Acoustic vector sensors for soldier and compound protection
localizing snipers, small arms fire, rockets, artillery, mortars, RPG’s and rotary wing aircraft

Hans-Elias de Bree¹, Henk te Kulve²
¹ Microflown AVISA (NL), ²MoD, The Netherlands

Summary

In cooperation with the Dutch Ministry of Defence (MoD) a live demonstration is prepared that shows the ongoing developments of the so called Discus project in the 'mix of sensors framework'.

In a compound defence scenario a mix of sensors is used. In order to create an enhanced situational awareness sensor fusion allows for instance the readings of fully spherical acoustic vector sensors to cue a narrow field of view electro optical PTZ camera in to a certain direction.

In this compound scenario several novelties are presented. The acoustic vector sensors that are presented are new and the Dutch MoD is the launching customer of this technology. In 2012, the Dutch MoD procured three systems for both target practicing and battlefield operations.

Human hearing comprises of two microphones (ears), providing a full spherical detection capability. Often, if one hears an event, the narrow field of view eyes are used to confirm the event. This approach has been industrialised by building arrays of sound pressure transducers/microphones that can be used for the acoustic detection and localization of threats.

However these systems have a narrow banded frequency where they can be used, as the intermediate distance in between the microphones determines the optimal frequency. With the invention of the Microflown, acoustic particle velocity has become a directly measurable quantity next to its twin sound pressure. Acoustic particle velocity is directional, i.e. a vector value.

Acoustic vector sensors combine a sound pressure transducer with three acoustic particle velocity sensors. Acoustic Vector Sensors (AVS) are broad banded, capable of detecting all sorts of threats along the acoustic spectrum, providing a multi threat detection capability rather than a narrow banded capability.

As the AVS are passive and low power, they can be used as unattended ground sensors, also for covert/silent watch operations. For compound protection the AVS can locate threats such as rockets, artillery, mortars (RAM), small arms fire (SAF), ground vehicles, rotary wing aircraft (RW), propeller driven fixed wing aircrafts. AVS hear all around in a full spherical bubble, require no line of sight and can be used also during unfavourable weather conditions, e.g. fog. AVS have local processing capabilities, putting only a modest burden on the bandwidth of a network such as the Dutch BMS.

AVS allow multi spectral measurements and provide synergies with other sorts of sensors. Narrow field of view cameras can be steered in to a certain direction, providing the eyes on target that are often required according to rules of engagement.

The acoustic localisation of mortar shots and multiple position SAF will be shown in the demonstration as well as the integration in the Dutch Battlefield Management System (BMS, Hyperion). The acoustic vector sensor localisation system has an open interface that is so straightforward that it took one hour for the experts to connect the acoustic vector sensor localisation system to the BMS.

Apart for the primary, and local use in this compound protection scenario, the acoustic vector sensors of various compounds can be linked creating a large area sensor coverage. Now the system acts as a border control that can be used to locate distant RAM, SAF etc. but also support UN missions in order to detect e.g. violations of treaties.

The acoustic localisation of RAM signatures is studied thoroughly by the Dutch MoD and Microflown AVISA in previous research programs. Novel findings and achievements that are found in studies preceding the compound protection demonstration are presented in this paper. They include SAF as well as RW detection, classification and localisation.
Demonstration of compound protection 26/27 February 2013

A the Dutch shooting range ‘ASK ‘t Harde’ a compound protection demonstration was given. The scenario was a group of people disembarking a ground vehicle. The group splits up. Two persons go north and the rest is moving west.

At a certain time the group starts shooting SAF and later they employ even 81mm mortars. In this demonstration for safety reasons the SAF shots are fired with blanks and the mortar was shooting outwards.

The SAF and mortar shots of the westward group is detected with the acoustic sensors, the mortar is tracked with Radar. The localisations of the acoustic system is communicated to the battlefield management system (BMS, Hyperion) and plotted on the map. With this localisation the electro optical camera is queued to the group and counted measures are taken.

At the same time second group that moved north shows to be a sniper and single shots are fired at 1km from the compound. Because all of the attention is focussed on the west group and because that group and the counter measures make a lot of noise, the sniper is unnoticed.

