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***Abstract*—Estimating the direction of arrival (DoA) of an audio signal from an aerial platform gives way to estimating the source localization. This paper addresses the problem of airborne shooter localization using a microphone array mounted on a drone. In this scenario, the noise of the propellers poses a great level of difficulty in estimating the DoA of the gunshot signals owing to low levels of SNR. This, combined with the fact that a moving drone records multiple gunshots at different positions, have discouraged the use of drones for shooter localization. Based on real gunshot signals recorded at a shooting site, we explore the advantages and limitations of using a drone for the task of audio surveillance and gunshot detection and localization.**

I. Introduction

Shooter localization is a topic that has attracted the attention of many researchers in the recent decades. Owing to the great number of situations where these devices can be used, e.g., civil protection, law enforcement, and support to soldiers in missions where snipers might pose a serious threat, the search for new possibilities and improvements is not showing any sign of fading away anytime soon. These devices can be based on the processing of either electromagnetic or acoustic signatures associated with the firing of a gun, or even a combination of both [1]. Yet, acoustic sniper localization systems [1] that estimates the shooter's position based on the estimation of the direction-of-arrival (DoA) of the muzzle blast and the shockwave are particularly attractive because of their quick response, usually within a fraction of a second, and the possibility to be used on both ground- and aerial-based platforms.

One of the main challenges when designing acoustic shooter localization systems is the problem posed by multipath propagation which is particularly important if the device is to be used in urban environments [2]. This issue can be significantly mitigated if airborne sensing is used as opposed to ground-based sensing as proposed in [3], where the acoustic sensors are deployed on an aerial balloon. Although effective in terms of mitigating the multipath propagation problem, the aerial balloon based solution does not meet today's challenges when it comes to cost efficiency and mobility. Owing to recent advances in modern technology, drone based solutions as the one proposed in [4] have become a feasible option and can be produced in large scale at a relatively low cost.

However, the use of drones in this application brings a new complication by worsening the SNR of the signals of interest caused mainly by the noise from the propellers. Therefore, the use of signal enhancement techniques such as adaptive filtering, spectral subtraction, and median filtering [5], [6], [7], [8], may be needed to improve the SNR prior to applying the algorithms for DoA estimation. A preliminary discussion on this issue has been presented in [4]. However, having an estimate of the DoA of the muzzle blast and of the shockwave may not be enough to pinpoint shooter's location. Further geometrical calculations are required which are dependent on the method that is used. Some require both DoAs of the shockwave and the muzzle blast to be available [9], [10], while others might require only one of them. An example is the method proposed in [11] that relies on the estimation of the DoA of the muzzle blast only, but the signal must be captured from an elevated platform and requires a digital map to estimate the intersection point of the estimated angles (azimuth and zenith) with the ground surface.

This paper addresses the problem of airborne shooter localization relying on the detection of the muzzle blast only using an array of microphones mounted on a drone. The muzzle blast is a consequence of the sudden expansion of gas following the explosion in the gun barrel. The generated acoustic energy is directly proportional to the volume of gas flow rate (volume velocity) at the source and propagates at the speed of sound.

Although the acoustic energy radiates in all directions, the sound pressure is highest in the direction the gun barrel is pointing to [12]. The angular peak overpressure (radiation pattern) is, therefore, a function of the azimuth angle, ϕ, measured with respect to the line-of-fire. One of the proposed models for the angular peak overpressure is given by [13]

$$p(\phi) = P_{0^o}\left[1 - \frac{P_{0^o} - P_{180^o}}{P_{0^o}}\sin\left(\frac{\phi}{2}\right)\right], \tag{1}$$

where P_{0^o} and P_{180^o} are the peak forward and rear pressures, respectively. Figure 1 illustrates the radiation pattern given by this model when P_{0^o} and P_{180^o} are set to 200 Pa and 120 Pa, respectively. Here we see that, despite the fact that multipath propagation is less of a problem in aerial gunshot detection, it is also true that the energy of the muzzle blast that reaches the microphones is also less. In this work, we assumed that the array of sensors may be moving and that the shooter's position is estimated using bearings-only target motion analysis (BO-TMA) techniques.

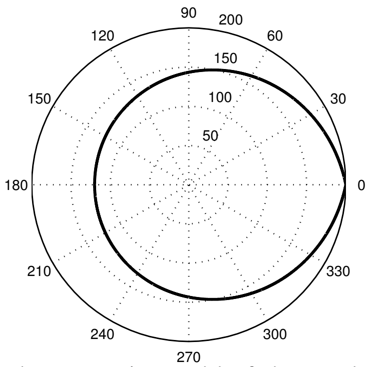

Fig. 1. Angular propagation model of the muzzle blast peak overpressure. Pressure values are in Pascal (Pa).

