Hear-and-Avoid for Micro Air Vehicles

E.H.G. Tijs[1],* G.C.H.E. de Croon[2], J.W. Wind[1], B. Remes[2], C. De Wagter[2], H-E de Bree[1,3], R.Ruijsink[2]
1: Microflown Technologies, HAN University, the Netherlands
2: MAV-lab, Faculty of Aerospace Engineering, Delft University of Technology, the Netherlands
3: HAN University

Abstract

This is the first feasibility study of *hear-and-avoid* on Micro Air Vehicles with acoustic vector sensors. The Microflown MEMS technology based sensor is used for this purpose. The three-dimensional acoustic vector sensor consists of three orthogonally placed particle velocity sensors and one sound pressure microphone. The usage of this sensor is explored for detecting the direction to other sound sources in the sky. The experiments involve adapting and mounting the MEMS sensor on a fixed wing MAV. The empirical results show that loud sounds as could be produced by civil aircrafts are clearly detectable by the sensor. In addition, they indicate that the detection of other MAVs is possible. In general, the long-range detection properties and the small weight of the sensors hold an important promise for enhancing the sense-and-avoid capabilities of MAVs.

1 Introduction

Micro Air Vehicles (MAVs) hold a promise as sensors in the sky for many applications. Recent developments have led to the wide availability of autopilots that allows MAVs to fly autonomously in open outdoor areas [1, 2]. However, one of the major remaining limitations for the wide-spread use of Micro Air Vehicles (MAVs) is their lack of sense-and-avoid capabilities.

There has been extensive research on this subject, which has mainly focused on sensors such as laser range finders, sonar sensors, infrared sensors, and cameras.

Notably, research on larger Unmanned Air Vehicles (UAVs) with high-resolution laser scanners (cf. [3, 4]) provided promising results for navigation in cluttered environments. However, these UAVs weighed more than 75 kg and had to use most of their payload capability to lift the laser scanner. Laser scanners have been miniaturized for use on MAVs by sacrificing both resolution and sensing directions. Scanners that measure distances to obstacles in a 2D plane through the MAV are now part of the most successful systems for indoor flight [5, 6]. The range of these scanners is < 30 m, which may not be sufficient for outdoor flight when the MAV is moving at higher speeds. In addition, for some obstacles such as other air vehicles or power lines, sensing in a 2D plane is not enough.

Research on outdoor sense-and-avoid for MAVs has mainly focused on the use of a camera. It is a light-weight, passive sensor and as such consumes less energy than active sensors such as laser scanners. In addition, a camera can provide information about a large part of the environment at once, including obstacles at large distances. Cameras have been mainly used in stereo vision and optic flow.

There have been some efforts to use stereo vision for obstacle avoidance on UAVs, e.g., [7]. However, stereo vision has a limited range in which it can determine the distance to obstacles. This range depends on the resolution of the images and the base distance between the two cameras. The base distance is inherently limited in MAVs, so stereo vision will only be useful for detecting obstacles at a relatively short range.

Therefore, the state-of-the-art methods for avoiding obstacles with MAVs focus on extracting three-dimensional information from images by employing optic flow [8, 9, 10, 11, 12]. In [12] an MAV uses multiple optic flow sensors and a reactive control scheme to successfully avoid obstacles such as groups of trees. The disadvantage of optic flow is that it heavily relies on texture in the images. As a consequence, obstacle avoidance on the basis of optic flow fails around many human-built structures, since they can have too little texture.

In order to provide information on other flying vehicles that are further away and in order to improve the robustness of close-range obstacle avoidance, a small acoustic sensor could be a useful addition to an MAV's sensor suite.

This article is the first feasibility study of hear-and-avoid on Micro Air Vehicles with acoustic vector sensors. The Microflown MEMS-technology based sensor is used for this purpose. The three-dimensional acoustic vector sensor (3D AVS) consists of three orthogonally placed particle velocity sensors and one sound pressure microphone. The usage of this sensor is explored for detecting the direction to other sound sources from the ground and in the sky.

