$$\sum_{i=1}^{N} |\overline{\pi}_{ij}(f)|^2 = 1, \quad (6)$$

for all $1 \le j \le N$.

2.2 Hilbert Space

A Hilbert Space is a complete pre-Hilbert space, where a pre-Hilbert space is a complex vector space $\mathscr{P}$ in which for each pair of vectors x, y of $\mathscr{P}$ there is a scalar product $(x|y)$ of x and y that is a complex number and obeys these rules:

1. $(y|x) = (x|y)^*$
2. $(x+y|z) = (x|z) + (y|z)$
3. $(\lambda|y) = \lambda(x|y)$
4. $(x|x) > 0$ when $x \neq \theta$

where θ is the zero vector and x and y can be functions having scalar values defined on a set $\mathscr{J}$ where $x = y$ when $x(t) = y(t)$, $\forall t \in \mathscr{J}$, and the functions θ, $-x$, $x+y$ and λx are defined by the formulas:

1. $\theta(t) = 0$
2. $(-x)(t) = -x(t)$
3. $(x+y)(t) = x(t) + y(t)$
4. $(\lambda x)(t) = \lambda x(t)$

thus being an vector space of scalar-valued functions on $\mathscr{J}$ (Berberian, 1961).

3 Material and Methods

This work can be divided into three parts: audio acquisition, pre-processing and analysis. Considering that, the following subsections describe in detail the evaluation of the proposed methodology and how each of these three parts was done.

3.1 Resources

The algorithms were implemented using a Jupyter Notebook interface for Python3. Scientific computation packages such as Numpy (Oliphant, 2006), Matplotlib (Hunter, 2007) and Connectivipy (Krzemiński e Kamiński, 2017) aid the algorithms.

The codes were run on a notebook with Intel (R) Core i3 M350 2.27GHz processor, 4Gb RAM and Linux Lite 4.0 operating system.

3.2 Simulation

To evaluate and exemplify, the proposed methodology was applied to analyse two signals $x_1(n)$ and $x_2(n)$ given by the equations 7 and 8 respectively

$$x_1(n) = 0.9x_1(n-1) - 0.5x_1(n-2) + e_1, \quad (7)$$

$$\begin{aligned} x_2(n) =& 0.8x_2(n-1) - 0.5x_2(n-2) + \\ & 0.16x_1(n-1) - 0.2x_1(n-2) + e_2, \end{aligned} \quad (8)$$

with $var(e_1) = 1$, $var(e_2) = 0.7$ and $cov(e_1, e_2) = 0.4$.

3.3 Acquisition

The audio acquisition was made in a controlled indoor environment. The room was 3m × 3m. Each of the capsules was dropped from a 1m height. Meanwhile, the handheld audio recorder was positioned at the height of 1.1m from the ground. The used handheld recorder was the TASCAM DR-05X[1] with a sampling rate of 44100 samples/s. The capsules used where .380, 9mm, .40, .45, 5.56 and 7.62 calibre. They were dropped in this order twice using the setup described.

[1] https://tascam.com/us/product/dr-05x/top

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3.4 Pre-processing

For the audio analysis, the audio had to be aligned to the start of the sound of the capsule. This way, the silence time before would not affect the analysis. The signals also needed to have the same length, to achieve that it a window size of 20.000 samples that was big enough to fit the first sound of the capsules was defined. This separation is shown in Figure 1.

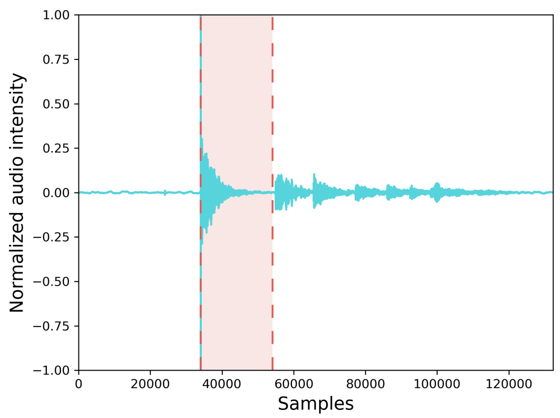

Figure 1: Plot of one of the capsules sound. The shaded region between the dashed lines is the region used for the analysis. This region was separated in the pre-processing.

3.5 Analysis

The analysis of the selected regions was done applying the PDC for the firsts audios of all the six capsules. After that, the PDC was applied for the second audio of the capsules comparing with the first audios.

4 Results and Discussion

The PDC of the theoretical signals used to evaluate the methodology is given in Figure 2.