The paper is organized as follows. Section II provides a brief description of DoA estimation and TMA techniques, Section III discusses experimental results, while conclusions are presented in Section IV.

II. DOA ESTIMATION AND TMA

A. Direction of arrival estimation

Many methods have been proposed to tackle the DoA estimation problem [14]. DoA estimation algorithms can be classified in three groups: 1) based on Time Difference of Arrival (TDoA). TDoA is mostly estimated by cross-correlation. 2) Steered Response Power, by steering out beams and finding high energy sound sources. 3) Eigenvalue based algorithms such as MUltiple SIgnal Classification (MUSIC). The TDoA-based algorithms have small computational complexity which helps the feasibility of a real-time solution. In order to make robust TDoA estimations, the correlations can be filtered as in the generalized cross correlation algorithm PHAse Transform (GCC-PHAT) [15] which is used in this work.

Some algorithms try to improve DoA estimation by selecting a subgroup of cross-correlations. This makes possible spurious signals to be discarded. For instance, Iterative Least Squares (ILS) algorithm discards iteratively cross correlations of channels of an array until a given subset of pairs remains [16]. The Exhaustive Search (ES) is another approach that selects a subset of n pairs of microphones: in this case, it evaluates the least-squares cost function yielded by all possible n cross-correlations and chooses the combination that corresponds to the least one [17]. Due to previous results on DoA estimation of gunshot signals collected by a quadcopter [4], the exhaustive search algorithm is used in this work.

B. Target motion analysis

Target motion analysis (TMA) is a process to determine the position $\mathbf{p}$ of a target using passive sensor information, from an array of microphones in our case. The set of signals required in this process is the noisy bearings of the shooter (estimated using the exhaustive search algorithm) and the quadcopter array positions (observer positions) measurements over a finite time interval. In this work, we have available the noisy bearings $\hat{\theta}_k$, $1 \le k \le N$, estimated in different observer positions $\mathbf{r}_k$, thus the BO-TMA [18] is used.

Passive BO-TMA has been studied since the sixties [19]. Many bearings-only algorithms have been proposed. Orthogonal vectors, linear least-squares, and total least squares are examples of methods that deal with this nonlinear estimation problem. Under the assumption that the bearings errors are very small, i.e. $\hat{\theta}_k - \theta_k \approx 0$, the linear least-squares (also known as the Stansfield solution) closed form solution is given by

$$\hat{\mathbf{p}}_{\mathbf{LS}} = (\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{b}, \tag{2}$$

where $N \times 2$ matrix $\mathbf{A}$ is defined as

$$\mathbf{A} = \left[\begin{array}{cccc} \mathbf{a}_1 & \mathbf{a}_2 & \cdots & \mathbf{a}_N \end{array} \right]^{\mathrm{T}}, \tag{3}$$

$\mathbf{a}_k$ being

$$\mathbf{a}_k = \left[\begin{array}{c} \sin\hat{\theta}_k \\ -\cos\hat{\theta}_k \end{array} \right], k = 1, \dots, N \tag{4}$$

$\mathbf{W}$ the $N \times N$ diagonal weighting matrix given by

$$\mathbf{W} = \left[\begin{array}{cccc} d_1^2\sigma_{n_1}^2 & & & \mathbf{0} \\ & d_2^2\sigma_{n_2}^2 & & \\ & & \ddots & \\ \mathbf{0} & & & d_N^2\sigma_{n_N}^2 \end{array} \right], \tag{5}$$

and the $N \times 1$ vector $\mathbf{b}$ is defined as

$$\mathbf{b} = \left[\begin{array}{cccc} \mathbf{a}_1^{\mathrm{T}}\mathbf{r}_1 & \mathbf{a}_2^{\mathrm{T}}\mathbf{r}_2 & \cdots & \mathbf{a}_N^{\mathrm{T}}\mathbf{r}_N \end{array} \right]^{\mathrm{T}}, \tag{6}$$

with $\mathbf{r}_k$ being defined as

$$\mathbf{r}_k = \left[\begin{array}{c} r_{x,k}, r_{y,k} \end{array} \right]^{\mathrm{T}}. \tag{7}$$

In these definitions, $d_k = \|\mathbf{s}_k\|_2$, $\mathbf{s}_k$ is the bearing vector between $\mathbf{r}_k$ and the target $\mathbf{p}$. The $\sigma_{n_k}^2$ is the noise variance.