The remainder of the article is organized as follows. In Section 2, the MicroFlown MEMS-technology based sensor is explained in further detail. Subsequently, in Section 3 an experiment is presented in which the sensor is mounted on a UAV and exposed to a loud sound source - at different speeds and with different angles. Then, in Section 4 the sensor is mounted on an MAV and experiments are performed in which it has to detect the sound of another MAV's propellor. In Sec-

*Email addresses: g.c.h.e.decroon@tudelft.nl, tijs@microflown.com, microuav@gmail.com

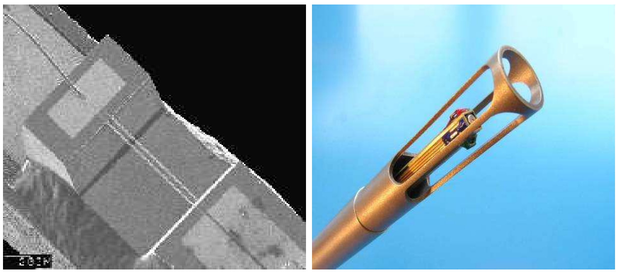

Figure 1: **Left:** Regular particle velocity sensor. **Right:** 3D sound intensity probe.

tion 5 preliminary results are shown while the MAV carrying the acoustic sensor is in flight. Finally, the conclusions are presented in Section 6.

2 MICROFLOWN ACOUSTIC 3D SENSOR

Until recently, sound pressure microphones were used to compute acoustic particle velocity by using the phase difference of microphones. The required spacing limits their broad banded use. For determining this phase difference at low frequencies large distances are necessary, while at high frequencies a small spacing is needed.

In the audio range for underwater applications, acoustic vector sensor based concepts have been applied, using accelerometers to approximate particle velocity. However, in the audio range in air, the concept was never really applied because of a lack of suitable sensors.

With the Microflown sensor it has become possible to measure acoustic particle velocity in a broad banded manner [13]. In essence the Microflown is an extremely sensitive thermal mass flow sensor. The working principle is based upon the measurement of the temperature difference between two closely spaced sensor wires. This temperature difference is proportional to the acoustic particle velocity. The left part of Figure 1 shows the Microflown sensor. The temperature difference between the two heated wires is measured, which is proportional to the acoustic particle velocity.

Three of these particle velocity sensors can be combined with a sound pressure microphone in one probe (Figure 1, right). With such a probe the 3D sound intensity vector can be measured in one spot. Whereas the directionality of spatially distributed sound pressure based systems are based only on the phase information of a sound source, with acoustic vector sensors the amplitude information can be used as well.

In several studies sound source localization with acoustic vector sensors from the ground has been discussed of single or multiple dominant sound sources in the far field [14, 15, 16, 17, 18, 19, 20, 21, 22]. It has been demonstrated that it is possible to detect the elevation, speed, heading, height, original frequency and distance of an aircraft flying over at the closest point [21, 22]. Here for the first time acoustic vector sensors are mounted on a small unmanned air vehicle.

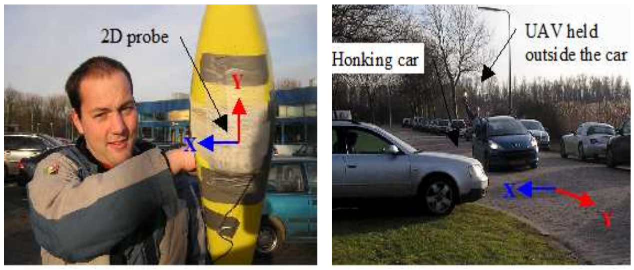

Figure 2: **Left:** Probe mounted below the MAV. **Right:** The MAV passes a honking car.

3 DETECTION OF A LOUD SOUND SOURCE

In order to test if it is feasible to measure other sound sources with the disturbance of the aircraft propeller and wind, first a non flying condition was tested. A probe that was mounted on an MAV was moved by a car which was passing a second car that was honking.

3.1 Description of the measurement

An acoustic vector sensor is mounted underneath an UAV. To protect the probe against wind it is covered by open porous foam that is attached to the MAV with a synthetic textile mesh (Figure 2, left). Since the MAV is an acoustic obstacle for the direction normal to the ground, the particle velocity in this direction is not measured. Nevertheless, the location of the acoustic source a car can be determined because it is likely to be on the ground. For easier handling the wings of the airplane are not attached. The MAV is held outside the car by a person, while driving in a straight line with 40km/h. The car drives from the north east to the south west. At the middle of the track a second car stands still and its horn functions as the acoustic source that is to be detected (Figure 2, right). Two conditions were measured: with and without the propeller of the airplane running.

