Acoustic Vector Sensors on Small Unmanned Air Vehicles

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Introduction

Acoustic sensors can be used to detect, classify and locate battlefield threats such as rockets, artillery, mortars (RAM), gun shots and vehicles such as rotary wing and fixed wing aircraft. Spatially distributed arrays of sound pressure microphones are commonly used for this purpose. The direction of arrival of the sound wave (DOA) is determined by the time of arrival at the microphones.

These spatially distributed microphone arrays are used because conventional sound pressure microphones are not directional. They measure only the scalar value of the sound field, such that measurements at a single point do not yield information on the DOA. The direction of arrival is calculated based on phase differences (or time differences) between the sound pressure microphones at different locations. This technique has some drawbacks, i.e. large system size, for each size the system is able to determine the DOA in a specific limited bandwidth, and, systems suffer from accuracy loss due to wind and temperature changes.

In this paper a new type of acoustic sensor is presented; the acoustic vector sensor (AVS). The AVS is a 4 channel sensor which consists of a (non-directional) sound pressure microphone and the three orthogonal acoustic particle velocity sensors, known as Microflowns, each of which is sensitive in one direction. The ratios between these signals are used to instantly determine the direction of the source (DOA), independent of frequency. This principle makes it possible to determine the direction of the aforementioned battlefield noise sources, from small arms to helicopters to artillery. Since the sensor is only a few millimetres across, it can be mounted on virtually any platform. This means acoustic vector sensors eliminate disadvantages of the array type systems making it a uniquely versatile technology.

A Microflown system for localising rockets, artillery and mortars, called RAM-SCORE, has been developed for the Dutch Ministry of Defence. This system is land based and consists of ten unattended AVS ground systems that are connected by wireless data link. With the experience of this land based system a novel application is now under development: the ability to do similar RAM localisation from a UAV platform. This is the topic of this paper.

Traditional acoustic localisation systems are usually applied on the ground and only rarely used in aviation systems because of their size and weight limitations. The novel AVS does not have these disadvantages. It can therefore even be applied to the smallest of such systems: unmanned micro air vehicles (MAV's). This paper reports on the first flight trials with small UAV's.

The acoustic vector sensor (AVS) on a UAV can be used for multiple applications. Five are discussed here: 1) reconnaissance, 2) sense-and-avoid, 3) landing assist, 4) turbulence sensor, and 5) relative airspeed sensing.

This paper reports on the first flight test results for the reconnaissance application and sense-and-avoid application. The other applications are on a lower technological readiness level and are addressed only briefly here.

The flight test data reported in this document are recorded and post processed. A small 7x7cm, low weight (<150g) and low power signal processing board with the required AVS algorithms has already been developed for a ground based system. It is expected to be ready for use in a UAV in early 2012.

The Acoustic Vector Sensor

Introduction

An AVS consists of a sound pressure microphone and three particle velocity sensors, so called Microflowns, see Figure 2. The Microflown is a relatively new type of sensor and therefore some background information is given below.

The Microflown sensor

The Microflown sensor, invented in 1994 is the world's only true acoustic particle velocity sensor. As can be seen in Figure 1, the sensor consists of two wires which are heated to 200°C above the ambient temperature during its operation. As air flows across the sensor, the upstream wire cools down and gives off some heat to the passing air. Hence, the downstream wire cools down less due to the heated air. This difference in temperature is measured electrically, making it possible to measure the acoustic particle velocity directly. The heating of the wires requires about 70mW.

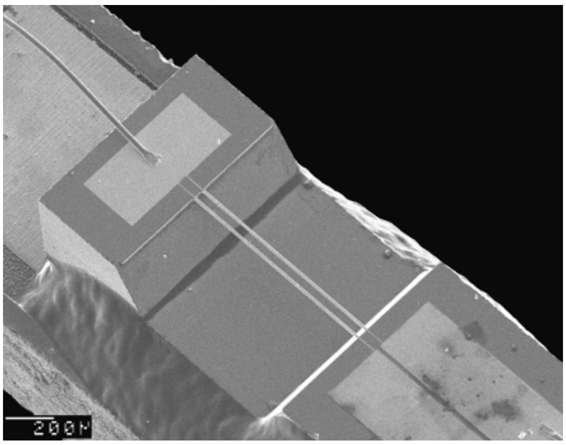

Figure 1: the Microflown sensor.

From 1994 to 2004, a large body of scientific research was undertaken worldwide by academia and industry alike, exploring a wide variety of Microflown measurement techniques leading to hundreds of scientific papers. From around 2004, the sensor became widely accepted, especially in the automotive industry. The technology is currently being used to improve the interior sound quality of the products of almost all major car manufacturers.