The orthogonal vector (OV) method is preferable over the Stansfield solution Eq. (2) when the range information is not available. It does not require the use of the weighting matrix and its solution is given by

$$\hat{\mathbf{p}}_{\mathbf{OV}} = (\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{b}, \tag{8}$$

that reduces the Stansfield estimator to the OV estimator.

However, these two methods do not take into account the error in the observer measurement. To improve the accuracy of the OV estimator, the concept of total least squares (TLS) can be invoked to deal with errors in both $\mathbf{A}$ and $\mathbf{b}$. The TLS is a method that mitigates bearing errors and observer position errors [18]. Bearing measurements errors are due to the additive noise buried in the gunshot signals (strong quadcopter noise and observational noise), reflections, among others. On the other hand, position measurements errors, in this work, may be caused by the wind that changes suddenly the position of the quadcopter. Also, GPS coordinates have a degree of inaccuracy.

Therefore, we shall use TLS algorithm [18] for shooter position estimation from gunshot bearings obtained from field recordings. This method was also chosen because of its superior performance over the Linear Least-Squares algorithm which performance has been compared in [4].

According to Doğançay [18], the total least squares solution can be writen as

$$\hat{\mathbf{p}}_{\mathbf{TLS}} = \frac{1}{v_{33}} \begin{bmatrix} v_{13} \\ v_{23} \end{bmatrix}, \tag{9}$$

where $\mathbf{v}_3 = [v_{13}, v_{23}, v_{33}]^{\mathrm{T}}$ is the third column of $\mathbf{V}$ which in turn is a unitary matrix obtained from the singular value decomposition of the augmented $\mathrm{N} \times 3$ matrix $[\mathbf{A}, -\mathbf{b}]$.

The total least squares solution is, in general, less biased than the Stansfield and OV solutions [18].

III. Results and Discussion

A. Data acquisition

We collected actual gunshot signals from a 7.62mm rifle recorded at a flat shooting site located at the Brazilian Army Evaluation Center (Centro de Avaliações do Exército, CAEx). The rifle fired 3 times at each of 10 shooter positions and we collected from 4 different recording positions, comprising theoretically (not all signals could be used, 10 of them had to be discarded) 120 signals times 5 (number of microphones in the array). During the recordings, the weather was sunny, the wind speed around 10Km/h, and the temperature around 23 degrees Celsius. The gunshot signals were captured by an array of microphones embedded in a quadcopter. Shooter and array positions are as depicted in Figure **??**. The quadcopter starts the flight from Q1 to Q4 and records three gunshot signals in each position. This procedure was repeated ten times to collect 30 gunshot signals of each shooter position, S1 to S10.

In our data acquisition, in order to have a more controlled experiment (minimizing the errors due to the inaccuracy of the GPS readings), we have recorded 3 shots per shooting position and moved the shooter until its last position. Only then the quadcopter was moved in order to simulate the flight. The only difference, to our understanding, corresponds to the nonexistence of any Doppler effect since the quadcopter was actually hovering above each recording position.

B. Experimental Results

DoA results were achieved with an estimation algorithm named Exhaustive Search [17], or ES(n), using the phase-transform generalized cross correlation (GCC-Phat) to find the best combination of four pairs of signal (n=4 being the best number of combinations as alleged by the authors for an array of seven microphones at SNR around -7dB). In this work we only use azimuth to estimate shooter location. This 2D setup was employed because the quadcopter was placed at the same height of the shooters implying in a fixed elevation angle close to zero (or, equivalently, a zenithal angle close to 90 degrees). Also, given the preliminary results presented in [4] pointing to the fact that signal enhancement schemes are not effective for all distances (between the array and the shooter) in this kind of application, we have processed the signals (detecting and estimating the DoAs) directly from raw data, without signal enhancement.

In Table I, the results of DoA and localization estimates are found for rifle signals. The average azimuth error for this experiment is $5.7°$, using ES(4) and no signal enhancement. It is important to note that shooter position related to the flight trajectory has a great influence on the accuracy of localization estimates. It should be noted that for shooter positions 3 and 4 (S3 and S4), the DoA estimates error are low due to the small distances (and consequent higher SNRs) if compared to other more distant positions. However, the localization error is degraded for the geometry of the array positions, almost forming a straight line towards the shooter (extreme case of non-observable trajectory). On the other hand, for the same drone trajectory, the position estimates improve for position S5 and S6 and degrades again as, due to a higher distance, the SNR decreases.