3.2 Measurement results

The pressure, velocity and intensity levels are plotted for the case with and without a running propeller. The angle of arrival is calculated from the angle of intensity in two directions.

No frequency filters are used to suppress the signal of the propeller. The displayed sound pressure, particle velocity and sound intensity levels are in dB, however the absolute sensitivity of the sensors is unknown.

The sound pressure and particle velocity signals are shown in Figure 3-4. The Doppler effect is clearly visible in all measurements as a frequency that changes when the MAV passes the car with the horn. In the right figures the propeller of the MAV and its harmonics are also visible as a constant frequency. After 9 seconds the propeller and the car horn are stopped. Between 9.5 and 10.5 seconds the propeller slows down which produces a tone with decreasing frequency.

From the sound pressure and the particle velocity the

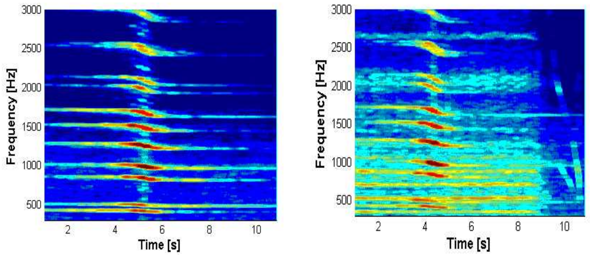

Figure 3: Spectrogram sound pressure. **Left:** horn. **Right:** horn and propeller.

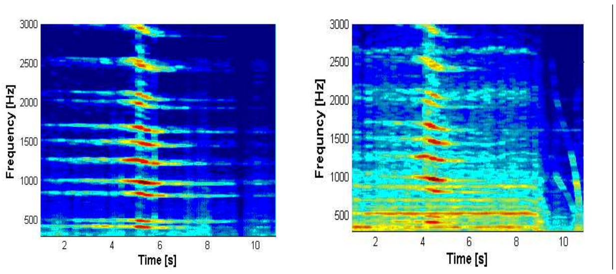

Figure 4: Spectrogram particle velocity X direction. **Left:** horn. **Right:** horn and propeller.

sound intensity can be calculated in both directions, Figure 6 and 7. For visualization the absolute value of intensity is shown. At points where there is a low coherence between pressure and velocity (Coherence $C < 0.7$) the intensity is displayed as transparent. The coherence is defined as: $C_{pu}(\omega) = \frac{|S_{pu}(\omega)|^2}{S_{uu}(\omega)S_{pp}(\omega)}$, where S_{pu}, S_{pp}, and S_{uu} denote the cross-spectrum between pressure and particle velocity, the autospectrum of the pressure and the autospectrum of the velocity respectively. The level of intensity that is measured depends on the orientation and the distance to the sound source. As expected the intensity in the X direction is high at the moment when the honking car is passed. The intensity in the Y direction increases as the car approaches and is low exactly when the car passes.

When the intensities in both directions are known the angle between them can be calculated. The estimated angle is shown in Figure 8, where angle represents color and signal

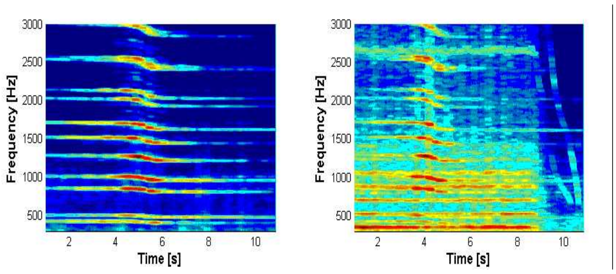

Figure 5: Spectrogram particle velocity Y direction. **Left:** horn. **Right:** horn and propeller.

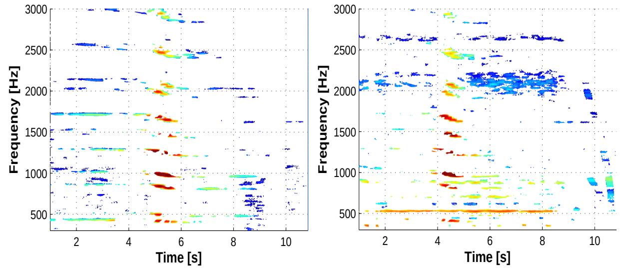

Figure 6: Spectrogram sound intensity X direction. **Left:** horn. **Right:** horn and propeller.