Analysing the figure 2, it becomes clear that there is an interaction from x_1 to x_2, but there is not an interaction from x_2 to x_1. In addition to that, the results show strong interaction from x_1 to x_1 and from x_2 to x_2, which was expected.

For the PDC of all the firsts audios of all the six capsules, Figure 3 was obtained. From it, it is clear that no capsule calibre has an effect on another on both ways, thus showing us that if you consider the sounds of the capsules as vectors in a Hilbert Space these vectors are orthogonal, which means that it is impossible to have a false positive on the identification using PDC.

The results for the PDC of two of the second audios with one of the first can be seen in Figures 4 and 5. This result confirms what was noted on the previous result that using PDC, it is impossible to

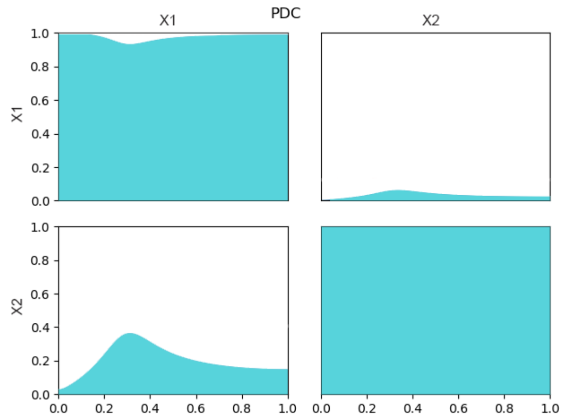

Figure 2: Example of PDC of the signals x_1 and x_2.

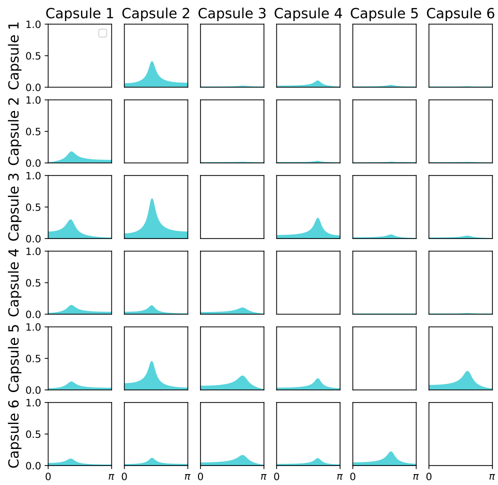

Figure 3: Result of the PDC applied to the firsts sounds of the capsules.

misjudge, which is the calibre of the capsule as the PDC is only maximum to the correct capsule.

5 Conclusion

From the results obtained, it is possible to conclude that the analysis using PDC is very useful for the identification of bullet calibre by the sound of the capsule hitting the ground.

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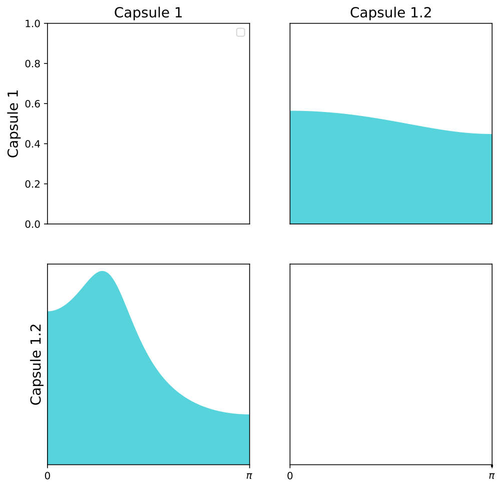

Figure 4: Result of the PDC applied to the first sound of capsule one and the second sound of capsule one.

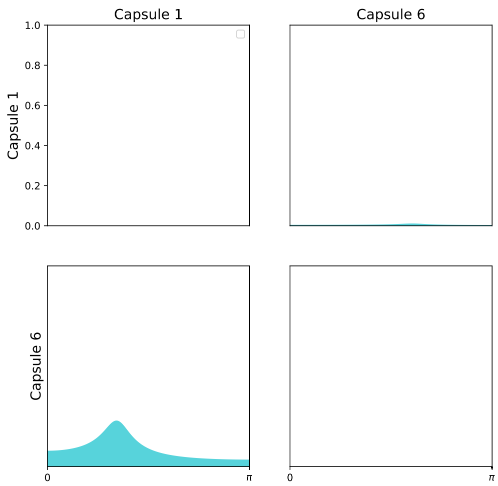

Figure 5: Result of the PDC applied to the first sound of capsule one and the second sound of capsule six.

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