Acoustic Localization and Tracking of the Multiple Drones

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ABSTRACT

Due to the social problems in the intrusion of privacy and the collision hazard, monitoring of the drones are needed for the regulations. To enhance the identification of multiple drones flying at a specific zone simultaneously, a new localization method other than the optical or electromagnetic methods is needed. In this work, a method to use the acoustic cues of the drone is presented, and the three-dimensional acoustic intensimetry (3DAI) is employed for the localization. The 3DAI implements the compensation algorithm for the spectral bias error of the probe configured in a tetrahedron shape. The blade passing frequency and its harmonics radiated from the quadcopter drones are adopted as the acoustical cues for the detection. The test for single drone is done within an anechoic chamber to estimate the localization error in the real-time. For the multiple drones, the test is carried out for the localization by using recorded sounds of three drones having different rotor sizes. The results show that the mean azimuth and elevation angle error is less than 5° for localization of multiple drones. The localization result is fine when BPFs are distinguishable, but, for the case with spectral overlap, it bears a large error.

Keywords: Source localization, 3D acoustic intensimetry, Drones
I-INCE Classification of Subject Number: 13, 72, 74

1. INTRODUCTION

The drone market is rapidly expanding with the extension of its application to various fields, and the advancement of its technology. However, the hazard of collisions with objects and other ethical issues related to the use of drones are being raised.[1] To mitigate these issues, regulations on the tracking and monitoring of drones are required. Some localization methods, such as the optical or electromagnetic means, have been proposed, but the other technique is also required to enhance the recognition ability, in particular, when multiple drones are flying simultaneously in a specific zone. In this study, the three-dimensional acoustic intensimetry (3DAI) method is employed for drone localization using the acoustic cues of drones. The method implements the recently developed compensation algorithm of the spectral bias error for the array configuration in a tetrahedron shape.[2] The blade passing frequency (BPF) of rotating propellers in the quadcopter drones, along with its harmonics, are considered as the acoustical cues for the detection.

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2. THEORY

In using the sound intensimetry for source localization, the spectral bias error caused by fluctuation creates a large error in the narrow frequency band as well as the conventional problems affecting the p-p method.[3-4] In particular, the localization error is maximized when the object is a flying drone, because the acoustic cue is rich at a specific frequency band due to the BPF. The aforementioned recent compensation method is adopted to eliminate the bias errors that occur in the narrow frequency band.[2]

2.1 Acoustical characteristics of quadcopter drone

The quadcopter drone uses four propellers to obtain thrust, creating a loud noise. Therefore, the sound composed of the BPFs and their harmonics due to the air-blade interaction is the appropriate acoustical cue for the localization of flying drones. Figure 1 shows the spectrogram obtained from the measured sound at a distance of 3.2 m from a drone fixed on a frame in an anechoic chamber. One can find that the four BPFs around 220 Hz and their harmonics are prominent. Such an acoustic spectral pattern of several scattered frequencies clustered in the narrow frequency bands, not in the exact harmonic orders, is due to the fact that each propeller has different rotational speed for attitude control or for changing the direction of motion.
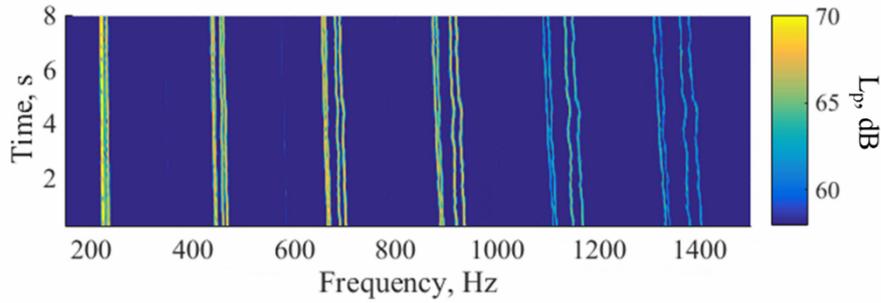

Figure 1. Spectrogram of the measured sound from a static quadcopter drone in an anechoic chamber. The color range exhibits the sound level at 3.2 m in distance.