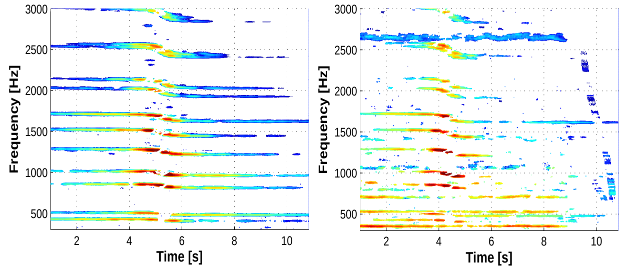

Figure 7: Spectrogram sound intensity Y direction. **Left:** horn. **Right:** horn and propeller.

strength is brightness.

The Doppler effect is fitted automatically from the calculated spectrogram. Using this information, the speed, angle and distance at the closest point of the source trajectory can be calculated. For the measurement without propeller, the speed was estimated to be 31.8km/h and the distance at the closest point of approach 3.58m. This is not far off from the 35km/h readout of the speedometer (which is usually an overestimation). During the second measurement the harmonics of the propeller are measured, but still the Doppler effect can be estimated quite accurately. During the second measurement with propeller the speedometer readout was 40km/h. The calculated speed was 36.7km/h and the estimated distance 3.6m.

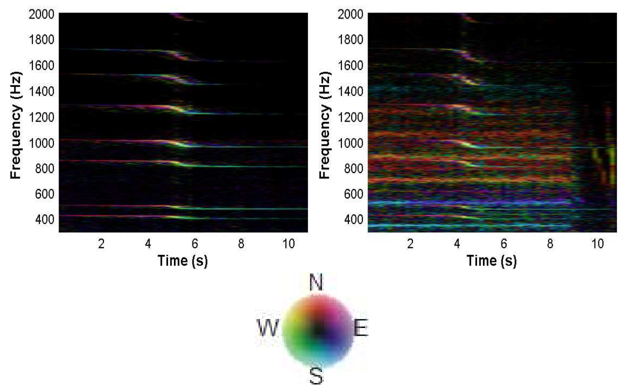

Figure 8: Spectrogram calculated angle. **Left:** horn. **Right:** horn and propeller.

4 DETECTION OF ANOTHER PROPELLOR

Sounds produced by civil aircraft can be assumed loud enough for detection by the acoustic sensor (as is the car horn). However, it would be highly useful if the acoustic sensor could also detect sounds as produced by other MAVs. In this section, experiments are performed to test the detection of the propellor of another MAV. It concerned the detection of a second propeller aircraft and to separate it from the noise of the first aircraft itself.

A first MAV with the sensor was held on the ground by a person. This propeller was driven with a constant rotational speed. A second MAV was held by another person at 5 and 20 meters distance. This second propeller was accelerated, then it was kept constant for roughly a second, and then it decelerated.

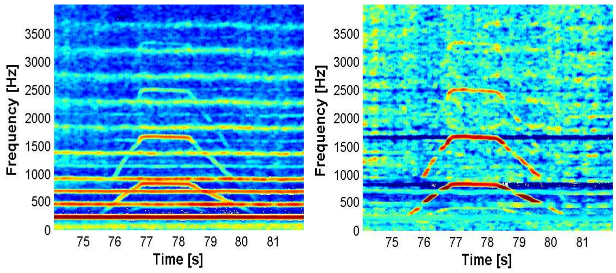

Figure 9: Spectrogram pressure. Second propeller at 5 meter. **Left:** raw signal. **Right:** filtered signal.

Below the spectrograms of the pressure microphone and the particle velocity sensor are shown at 5 and 20 meter (Figure 9 and 10). On the left the raw sensor signals are shown. Clearly the harmonics of the first MAV are visible as its frequency remains constant. Also the second MAV is visible with the frequency of its harmonics going up, remaining constant, and then going down again.

On the right the filtered signals are shown. Here the spectrum is calculated from the whole duration of the measurement. Mostly the harmonics from the first MAV will be dominant as they are constant in time. Then these values are subtracted from the spectrum that is calculated at each small section of time. The harmonics of the first MAV are reduced considerably. In the future different types of filters and suppression techniques should be tried out in order to reduce the disturbance from the aircraft itself as much as possible.

