Smart sound meter for shooting noise monitoring

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Summary
Shooting is a very wide-spread recreational activity but also a source of noise pollution when practiced in outdoor facilities. The annoyance due to such shooting ranges can be reduced by limiting the number of shots. However, the maximum number of shots accepted during a period of time for not exceeding the noise limit defined by the local legislation highly depends on meteorological conditions. In this context, this paper proposes an automatic gunshot detection using a correlation threshold method as part of a noise monitoring system. The detection method is applied on real life audio recordings. As noise measurements are usually performed at several hundred meters from the source, shooting noise levels can be of the same magnitude as other environmental noises (singing birds, barking dogs, cars,...). Results are thus discussed from the point of view of limited false detection rates and reliable annoyance assessment.

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1. Introduction

Gunshot sounds are basically caused by the high pressure combustion gases rapidly expanding when a bullet is propelled from the barrel (muzzle blast). This results in an impulsive and high amplitude acoustic wave. When the bullet travels at supersonic speed, an acoustic shock wave is also produced. Shooting noise is therefore especially annoying and can be heard up to several kilometers.

Outdoor shooting activities, such as ball-trap, are thus an important source of noise pollution.To deal with the annoyance in the neighborhood, civil shooting ranges are subject to regulations that limit the acoustic load due to all detonations recorded during a period of time, which amounts to limiting the number of shots during this time period (usually one hour).

However, meteorological conditions significantly affect the sound propagation. In a previous study [1], we have noted a mean difference of 12 dB between noise annoyance levels measured at the same place but with very different wind directions. So, the maximum number of shots accepted during the reference time period for not exceeding the noise limit defined by the local legislation can significantly vary from one day to another.

As a result, it's very difficult for managers of shooting clubs to combine cost-effectiveness with respect of environmental standards. Moreover, occasional police controls can be non-representative of the overall situation and lead to unfair sanctions.

In this context, a monitoring system able to compute in near real-time the noise annoyance level and generating an alarm when limit is exceeded is developed. This system needs to be able to estimate the noise annoyance level with a comparable accuracy to manual analysis with no expensive computational cost.

In the literature, gunshot detection is often addressed in the context of audio events detection for surveillance or security applications. Typical audio-based surveillance systems is made up of a detection module followed by a classification step. A presentation and comparison of different detection methods as well as recognition techniques of impulsive sounds can be found in [2]. Each of the four recognition techniques (Bayesian classifier, Gaussian Mixtures Model (GMM), Hidden Markov Model (HMM) and Multi-Layer Perceptron) was tested with different signal features (e.g. spectrograms, Linear Predictive Coding (LPC), Mel-frequency cepstral coefficients (MFCC), ...) at different SNR levels. In the specific context of gunshot detection, studies of other features and/or classifiers can also be found in [3, 4].

More recently, a comparative study of 6 algorithms of gunshot detection with low computational cost has been presented in [5]. It concludes that the detection method based on correlation against a template presents the best performances. This method has also been compared to more complex methods using HMM with LPC, MFCC and impulsivity parameter in [6]. Even in noisy environments, the correlation against template gives the good results.

Considering these last results, this paper presents an experimental study of an automatic gunshot detection using a correlation method applied to real-life audio recordings.

This paper is organized as follows : Section 2 presents the shooting noise annoyance assessment procedure and the noise monitoring architecture; Section 3 describes the detection scheme; the experimental results are analyzed in Section 4 and conclusions are discussed in Section 5.

2. Shooting noise annoyance assessment and monitoring

ISO 1996 international standard [7, 8] defines the procedures for the measurement and assessment of environmental noise.

It recommends the use of the sound exposure level L_E to describe isolated events and the equivalent continuous sound level measured over the time period T_n as rating level L_{Ar,T_n}. T_n is generally fixed to one hour. Correction factors can be added to L_E according to source types, noise characteristics or time of the day. For high impulsive noise such as small caliber firearm, a penalty of 12 dB is recommended. Except for high energy impulsive noise, the A-frequency weighting shall be used. All these guidelines are in accordance with literature [9, 10].

Mathematically we have

$$L_{Ar,T_n} = 10\ log_{10} \left[\frac{1}{T_n} \sum_{j}^{n_t} 10^{0.1\ L_{AE_j}} \right] + K \quad (1)$$

where L_{AE_j} is the exposure level of the j^{th} shot, K is the penalty of 12 dB and n_t is the number of shots recorded during the measurement period T_n.