The acoustic localisation system however locates the sniper together with all other acoustic localisations. The location of the sniper is communicated to the BMS. A quad copter UAV is checking the location of the sniper and with eyes on target the appropriate counter measures are taken.

In order to host the groups in an appropriate way, the demonstration was repeated four times. One time for the press, one time for the 70 international attendees and the next day two times to host the 130 Dutch attendees of MoD and law enforcement.
Introduction

Traditionally acoustic sensors (microphones) have been used to detect, classify and locate battlefield threats such as rockets, artillery, mortars (RAM), small arms fire (SAF), ground vehicles, rotary wing aircraft (RW), propeller driven fixed wing aircraft and jets. Spatially distributed arrays of microphones are commonly used for this purpose. As the array size determines the frequency range of localisation, for each threat a specific different size array of microphones is required.

In this paper a novel type of broad banded and therefore multi-threat acoustic sensor is presented: the Acoustic Vector Sensor (AVS). The AVS is a 4 channel sensor which consists of a (non-directional) microphone and three orthogonal acoustic particle velocity sensors, each of which is sensitive in one direction. 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 pre-mentioned battlefield sources.

The typical size of an AVS sensor is only a few millimetres, it weighs less than 10g and it consumes almost no energy (<100mW) therefore this broad-banded multi-threat sensor can be used on almost all platforms. The AVS is passive, requires no line of sight and has a fully spherical field of regard. This means that an AVS removes many of the disadvantages of the traditional array type systems making it a uniquely versatile technology.

In cooperation with the Dutch MoD, AVS ground sensor systems have been developed that are now in daily use on shooting ranges for the following uses: as a safety system, as plotting system for the annual mortar shooting competition, to certificate the forward observer for its ability to localize impacts, and to analyze the mortar fire support chain. The ground based systems are tested and sold worldwide.

In cooperation with the Dutch MoD AVS are now upgraded to be used on (convoys of) ground vehicles in order to localize (urban) SAF, RPG's, RAM and rotary wing aircraft. In cooperation with several UAV manufactures the AVS is now being upgraded to be able to localize RAM and SAF in flight. In cooperation with the Dutch MoD the AVS is also being developed to be able to localize RAM and SAF from a rotary wing aircraft in order to develop a hostile fire indicator.

Acoustic Vector Sensor

An acoustic vector sensor (AVS) is capable to instantly determine the direction of arrival (DOA) of a sound wave emitted by any relevant sound source of the battlefield.

To get a proper understanding of the AVS, the traditional technique to determine the DOA of a sound wave is explained in relation to this novel technology.

Because conventional microphones are not directional, acoustic measurements at a single point do not yield information on the DOA. To obtain directional information, microphones are spatially separated. The DOA is calculated based on phase or time differences between the sound pressure microphones at different locations. This technique has drawbacks.

**Large system size**, starting from 50cm for SAF up to 25m for RAM localization. A complete AVS system (sensor, data acquisition, digital signal processor, GPS module and transmitter) has a size of less than 27cm and weighs less than 2kg.

For each size the traditional array system is able to determine the DOA in a specific **limited bandwidth**. So for each specific threat a specific array size is required. The AVS is capable of localising all relevant battlefield acoustic signatures all with the same sensor.

Traditional systems suffer from **DOA accuracy loss due to wind and temperature** changes. For RAM localization systems weather stations are required increasing the complexity, size and weight of these systems. The AVS DOA accuracy is not affected by wind and temperature.

The physical size of **arrays limits the use in certain sound fields**. A lot of sound fields are contaminated with (early) reflections compromising the DOA determination. This is for instance the case in urban SAF localization. The AVS sensing element has a typical size of a few millimetres. The DOA therefore is determined at a single spot in space and is a direct output of the AVS sensor and is available with each audio sample. This means that the DOA can be determined before any reflections might occur.

The AVS is in daily use with the Dutch MoD and the systems have shown to be ruggedized and reliable.
Fig. 3: The AMMS is used by the Dutch MoD

The commercial name for the AVS ground sensor depicted in Fig. 3 is the Acoustic Multi-Mission Sensor, or AMMS.