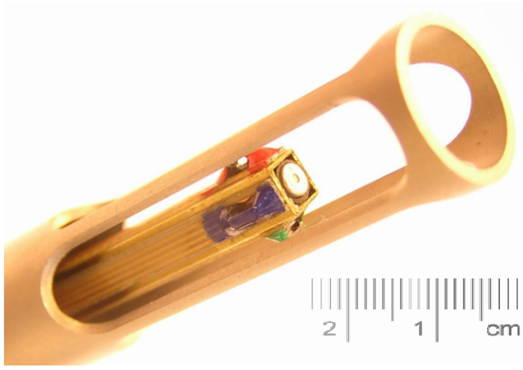

Figure 2: An acoustic vector sensor consisting of a sound pressure microphone and three orthogonally placed Microflown sensors.

A microphone senses the potential energy of a sound wave which is a scalar value (a number). A Microflown senses the kinetic energy of a sound wave which is a vector value (a number with a direction). Both sensors measure acoustics but entirely separate quantities.

One could see the microphone as an 'acoustic voltmeter' and the Microflown as an 'acoustic ampere meter'. The combination of the sensors provides a full understanding of the sound field. An acoustic vector sensor could therefore be thought of as an 'acoustic multimeter'.

This novel 'acoustic multimeter' gives rise to new possibilities in acoustics. The novel possibility that is the topic in this paper is the ability to localise rockets, artillery and mortars from a UAV platform.

Acoustic Vector Sensor based Reconnaissance on a UAV

Introduction

Usually UAVs are used for electro-optical reconnaissance; they are eyes in the sky. The information that these systems provide is significant, as can be understood from the increasing world-wide use of such vehicles.

Although the optical data provides crucial intelligence, the amount of relevant information is somewhat limited. It is very difficult to simply search for threats by visual observation alone. If the sensor suite on a UAV is enriched with an acoustic vector sensor, it can be capable of detecting and localising gunshots, rockets, artillery and mortars. The acoustic detection and localisation from the UAV has 360 degree coverage with a range of several kilometres. The acoustic range and coverage is much larger than that of optical systems (order of magnitude is around 250), as can be seen from Figure 3.

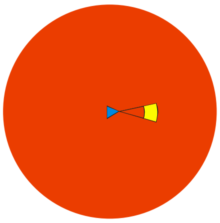

Figure 3: Field of regard comparison acoustic (ROM 80km^2, in orange) versus camera (ROM 0.3km^2, in yellow).

Acoustic localisations can be plotted on the same map that is used to control the UAV and also be transmitted to the battlefield management system (BMS). Once a particular localisation is deemed interesting, the UAV can divert its course to further explore the potential threat optically.

Once a threat is in visual range and localised it is possible to calculate the time difference between the acoustic detection and the actual event. The speed of sound is a known quantity, 340m/s, meaning sound takes approximately three seconds to travel one kilometre. If video data covering the event is stored (for a few seconds) it is possible to 'look back in time' so that the event is selected. Because the location is known, this video-still can be cropped in the direction of the event, meaning a simple picture of the event can be transmitted. These pictures (video-stills) require a low bandwidth and contain just the most relevant information.

The technical specifications, i.e. size, weight and power consumption, allow the AVS to be integrated onto the UAV. This paragraph reports on the first flight tests proving the concept.

First ISR flight tests

The first Intelligence, Surveillance and Reconnaissance (ISR) flight test of an AVS on a UAV was undertaken in 2010. A standard AVS was simply strapped onto a radio controlled aircraft. This test showed that it is possible to detect a source from the ground despite acoustic disturbances such as wind and engine noise. The source was an impulse generated on the ground by a person striking two wooden blocks against each other.

Because of these encouraging results, measurements were repeated with a UAV, controlled by an autopilot from the MAV-Lab of Delft University of Technology. The test platform is a foam Skywalker (wingspan: 168cm, length: 115cm, empty airplane weight: 700 grams), as shown in Figure 4.

Figure 4: A foam Skywalker with an AVS mounted on the nose, just before landing.

The first test was taken at an army airfield with light rain and moderate wind. The UAV was flying at 100 meters altitude with a 10m/s airspeed. As an impulsive source on the ground an Mk9 Thunder Flash (SPL 185dB at 1m) was used.

For these first test trials the signals of the AVS were recorded and post-processed.

Platform noise on the UAV can be categorised as wind noise, propeller noise and platform vibration. The recorded signals are processed in order to attenuate the propeller noise and platform vibration. After this signal processing step the acoustic signals are detected at the UAV with a high signal to noise ratio.