2.2 Localization by using 3DAI

It is well known that the 1D acoustic intensity can be measured by employing a pair of microphones and using the finite difference approximation of Euler equation. This can be implemented in a digital way by calculating of the cross power spectral density (CPSD) between two signals. Similarly, the 3D acoustic intensity can be measured by using the sets of CPSD's estimated from the possible pairs of the microphone array.[5] However, the obtained 3D intensity has usually a large spectral bias error. When the most of acoustic energy of the signal is contained in a narrow frequency band such as the drone sound, the spectral bias error can invoke a significant error in the localization result. In this work, the 3DAI method adopts the recently developed compensation algorithm of the spectral bias error for the microphone array in a tetrahedron configuration.[2] In Cartesian coordinates, each vector component of the 3D sound intensity estimated from an array module can be written as

$$I_a(\omega) = \sum_{i=1}^{4}\sum_{j=i+1}^{4} \alpha_{ij}\overline{G}_{ij} \Big/ \omega d , \tag{1}$$

where d is the spacing between adjacent microphones, ω is the circular frequency, $\overline{G}_{ij}$ is the filtered cross spectrum between the measured pressure data at the ith and j^{th} sensors in the probe, and α_{ij} is the weighting of $\overline{G}_{ij}$.

2.3 Localization of multiple drones

The acoustical cues for localization of multiple drones, which have different RPM bands of the propellers, can be obtained by the following pre-processes for the signature separation. First, one calculates the frequencies corresponding to the local maxima of the peaks in a narrow band of the measured spectrum to extract the BPF and its harmonics of the drone sound. The broadband noise can be suppressed by adopting the phase-shift algorithm.[6] Second, one applies a finite impulse response filter to extract the specific single tone and its harmonics to improve the localization accuracy when the signal-to-noise ratio is low. In this work, the following values are used: filter order=7000, pass bandwidth=1 Hz, center frequency<1 kHz. It is because the most of acoustical cues exists in the range less than 1 kHz. The number of harmonic orders is adjustable, so the comparison of the localization results can be done according to the order. Based on the measured sound pressure in the time domain, one can obtain the filtered data as follows:

$$\bar{\mathbf{p}}(t) = \begin{bmatrix} p_1(t) & \cdots & p_4(t) \end{bmatrix}^T * \begin{bmatrix} h_1 & \cdots & h_N \end{bmatrix}. \tag{2}$$

Here, h_j denotes the filter with a center frequency at the jth peak, $p_i(t)$ the measured raw time data from the ith microphone, and $\bar{\mathbf{p}}$ the filtered data set of N bands.

3. REAL-TIME TRACKING OF A SINGLE DRONE

A test is conducted to estimate the location of a flying drone in real-time inside an anechoic chamber. The intensity probe with 4 MEMS microphones (ADMP401, Analog Device) configured in a tetrahedral shape is used. The test drone (Spark, DJI) with a maximum length of 300 mm is used as the source. For a randomly flying drone in a limited distance range, the localization result is compared with the data measured by using an optical depth sensor (KinectV2, Microsoft).[7] The direction of arrival of the flying object is tracked in a nearly real-time with an update rate of about 3 FPS. Figure 2 exhibits the real-time localization test result. Compared to the optically measured data, the mean deviations in azimuth and elevation angles are 3.6° and 4.9°, respectively, and the 90% confidence interval for the bearing angle deviation is less than 10°.
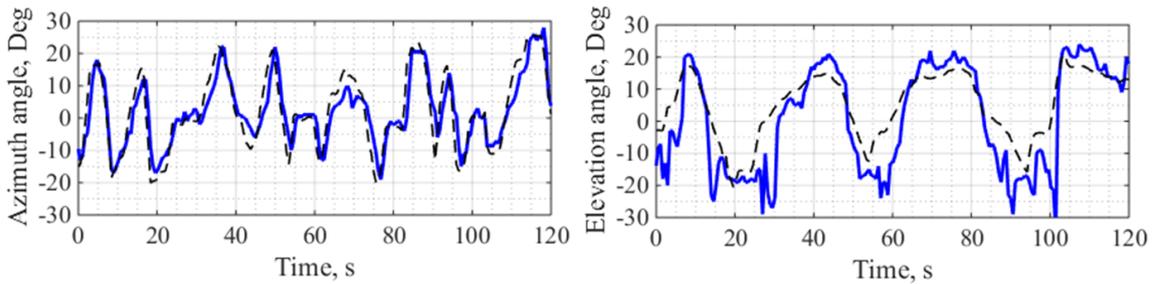

Figure 2. Test result of real-time localization and tracking of a flying drone in an anechoic chamber: —, 3DAI method; --, optical sensor tracking.