TABLE I
LOCALIZATION AND DOA ERROR ESTIMATES (120 GUNSHOT SIGNALS) WITH ES(4)

Shooter	1	2	3	4	5	6	7	8	9	10
e_{Loc}	29.7	20.7	54.0	42.9	29.6	18.3	29.7	36.5	60.8	73.3
e_{DoA}	6.6	4.0	6.7	3.3	3.4	3.7	4.6	4.8	5.5	14.5

To tackle the problem of a varying SNR, as an attempt to improve the results, we have varied n, the number of pairs in the ES(n) algorithm, from 2 to 5 (from a maximum of 10 possible pairs) and picked the best result for each shooter position. The DoA estimation, as seem in Table II, presented a lower average error ($5.0°$) and the number of pairs (n), as expected, varies with the shooting position (distance). These results suggest that measuring the SNR and deciding based on its estimated value which value of n to use, as in the decision tree employed in [20], would be the best for a more accurate solution. Yet, a better DoA estimation does not always yield an accurate position estimate which is heavily dependent on the recording geometry (observation points or quadcopter trajectory).

Shooter 4 and 6 position estimates are depicted in Figure 2. The DoA estimation error is low (3.7 degrees in average) for shooter 6 (S6). It is likely that this good result is due to the high SNR of the signals and also to the trajectory of the quadcopter (the positions where the DoAs were estimated and the position of the shooter). Consequently the estimates have low localization error. The coordinates of the estimations create an elipse near the shooter true position. All these estimates are located in an area of approximately 600m^2 area. On the other hand, the localization estimates of shooter 4 (S4), although the DoA error is lower, the localization estimates are degraded due to the array trajectory. It can be seen that for shooter position S4, the estimates cover a larger area (around 3600 m^2). It is possible to infer that, in real situations, one must consider the trajectory of the array in order to minimize localization estimation error.

IV. Conclusions

The mobility of a quadcopter with an embedded array of microphones allows us to collect a set of muzzle blasts in

TABLE II
LOCALIZATION AND DOA ERROR AND RESPECTIVE NUMBER OF PAIRS (N) USED IN EXHAUSTIVE SEARCH ES(N) (120 GUNSHOT SIGNALS)

Shooter	1	**2**	3	**4**	**5**	6	7	8	9	**10**
n	4	**2**	4	**3**	**3**	4	4	4	4	**2**
e_{Loc}	29.7	**21.5**	54.0	**50.7**	**27.6**	18.3	29.7	36.5	60.8	**93.6**
e_{DoA}	6.6	**3.7**	6.7	**2.7**	**2.6**	3.7	4.6	4.8	5.5	**9.9**

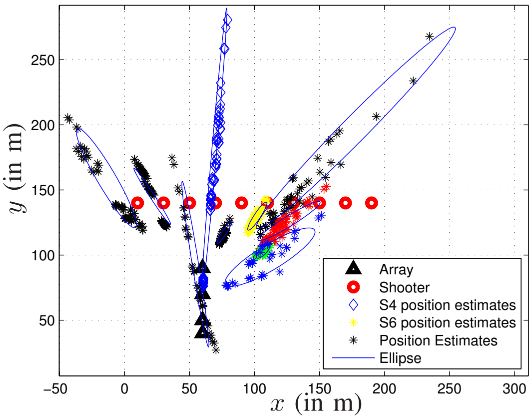

Fig. 2. Position estimates of S4 and S6.

different positions. In real-life situations, this scheme permits the use of statistical methods to estimate shooter localization. In this work, it is shown with actual gunshot signals that the bearings estimated with Exhaustive Search can be used to estimate shooter localization. The accuracy of the shooter localization estimation depends on the number of measurements, the distance between the array and the shooter, and also the trajectory of the array. As the distance increases, the number of measurements used must be larger to maintain the same mean localization error. Finally, we conclude that the results for shooter localization using a drone are a compromise between the distance (between the array and the shooter) and the drone trajectory. We also highlight the importance of a higher altitude flight to avoid non-line-of-sight recordings and the existence of reflection, possibly stronger than the signal from the direct path. In spite of its limitations, as pointed out in this work, the quadcopter seems to be a feasible option to be deployed in urban areas.

REFERENCES

[1] A. L. L. Ramos, "Acoustic sniper positioning systems," Ph.D. dissertation, University of Oslo, 2015.

[2] A. L. L. Ramos, S. Holm, S. Gudvangen, and R. Otterlei, "The multipath propagation effect in gunshot acoustics and its impact on the design of sniper positioning systems," in *Proc. SPIE, Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense XII*, vol. 8711, June 2013, p. 87110A.

