Chapter 10
Acoustic Operational Monitoring of Unmanned Aerial Vehicles Near Vertiports

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Nomenclature

DATEMM	Disambiguation of TDOA estimates in multi-path multi-source environments
FFT	Fast Fourier transform
ICA-SCT	Independent component analysis with state coherence transform
SPrL	Sound pressure level
SPwL	Sound power level
SRP-PHAT	Steered-response power phase transform
TDOA	Time difference of arrival
UAM	Urban air mobility
UAS	Unmanned aerial systems
UTM	Unmanned aircraft system traffic management

10.1 Introduction

It is expected that UAS will be able to operate safely soon within both controlled and uncontrolled airspace with no human intervention. UAS operations in urban environment significantly increase collision risks and corresponding damage, because operations will occur near people, infrastructure and other urban air mobility (UAM) participants. The future technologies, such as advanced detect and avoid systems, will allow UAS operations in congested areas over densely populated communities. In-flight separation services will be provided by automation systems, and contingency procedures used to handle both small- and large-scale off-nominal events. In this paper, acoustic localization system is used as a part of the collision

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avoidance support decision system for UAS Traffic Management (UTM). This section is aimed on provision of the means to support the management of UAS operations in uncontrolled airspace, reduce risk collision with static ground objects and sounding dynamic objects in populated zones. Within the UTM concept UAS coordinates are also required to provide services such as corridors, dynamic geo-fencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning, re-routing, separation management, sequencing, spacing, and contingency management.

10.2 Proposed Algorithm

Figure 10.1 shows the proposed algorithm of UAS localization in line of sight. This algorithm is invariant with respect to UAS speed and number of sound wave reflections.

The method of determining the UAS coordinates by acoustic parameters is based on the use of algorithms for statistical processing of noise, which engine, screw and UAS elements generate. The signals from array of microphones are amplified by low-noise broadband amplifiers and fed to the input of analog-to-digital converter. The digital signals are transmitted to computer, which digitally processes the measured acoustic signals and calculates UAS location in 3D space.

As a method of UAS localization, a method based on the calculation of coordinates directly from the delays between acoustic signals is chosen, similar to the DATEMM algorithm in Zannini et al. (2010) and Scheuing and Yang (2008). Space scanning, which is characteristic for SRP-PHAT and ICA-SCT localization algorithms, results in higher computer memory costs to achieve the required accuracy, and most importantly, longer calculations (Loesch et al. n.d.).

The Doppler effect, which distorts the shape of the signals, is taken into account when detecting signals from moving objects. To eliminate the consequences of this effect, changes in the time scale of the signals are applied, and before the calculation of the correlation function, the time scale of the signals is changed. For this purpose, a resampling algorithm is used to change the time between discrete signal values. Resampling is used to change the sampling rate of a signal. This allows us

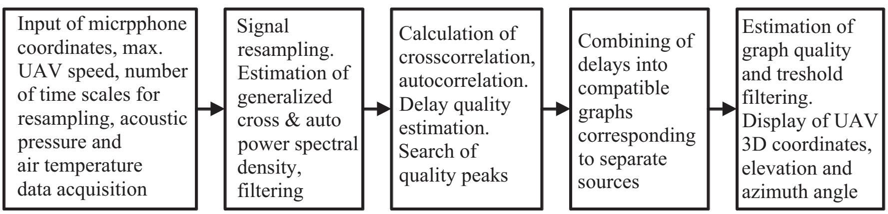


Fig. 10.1 Scheme of UAS localization algorithm

constructing a signal detection procedure independent of the possible speed of the sound source.

To separate the UAS signal from the mixture of sounds coming into the microphone, bandpass filtering is performed using Fast Fourier Transform (FFT). For frequency bands, at which SPrL of UAS computed at a distance of 1 m are less than background SPrL, the generalized cross and auto-power spectral density values are replaced with zero. Since the FFT operation is used to calculate the correlation function by the spectral method, this filtering technique does not lead to additional computational costs.