A time-frequency representation of the signals is shown in Figure 5 with colour indicating the sound level. In this representation two impact signals are clearly observed. It can be concluded that it is fairly simple to detect impacts with AVS on a UAV.

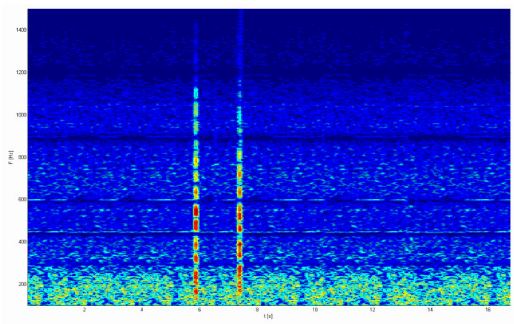

Figure 5: Signals from the AVS on the UAV of two Thunderflash shots on the ground.

The shots are detected at a distance of 300 metres in this example. From these signals and the improvements to be expected in signal processing and packaging, a rough estimation of the detection range is in the order of 5km.

With the AVS it is possible to detect an acoustic event and determine the 3D DOA. The location of the impact is found by combining this 3D DOA with the UAV attitude (pitch, roll and yaw) and position. The accuracy of localisation then is dependent on the range. Directly under the UAV the accuracy is very high (the order of magnitude is metres) with the localisation of a distant (3km) blast being less accurate (order: 200m CEP50). It has to be noted that these values are expectations.

After the promising results of the detection of Thunderflash explosions, a similar test was done at a Dutch mortar shooting range.

81mm high explosive (HE) mortars were shot when the UAV with AVS was flying above and close to the training area. The weather conditions were moderate wind, foggy with a temperature of about 10ºC.

In Figure 6 a time frequency plot is shown. At approx. t=8s a mortar is launched. At that moment the UAV was approximately 500m behind the mortar (downwind). At t=42s the mortar exploded at a distance of approximately 3km from the UAV (downwind).

Both launch as impact can be detected with a large signal to noise ratio.

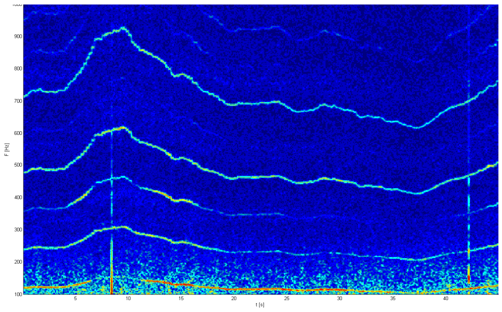

Figure 6: Signals from the AVS on the UAV of 81mm HE mortar launch (approx. 500m distance) and impact (approx. 3km distance).

In Figure 7 the launch is shown in another time-frequency representation. Now the colour indicates a DOA and the brightness is a measure for signal strength. The DOA of the launch (vertical line at t=0.85s) can clearly be seen. The horizontal lines are the propeller harmonics.

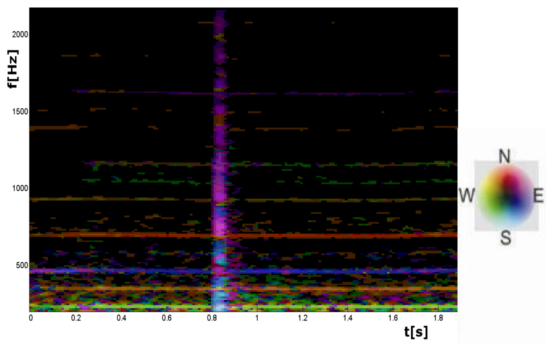

Figure 7: DOA signals from the AVS on the UAV of 81mm HE mortar launch (approx. 500m distance).

It is difficult to determine the accuracy of a DOA signal if the UAV is in flight. This is because the accuracy of the attitude (pitch, roll and jaw) of the UAV is low. In a following paragraph this topic is discussed more extensively.

AVS based Sense & Avoid

Introduction

Unmanned Aerial Vehicles hold a promise as sensors in the sky for many applications. Recent developments have led to the wide availability of autopilots that allow UAVs to fly autonomously in open outdoor areas. However, one of the major remaining limitations for the wide-spread use of UAV's is their lack of sense-and-avoid capabilities.

There has been extensive research on this subject, which has mainly focused on laser range finders, radar, infrared, and cameras. These sensors and corresponding processing algorithms currently can provide UAVs with a capability to avoid static, relatively close-by obstacles. However, none of the aforementioned sensors has proven successful in detecting other dynamic, fast-moving aerial vehicles at large ranges from small unmanned aircraft.