In practice, shots are spotted on continuous equivalent levels recordings (integration period T less than 1s) and the exposure levels are calculated by

$$L_{AE_j} = 10\ log_{10} \left[T \sum_{i=1}^{n_i} 10^{0.1\ L_{Aeq,T,ji}} \right] \quad (2)$$

where $L_{Aeq,T,ji}$ is the i^{th} $L_{Aeq,T}$ of th j^{th} shot measured with time integration T.

Each country or region can establish its own regulation. Usually, the rating level is a continuous equivalent level as stated in the ISO standard. However, many countries use, for historical reasons, maximum A-levels (with I or F time-weighting) to characterized each detonation. The conversions between L_{AE} and $L_{AI,max}$ or $L_{AF,max}$ are based on empirical relationships [11]. Depending on the distance between the source and measurement point, this can lead to significant difference between rating levels based on maximum levels and equation 1.

In the rest of this paper, the shooting noise annoyance will be assessed according to the ISO standard.

At each moment, by knowing the shooting noise rating level and the number of shots during the past hour, the mean noise exposure level of a detonation and the corresponding number of shots authorized per time period T_n can be estimated. With this information, the shooting club manager can adapt the number of shooters or temporally suspend shooting to stay under the noise limit.

3. Data sets description

Detection is performed on audio files recorded with a class 1 sound level meter together with continuous equivalent levels with 50ms time integration period ($L_{Aeq,50ms}$). We use data from two different noise measurement campaigns around outdoor shooting ranges. During the first campaign, noise was measured at two different places at the same time (Datasets 1 and 2) while during the second, noise was assessed at the same place during two consecutive time periods (Datasets 3 and 4). Table I summaries the measurement conditions. For each dataset, a manual analysis of the $L_{Aeq,50ms}$ is performed to localize the shots and derive the shooting noise rating level (except for dataset 1). The outcomes of this analysis are used as reference for the validation step.

All audio signals were sampled at 48 kHz and a A-weighting filter was applied to suppressed low frequency background noise.

4. Gunshot detection scheme

The proposed detection scheme relies on a correlation threshold method. Audio files are divided in time sequence of 0.3s corresponding to the minimal time difference between to detonations. A shorter value would lead to redundant detections of the same detonation. Each frame is then cross-correlated with a gunshot template, giving a measure of the similarity between the signals and the delay between them. The cross-correlation is performed on z-score normalized signals If the maximum of the cross-correlation sequence is greater then a threshold, the frame is labeled as a gunshot and its precise beginning is determined by the given delay.

Table I. Measurement conditions

Dataset	Duration (min)	Distance from the source (m)	Number of shots	Other noises
1	17	100	159	-
2	18	700	159	Traffic noise
3	29.5	700	218	Some cars, barking dogs, singing birds
4	19.5	700	240	Idem Set3

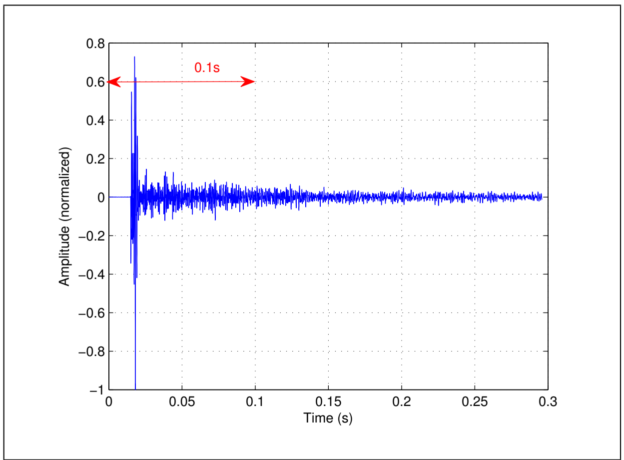

Figure 1. Typical detonation signal recorded at +/- 100 m from the source

The exposure level can then be calculated for each shot and the rating level is derived considering a one hour sliding window.

4.1. Template choice

Using the timestamps coming from the manual analysis, the signal portions containing detonations are extracted. Signal duration is set to 0.3s. Detonations are then aligned according to the position of the absolute maximal value. The template is obtained by averaging the aligned detonation signals and only retaining the first 0.1s of the signal. This duration corresponds to the most relevant part of the signal (Figure 1).