Our approach for selecting the positions of noise sources among the erroneous positions generated by the combination of delays is to set a threshold for the value of the graph quality V:

$$V = \frac{1}{\sum_{\{i,j\}\in P} F_{ij}^2} \sum_{\{i,j,k\}\in C} \left(r_{ij} + r_{jk} + r_{ik}\right) \Gamma_{\Sigma}\left(\Delta_{ij} + \Delta_{jk} + \Delta_{ki}\right) \Gamma_{\Pi}\left(\beta_{ij}\beta_{jk} - \beta_{ik}\right), \quad (10.1)$$

where the set C consist of all microphone triples $\{i, j, k\}$ included in compatible graph, and the set P consist of all microphone pairs $\{i, j\}$ included in compatible graph, Δ_{ij} is the delay of sound propagation between microphone i and j in samples. β_{ij} is factor of i-th signal relative to j-th signal time scaling, which was determined during resampling for each pair of signals. The function indicates how good sound source coordinates (x_s, y_s, z_s) correspond to delay τ_{ij} found from crosscorrelation r_{ij}. F_{ij} is given by equation.

$$F_{ij} = \sqrt{\left(x_s - x_i\right)^2 + \left(y_s - y_i\right)^2 + \left(z_s - z_i\right)^2} - \sqrt{\left(x_s - x_j\right)^2 + \left(y_s - y_j\right)^2 + \left(z_s - z_j\right)^2} - c\tau_{ij} \quad (10.2)$$

where τ_{ij} is the time delay of the arrival of acoustic waves from the microphone i to the microphone j, c is the sound speed.

The function Γ_{Σ} in Eq. (10.1) is designed to ensure the operation of the localization system in conditions of inaccuracies in cyclic sums. The function Γ_{Π} is used because of inaccuracies in cyclic products, which arise due to finite discretization of sound source speeds.

To determine the coordinates of the noise source, a geometric method is used: the intersections of the hyperboloids obtained as a result of the construction of surfaces for (i, j) pairs of microphones are found. In case of exact intersections, $F_{ij} = 0$ for all possible pairs of microphones. However, due to errors in determination of microphone coordinates, discrete sampling and finite size of sound source exact intersections never appear in practice. Sound source coordinates (x_s, y_s, z_s) are defined as the result of solving an optimization task:

$$\min_{x_S, y_S, z_S} \quad F_{ij} = 0 \tag{10.3}$$

To speed up solution, especially at assumption of sound source location in far field, hyperboloids are replaced with cones. This leads to transformation from non-linear optimization problem to the problem of solving of overdetermined system of linear algebraic equations.

10.3 Selection of Optimal Antenna Structure for Sound Source Localization

To select an optimal microphone location let us consider error caused by inaccuracy of microphone positioning. Assume that the error of microphone location has normal distribution with standard deviation of 0.01 m. Good localization accuracy can be achieved with several microphone arrays distributed in urban terrain. Figure 10.2 shows localization error for microphone arrays located near vertiport landing pad and on top of nearby tall building. Both microphone arrays acquire data for single localization system, although only TDOA between microphones within each array are used. These arrays consist of five microphones located in vertices of square pyramid with 10 m edge length.

10.4 Experimental Verification of Localization Algorithm for UAS

Field tests of the UAS localization system were performed for the syma 8 M quadcopter for the stationary UAS position (Fig. 10.3). The location of microphones and stationary UAS in the experiment is shown in Table 10.1.

Figure 10.3 shows the coordinates of the multicopter at the stationary position of UAS syma 8 M in the microphone coordinate system. The microphone coordinate system is constructed in such a way that the points at which the microphones 1, 2, and 3 are placed define the plane 0*xy*. The beginning of the coordinate system is in the position of the first microphone. The 0*x* axis is directed to the second microphone.