An AVS may be crucial for the avoidance of distant, fast-moving air vehicles. In our previous study, we termed such a strategy "hear-and-avoid". That study involved tests where the sound source was located on the ground. In this article, we report on a hear-and-avoid flight test where the "sound source" is another air vehicle.

First hear-and-avoid flight tests

As mentioned above, the first measurements were undertaken with sound sources on the ground. At first, a UAV fuselage body was positioned on a moving ground vehicle and a test signal (car horn) was measured. Subsequently, a MAV with an AVS on-board flew over a person that striking wooden blocks against each other. Both tests led to successful detections.

Because of the promising results, a test flight with the Skywalker UAV plus AVS and a Cessna 172 Skyhawk (four-seat, single-engine, high-wing fixed-wing aircraft) was arranged in such way that both aircrafts passed by each other at very close range.

On the UAV the data was collected with a 4 channel recorder and later post-processed. In Figure 8 the signals showing the Cessna pass-by are displayed in a time-frequency representation. The colour indicates the signal strength (blue is low, red is high). The upper line (around 450Hz) is the UAV propeller noise and as can be seen, the RPM is not constant.

Below that the signal of the passing Cessna is seen. First the frequency is somewhat constant (375Hz) and it drops after 6 seconds to around 280Hz. This is due to the Doppler Effect. At lower frequencies this pattern is repeated.

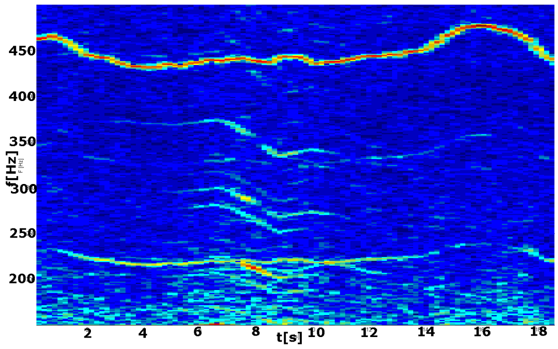

Figure 8: Time-frequency signals of an AVS on a flying UAV during Cessna pass-by. Colour represents signal strength.

This initial test flight shows that it is possible to detect small aircraft at least 6 seconds before the closest point of passing. Speed of approach was around 65m/s. This result is quite promising, especially considering the low-weight, energy efficient AVS sensor, the relatively straightforward signal processing, and the 360° sensing capability. As an illustration, we note that visual inspection of the images made on-board the Cessna and MAV never resulted in detection times greater than 3 seconds before the closest point of passing, if the other aircraft was even visible at all. Automatic processing of the images would certainly be computationally demanding, while not ensuring the same results.

In Figure 9 the same event is shown in another time-frequency representation. Now the colour indicates a DOA and the brightness is a measure for signal strength.

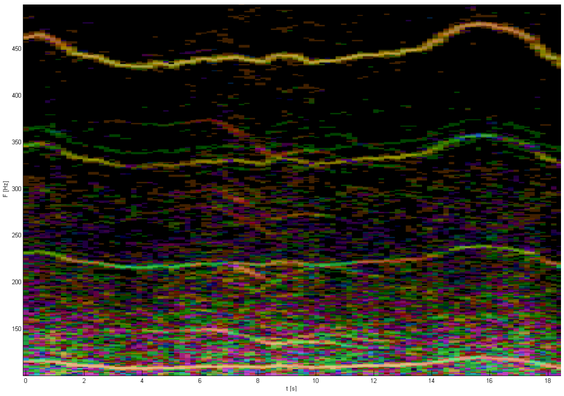

Figure 9: Time-frequency signals of an AVS on a flying UAV during a passing Cessna. Colour indicates a DOA.

Here it can be seen that the propeller noise of the UAV has a certain colour (indicating a certain direction) and the sound of the Cessna has another, varying colour. This indicates a sound source from a different direction. This extra direction information helps with the classification robustness.

In this study only the raw signals are displayed and no dedicated signal processing is done and no optimized mounting is used. The detection range is therefore expected to increase significantly.

A Note on Acoustic Localisation

Introduction

By applying an acoustic vector sensor (AVS) on a UAV it is possible to detect rockets, artillery and mortars as well as other aircraft. The accuracy of the DOA is not tested in the field yet. The actual field test is quite difficult to perform. The precise attitude (pitch, roll and yaw) of a UAV is difficult to obtain in real time and this makes testing the accuracy of the DOA in flight a challenging task. In-flight accuracy tests are planned in 2012.