[3] C. Reiff, T. Pham, M. Scanlon, J. Noble, A. Van Landuyt, J. Petek, and J. Ratches, "Acoustic detection from aerial balloon platform," DTIC Document, Tech. Rep., 2004.

[4] R. P. Fernandes, A. M. C. R. Borzino, A. L. L. Ramos, and J. A. Apolinário Jr, "Investigating the potential of UAV for gunshot DoA estimation and shooter localization," in *Simpósio Brasileiro de Telecomunicações e Processamento de Sinais*. SBrT, 2016, pp. 383–387.

[5] R. P. Fernandes, E. C. Santos, A. L. L. Ramos, and J. A. Apolinário Jr., "A first approach to signal enhancement for quadcopters using piezoelectric sensors," in *Proceedings of The 20th International Conference on Transformative Science and Engineering, Business and Social Innovation*. Society For Design And Process Science. SDPS, 2015, pp. 536–541.

[6] A. L. Ramos, S. Holm, S. Gudvangen, and R. Otterlei, "Real-time vehicle noise cancellation techniques for gunshot acoustics," in *SPIE Defense, Security, and Sensing*. International Society for Optics and Photonics, 2012, pp. 835 917–835 917.

[7] A. M. C. R. Borzino, J. A. Apolinário Jr., and M. L. R. de Campos, "Estimating direction of arrival of long range gunshot signals," in *Telecommunications Symposium (ITS), 2014 International*. IEEE, 2014, pp. 1–5.

[8] A. M. C. R. Borzino, J. A. Apolinário Jr., M. L. R. de Campos, and L. W. P. Biscainho, "Signal enhancement for gunshot DOA estimation with median filters," in *Circuits & Systems (LASCAS), 2015 IEEE 6th Latin American Symposium on*. IEEE, 2015, pp. 1–4.

[9] J. N. Ash, G. T. Whipps, and R. J. Kozick, "Performance of shockwave-based shooter localization under model misspecification," in *2010 IEEE International Conference on Acoustics, Speech and Signal Processing*. IEEE, 2010, pp. 2694–2697.

[10] Y. Luo, J. Sallai, and A. Ledeczi, "A Hough Transform based approach to acoustic shot localization," in *Information Fusion (FUSION), 2016 19th International Conference on*. ISIF, 2016, pp. 1420–1426.

[11] D. M. P. Calderon and J. A. Apolinário Jr., "Shooter localization based on doa estimation of gunshot signals and digital map information," *IEEE Latin America Transactions*, vol. 13, no. 2, pp. 441–447, Feb 2015.

[12] S. D. Beck, H. Nakasone, and K. W. Marr, "Variations in recorded acoustic gunshot waveforms generated by small firearms," *Journal of the Acoustical Society of America*, vol. 129, no. 4, pp. 1748–1759, April 2011.

[13] W. E. Baker, *Explosions in Air*. Texas, USA: University of Texas Press, November 1973.

[14] H. L. Van Trees, *Optimum array processing - part iv - detection, estimation, and modulation theory, optimum array processing*. John Wiley & Sons, 2004.

[15] B. Van Den Broeck, A. Bertrand, P. Karsmakers, B. Vanrumste, M. Moonen *et al.*, "Time-domain generalized cross correlation phase transform sound source localization for small microphone arrays," in *Education and Research Conference (EDERC), 2012 5th European DSP*. IEEE, 2012, pp. 76–80.

[16] I. L. Freire, "Robust direction-of-arrival by matched-lags, applied to gunshots," *The Journal of the Acoustical Society of America*, vol. 135, no. 6, pp. EL246–EL251, 2014.

[17] A. M. C. R. Borzino, J. A. Apolinário Jr., and M. L. R. de Campos, "Robust DOA estimation of heavily noisy gunshot signals," in *Acoustics, Speech and Signal Processing (ICASSP), 2015 IEEE International Conference on*. IEEE, 2015, pp. 449–453.

[18] K. Doğançay, "Bearings-only target localization using total least squares," *Signal Processing*, vol. 85, no. 9, pp. 1695–1710, 2005.

[19] C. Jauffret, D. Pillon, and A.-C. Pignol, "Bearings-only TMA without observer maneuver," in *Information Fusion, 2008 11th International Conference on*. IEEE, 2008, pp. 1–8.

[20] A. M. C. R. Borzino, J. A. Apolinário Jr, and M. L. R. de Campos, "Consistent DOA estimation of heavily noisy gunshot signals using a microphone array," *IET Radar, Sonar & Navigation*, 2016.