5 PRELIMINARY FLIGHT TEST

Finally, we have also performed a preliminary flight test with a 3D AVS probe. To shield the probe against wind a protective cap was used that is made from open foam covered with a windscreen made from fur and foam. The probe was mounted at the nose of the MAV in a frame that would separate the probe easily during a crash, to prevent that the probe would break, see Figure 11. The data was recorded on a small and light-weight 4-channel digital recorder.

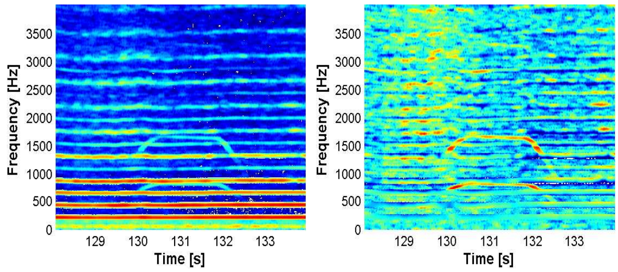

Figure 10: Spectrogram pressure. Second propeller at 20 meter. **Left:** raw signal. **Right:** filtered signal.

Figure 11: AVS probe mounted on the nose of the MAV

The objective of this test was to measure the response of the probe to a source from the ground and to disturbances such as wind and the motor. An impulse generated on the ground by a person who slapped two wooden beams against each other, see the lower left corner in the photo of Figure 12. There were no compass, gps, or tilt sensors on board, so it was not possible to calculate the angle relative to the aircraft and to localize the sound source.

In the right part of Figure 12 the spectrogram of the mean intensity during a short flight is shown. Nine claps were generated during the measurement. After 2.5 seconds the MAV motor was started and released. Then the motor speed was kept constant for two seconds and then decreased. After this the speed was increased slightly again and then decreased (7.5-9.8s).

Most claps are detected and are visible in the spectrogram as straight vertical lines which contain all frequencies. Three claps were not detected. The noise from the engine and fan was high at these moments, but the main source of disturbance here is expected to be electrical noise from the MAV

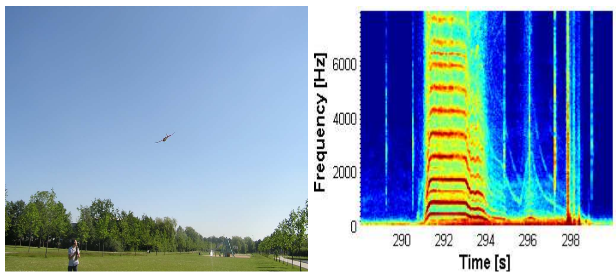

Figure 12: Flight test. **Left:** the MAV in flight. **Right:** spectrogram mean intensity during a short time interval of the flight.

receiver. The probe cable was long and both the probe and recorder were not shielded during this measurement. With the protective cap the influence to wind seems to be relatively low. There is an effect of low frequency turbulence during the flight, mainly below 300 Hz.

6 CONCLUSIONS

For the first time a 3D AVS probe was successfully mounted on a MAV and the results are promising. Three tests were performed: (1) a honking car was localized while the MAV was moved by a car, (2) on fixed positions on the ground the noise of a second MAV was detected, and (3) a short flight was made in which clapping sounds originating from the ground could be detected. The empirical results suggest that sounds as produced by civil aircraft will be clearly detectable by the sensor. In addition, they indicate that the detection of other MAVs is possible.

There are many topics to investigate in the future. The accuracy of the direction and localization measurements has to be tested in practical in-flight situations. Moreover, the sensor position on the MAV and the algorithms for the separation of multiple different sound sources have to be optimized. In addition, the reduction of noise from the MAV's own propeller, the wind and the electronics is an issue that deserves further investigation. In case of success, the acoustic vector sensor may also be used to detect the reflection of the sound produced by the MAV itself for determining its height and its distance to large stationary obstacles.

In general, the long-range detection properties and the small weight of acoustic vector sensors hold an important promise for enhancing the sense-and-avoid capabilities of MAVs.

REFERENCES

[1] R.W. Beard, D. Kingston, M. Quigley, D. Snyder, R.S. Christiansen, and W. Johnson. Autonomous vehicle technologies for small fixed-wing uavs. *Journal of Aerospace Computing, Information, and Communication*, 2(1):92 – 108, 2005.