10.5 Conclusion and Further Research

This investigation presents approaches to modelling of sUAS noise emission at takeoff and landing modes. Presented UAS localization procedure will be used for providing safe UAS operations in urban environment. If the aircraft detection method in Chervoniak et al. (2017a, b) has demonstrated merely the main principle and efficiency of the proposed approach, currently, the method is of practical use for

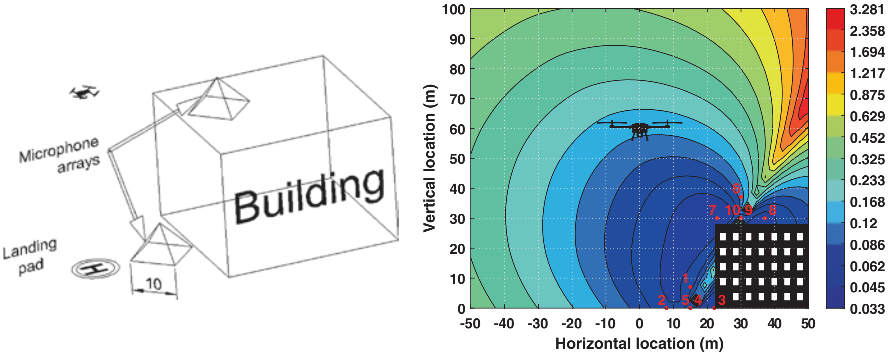
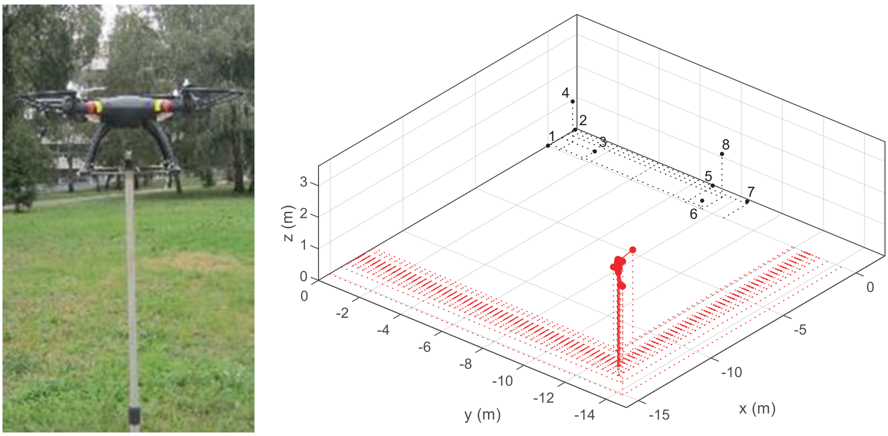


Fig. 10.2 Localization error in *yz* plane, $x = 0$, for microphone arrays placed on ground and on top of the 30 m height building. (**a**) Scheme of microphone array location; (**b**) UAS localization error above landing pad



(a)Photo of fixed syma 8M

(b) Syma 8M microphone and its estimated location in 3D space

Fig. 10.3 Experimental verification of algorithm for the stationary position of UAS. (**a**) Photo of fixed syma 8 M; (**b**) Syma 8 M microphone and its estimated location in 3D space

Table 10.1 Location of microphones and sound source in meters

Microphones	*xm*	*ym*	*zm*
1	0	0	0
2	1.87	0	0
3	0.935	−1.619	0
4	0.948	−0.532	1.287
5	1.893	−6.679	0.019
6	0.169	−7.382	0.196
7	1.647	−8.53	0.083
8	1.385	−7.488	1.379
Syma 8M	12.721	12.114	3.346

localization, flight and velocity tracking. The usage of measured SPwL for signal filtering allowed removing UAS unrelated noise influence on accuracy of 3D coordinates estimation. This study also shows how the usage of small acoustic antenna can lead to fast location estimation for moving UAS. Conducted experimental researches show potential for application of passive acoustic localization system for UTM services more specifically and for urban noise monitoring in general (Bukala et al. 2019).

Further investigation required to test the efficiency of sound localization system as part of UAS on-board equipment. In the future, it is planned to use the results of these studies in the following areas:

- considering the impact of complex urban topologies, dangerous and unpredictable atmospheric hazards, such as unsteady wind-fields;
- reducing the risk of UASs operation taking into account ground static objects (power lines, towers, structures, overpasses) and other aircraft (manned and unmanned); and
- separation assurance and collision avoidance between air vehicles in a mixed-use airspace.

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