4. TEST WITH MULTIPLE DRONES

In this test, the 3 quadcopter drones with different rotor diameters are considered: *drone A*, 240 mm (Phantom4, DJI); *drone B*, 120 mm (Spark, DJI); and *drone C*, 80 mm (Tello, DJI). Each bears a unique BPF because the motor RPM for obtaining the minimum thrust for hovering is different for each drone. The recorded sound of each drone, 1 s in length, is used to characterize the acoustic field and identify the location of drones. Figure 3 exhibits an SPL measured 3.2 m from the geometric center of each drone in the anechoic chamber. In the test, 3 drones are

operated simultaneously, but their positions, i.e. the reference azimuth and elevation angles, are fixed: (30°, 10°), (50°, 60°), and (-60°, 0°), respectively.

The test result is presented in Fig. 4. In total, 41 acoustical cues are observed in the range of $200 \leq f < 1000$ Hz, and the resultant localization data are clustered by using the k-means algorithm for the validation.[8] As a result, the errors in azimuth and elevation angles appear to be (-0.2°, 0.2°), (-2.7°, -3.2°), and (0.9°, 0.2°), respectively for each drone. The test result exhibits that *drone A* has the lowest localization error, because the acoustical cues corresponding to the high acoustic energy are mostly responsible from that drone. In the case of *drone B*, some cues are very close to those of *drone A*'s, so it exhibits a large error. In the case of *drone C*, most of the identification cues are smaller than the broadband noise of *drone A*, but the error amount is very small. This is due to the fact that spectral overlap does not occur between *drones A* and *C*.
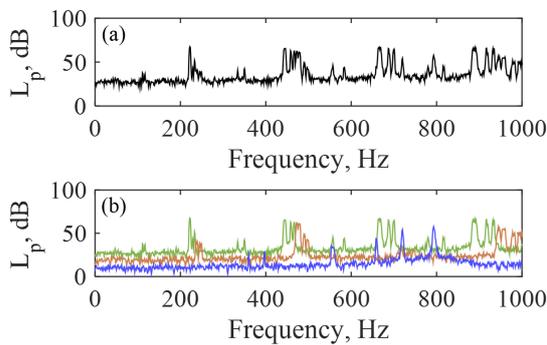

Figure 3. Measured sound level spectra of the tested drones: (a), in the simultaneous operation mode; (b), individual operation mode: ▬, drone A; ▬, drone B; ▬, drone C.
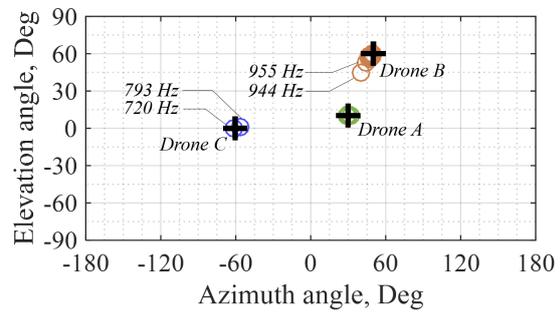
Figure 4. Localization result of the tested drones in simultaneous operation. The symbol + denotes the reference position of each drone: ○, drone A; ○, drone B; ○, drone C.

5. CONCLUDING REMARKS

In this study, a good potential of applying the 3DAI method to the precise localization of the flying objects, as far as the proper compensation for the bias error is given. Compared with the optical tracking method, the difference is less than 5° in the real-time tracking of the source position, but the absolute error cannot be identified because both experimental methods are in error and the transient response is also influencing the final result. The test result on the multiple drones show that both the mean azimuth and elevation angle error are less than 3.2°. The localization results are sufficient when BPFs are distinguishable; however, for cases with spectral overlap, they incur large errors. It is expected that the proposed method would improve the localization accuracy of drones in combination with other means such as optical or electromagnetic methods.

6. ACKNOWLEDGEMENTS

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