To get an understanding of the accuracy, a demonstrator is developed comprising a model UAV with an AVS mounted on the nose.

Some preliminary tests have been undertaken with hand claps and loudspeaker signals. The test signals are therefore different from RAM signals. The tests are done in a lab so reflections are present. The effect of the reflections is suppressed with signal processing.

The accuracy of the lab test shows that the accuracy of DOA is high. Even with the propeller switched on, with the sound of the propeller cancelled by signal processing, the accuracy of DOA estimation is hardly reduced.

The UAV demonstrator is also shown at conferences and exhibitions worldwide. This shows that the software and hardware is reliable. The localisation results are displayed in the view of a wide angle camera. In this way there is a direct feedback on the DOA accuracy.

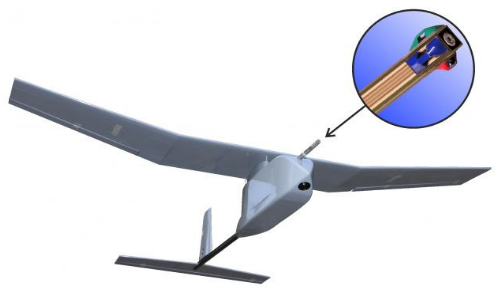

Figure 10: The UAV DOA demonstrator. An AVS is placed on the nose and localisation results are displayed in the view of a wide angle camera.

An accuracy of DOA of 0.6 degrees (CEP50) is not uncommon for a ground based acoustic vector sensor (unattended ground sensor) for a mortar launch at 3km. Uncertainties in the field (wind, topography, reflections) are larger than those on a UAV. On the UAV the wind (speed and direction) is known and the sound will travel undisturbed, in a straight line. The accuracy of DOA on a UAV is therefore expected to be higher than that of a ground based system.

Additional use of AVS on UAVs

Introduction

Once the AVS is mounted on a UAV it is possible to use it for applications other than reconnaissance and sense-and-avoid.

AVS landing assist on a UAV

The automated landing of a UAV is a difficult task, because the various available sensors to measure altitude all have apparent drawbacks. For example, available sonar sensors encounter significant problems when flying over a textured surface such as grass. In addition, laser and infrared scanners are hampered by ambient light conditions, especially in bright light conditions commonly found outdoors. Finally, in combination with inertial sensors, cameras can provide accurate information on altitude. However, the algorithms are computationally expensive and typically rely on either a known target landing zone or the presence of a lot of visual texture. Of course, one can limit the problem of accurately sensing the altitude by employing strategies such as landing in a net, capturing the UAV on a rope or landing by means of a slow-glide flight or parachute.

The AVS could be an additional sensor for measuring the MAV's altitude. The AVS is capable of detecting multiple acoustic sources in 3D. If a UAV is in the landing phase and close to the ground, the noise of the propeller reflects on the ground. It may be possible to localize this reflected sound in order to determine the UAV's altitude. This method depends on the type of soil and the propeller of course needs to be powered.

Another method can be a homing loudspeaker on the ground. Because the AVS can determine the DOA, it is possible to determine the height of the UAV and the location of the landing place. A simple test showed that a small 1W loudspeaker provides a good noise signal at the landing UAV.

If an acoustic homing signal is used it is also possible to land on a moving platform like a driving ground vehicle or sea vessel.

AVS turbulence sensor

In order to get a smooth flight path turbulence is a problem for a small and slow flying MAVs.

The internal sensors are not capable of measuring the turbulence (only the effects of turbulence). It is possible to apply outboard sensors but these are not very practical.

The AVS consists of three particle velocity sensors that are also capable of measuring DC flow. The two sensors that are perpendicular to the flight path can be used to determine the up-down and left-right turbulence.

This idea has not yet been tested on an MAV. Lab tests however have been undertaken where the combination of acoustic signals and the DC flow is made.

AVS as airspeed sensor

Usually a Pitot tube is used to measure the airspeed of the UAV. It is also possible to use a Microflown sensor to determine the airspeed. The Microflown sensor is very sensitive and will overload if the airspeed is directly fed to the sensor. It is possible to use a shunt and send only a fraction to the sensor. It is also possible to use the Microflown sensor as a hot wire anemometer.

Conclusion

In this paper the use of an acoustic vector sensor on a UAV is demonstrated. The sensor is very small, lightweight and low in power consumption.

It was shown that it is easily possible to detect mortar launches and impacts up to 3km distance.

In another realistic flight trial it was shown that it is possible to detect other aircraft (in this case a Cessna) 6 seconds before the closest pass by distance of the UAV and other aircraft.

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