[2] K.P. Valavanis. *Advances in Unmanned Aerial Vehicles*. Springer, 2007.

[3] D.H. Shim, H. Chung, H.J. Kim, and S. Sastry. Autonomous exploration in unknown urban environments for unmanned aerial vehicles. In *AIAA GNC Conference, San Francisco*, 2005.

[4] S. Scherer, S. Singh, L. Chamberlain, and S. Saripalli. Flying fast and low among obstacles. In *Proceedings International Conference on Robotics and Automation*, 2007.

[5] A. Bachrach, R. He, and N. Roy. Autonomous flight in unstructured and unknown indoor environments. In *European Micro Air Vehicle conference and competititons, EMAV 2009, the Netherlands*, 2009.

[6] S. Grzonka, G. Grisetti, and W. Burgard. Towards a navigation system for autonomous indoor flying. In *Proc. IEEE International Conference on Robotics and Automation 2009 (ICRA 2009), Kobe, Japan*, 2009.

[7] R.K. Mehra, J. Byrne, and J. Boskovic. Flight testing of a fault-tolerant control and vision-based obstacle avoidance system for uavs. In *Proceedings of the 2005 Association for Unmanned Vehicle Systems International (AUVSI) Conference, North America*, 2005.

[8] N. Franceschini, J.M. Pichon, C. Blanes, and J.M.Brady. From insect vision to robot vision. *Philosophical Transactions: Biological Sciences*, 337(1281):283–294, 1992.

[9] J.S. Humbert and M.A. Frye. Extracting behaviorally relevant retinal image motion cues via wide-field integration. In *American Control Conference*, number 14–16, page 6 pp, 2006.

[10] J. Serres, D. Dray, F. Ruffier, and N. Franceschini. A vision-based autopilot for a miniature air vehicle: joint speed control and lateral obstacle avoidance. *Autonomous Robotics*, 25:103 – 122, 2008.

[11] M. Hwangbo. Robust monocular vision-based navigation for a miniature fixed-wing aircraft. Ph.D. proposal, Robotics institute, Carnegie Mellon University, 2009.

[12] Antoine Beyeler, J.-C. Zufferey, and D. Floreano. Optipilot: control of take-off and landing using optic flow. In *European Conference and Competitions on Micro Air Vehicles (EMAV 2009)*, 2009.

[13] H-E de Bree, P. Leussink, T. Korthorst, H. Jansen, T. Lammerink, and M. Elwenspoek. The microflown; a novel device measuring acoustical flows. *Sensors and Actuators: A, Physical*, SNA054/1-3:552–557, 1996.

[14] T. Basten, H-E de Bree, and E. Tijs. Localization and tracking of aircraft with ground based 3d sound probes. Technical Report ERF33, 2007.

[15] T. Basten, H-E de Bree, and S. Sadasivan. Acoustic eyes, a novel sound source localization and monitoring technique with 3d sound. In *ISMA 2008*.

[16] J. Wind, H-E de Bree, and E. Tijs. Source localization using acoustic vector sensors, a music approach. In *NOVEM*, 2009.

[17] H-E de Bree S. Sadasivan, T. Basten. Acoustic vector sensor based intensity measurements for passive localization of small aircraft. In *NSA India*, 2009.

[18] T. Basten, H-E de Bree, and W.F. Druyvesteyn. Multiple incoherent sound source localization using a single vector sensor. In *ICSV 16*.

[19] H-E de Bree, J. Wind, and S. Sadasivan. Broad banded acoustic vector sensors for outdoor monitoring propeller driven aircraft. In *DAGA*, 2010.

[20] E. Tijs D. Yntema J. Wind, H-E de Bree. Acoustic vector sensors for aeroacoustics. In *CEAS Buchares*, 2009.

[21] H-E de Bree and W.F. Druyvesteyn. An acoustic vector sensor based method to measure the bearing, elevation and range of a single dominant source as well as the ground impedance. In *Euronoise*, 2009.

[22] A. Linares, W.F. Druyvesteyn, J. Wind, and H-E de Bree. Determination of the location of a sound source in 3d based on acoustic vector sensors on the ground. In *ASA NoiseCon*, 2010.