4.2. Threshold optimization

As suggested in [5], the true positive rate TPR and the false positive rate FPR are calculated for various threshold values. TPR and FPR are defined as follows :

$$TPR = \frac{\text{True positive frames detected}}{\text{Total number of positive frames}} \quad (3)$$

$$FPR = \frac{\text{False positive frames detected}}{\text{Total number of negative frames}} \quad (4)$$

where the total number of positive and negative frames is defined using the manual analysis.

The optimal threshold is chosen as the one that minimize the euclidean distance between the corresponding pair (TPR,FPR) the perfect detector (1,0).

5. Experimental Results

5.1. First measurement campaign

Firstly, simple validation of the method is performed on datasets 1 and 2 separately. For each set, a template is derived and the same data are used for the validation step. Very good results (see Table II) are obtained in both cases, with no missed detonation in the first and only two in the second. The false positive gunshot detections correspond to frames beginning during a detonation.

In a second time, we investigate the opportunity of using the detection scheme at one place with a template derived from measurements at another one. The template extracted from dataset 1 is used with dataset 2 (with an adaptation of the threshold). The results are less good regarding the detection performances but the rating levels derived for dataset 2 with both templates are very close to the reference value (Table III). Indeed, as one can see in Figure 2, sound exposure levels of most false positive gunshots are significantly lower than true positive ones. In this case, the monitoring systems correctly estimate the rating level but not the effective number of gunshots.

5.2. Second measurement campaign

A template is derived from dataset 3 and used with dataset 3 for simple validation and with dataset 4 for cross-validation (without threshold adaptation). Results are summarized in Table IV. For simple validation, nearly all the detonations were detected but a significant number of false positives appears. As previous, a part of them is due to detonations occurring on the border between two frames but other sounds like barking dogs and singing birds were also detected as gunshots. As previous, the noise rating level is not affected by these (see Table V) but gunshots number is not correct. The cross-validation leads to similar results although more detonations were not detected.

Table II. First measurement campaign - Confusion matrices : rows correspond to detection outcomes and columns to the reference classification

Set 1 **Template Set 1**	Gunshot	Not a gunshot
Gunshot	159	5
Not a gunshot	0	3236
Set 2 **Template Set 2**	Gunshot	Not a gunshot
Gunshot	157	6
Not a gunshot	2	3435
Set 2 **Template Set 1**	Gunshot	Not a gunshot
Gunshot	140	420
Not a gunshot	19	3021

Table III. Comparison of rating levels - First measurement campaign

L_{Ar} **(dBA)**	Automatic detection	Reference
Set 2 Template Set 2	58.2	58.6
Set 2 Template Set 1	58.5	58.6

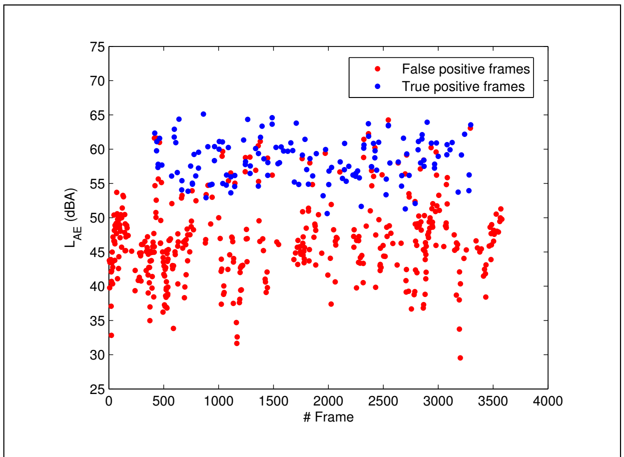

Figure 2. Exposure levels of gunshots detected in dataset 2 with template from dataset 1 (True positives in blue and false positives in red)

6. Conclusions

The proposed gunshot detection scheme uses a threshold on the correlation against a template derived from real-life audio recordings and labels audio segments as "gunshot" or "not a gunshot". The gunshot segments are then used to compute noise rating levels. Good results were obtained in terms of noise annoyance assessment but the presence of false positive detections lead to overestimated number of gunshots. In future work accent will be put on the rejection of false positives.

Table IV. Second measurement campaign - Confusion matrices : rows correspond to detection outcomes and columns to the reference classification

Set 3 **Template Set 3**	Gunshot	Not a gunshot
Gunshot	216	116
Not a gunshot	2	5569
Set 4 **Template Set 3**	Gunshot	Not a gunshot
Gunshot	225	118
Not a gunshot	14	3543

Table V. Comparison of rating levels - Second measurement campaign

L_{Ar} **(dBA)**	Automatic detection	Reference
Set 2	48.6	48.3
Set 3	47.6	47.2

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