The AMMS weighs less than 2kg and consumes less than 2W to power the AVS sensor, the data acquisition and signal processing unit, the GPS and communication port (that can be a transmitter up to 10km LOS, Internet Protocol, or wired to, e.g. the battlefield management system).

By fielding multiple AMMS, a network is created which is able to detect, classify and accurately localize RAM, RPG, SAF and RW signatures.

Each AMMS communicates (through a wireless connection, IP or wired) with the Main Station Command Post (MSCP) which combines the information of all AMMS to a localization.

The DOA accuracy of the individual AMMS is dependent on signature, environment and signal to noise ratio. Based on numerous localizations at several shooting ranges world wide, typically the DOA error is just above one degree CEP for RAM signatures ranging 1 km to 10km and below 1 degree CEP for SAF signatures up to 1km.

Typical detection range for RAM is in the order of 20km for e.g. 81mm mortars. For SAF such as 5.56mm, 7.62mm and .50 cal. the typical detection range is in the order of 5 - 7km.

An AMMS can record raw audio data for twelve hours continuously. This feature is used for R&D purposes.

RAM-SCORE

RAM-SCORE is the product name for target practising on shooting camp systems as sold from 2012. The system consists of between 6 and 10 ground based acoustic vector sensors (AMMS) that are positioned semi static around a shooting range.

The AMMS are powered (for about a month) with a normal 12V car battery. Each acoustic event triggers the sensors, the signal is classified and when relevant, the detection is (DOA) localized and transmitted wirelessly to the command post.

The system is now operational and used on a daily basis by the Dutch MoD as safety system, as RAM impact plotting system for the annual mortar shooting competition, to certify forward observers for their ability to localize impacts and to analyze the mortar fire-support chain.

The RAM-SCORE system shows to be easy to set up (fielding takes a few minutes per sensor), highly reliable (much less than 1 false alarm per day) and very accurate (accuracy is a few square meters for a shooting range of 40km² or 5x8km).

All localizations of the point of origin (POO) and point of impact (POI) of an 81mm mortar shooting competition are shown in Fig. 4 and Fig. 5 as an example.

The accuracy of the system is better than 8.5m CEP while the repeatability is better than 2m, see Fig. 5.

Fig. 4: All mortar launches and impacts of a day.

Fig. 5: Zoomed in graph from Fig. 4. The repeatability of launch localizations is very good: four shots from the same position are localized within 2 meter.
Compound protection, RAM

In the last few years the AMMS acoustic vector sensor is tested in many scenario's, mostly on artillery and SAF shooting ranges.

The RAM-SCORE system locates RAM signatures with various ground sensors surrounding the target area. The system is used to accurately locate (within 10m) RAM signatures. In such a scenario SAF signatures are normally seen as noise that needs to be suppressed.

In this paper the focus is on compound protection.

In the compound protection scenario the sensors are placed around a certain area where human activity takes place that introduces background noise. The localizations of threats needs to be facing outwards.

The main purpose of the system is to detect classify and locate (acoustic) threats in order to alert and to be used to steer an electro-optical camera and/or Remote Weapon Station (RWS) for verification and possible counter actions.

The required accuracy of the system is linked to the camera system and has a rough order of magnitude of 1 degree angular and 20% of distance. The false alarm rate must be much lower than one error per day.

In cooperation with the Dutch MoD the compound protection scenario is being tested in February 2013.

In preparation of this scenario several tests are done at the ASK shooting camp (NL) and in WTD91 Meppen (Germany). Gridlines on the map represent 1km. The position of the POI and POO are measured accurately with DGPS and marked with a yellow star, the localisations are marked with a red square and the AMMS sensors positions are indicated with blue circles.

In the Meppen test a propane cannon (similar to that used to scare birds) was used to simulate RAM signatures. Four sensors are positioned in an approximate line of 850m from end to end. Ten shots per location are detonated. The accuracy of localisation in this scenario was very high except for two outliers. The most outward impact location (1300m NE) is observed. Eight out of ten impacts are very accurate with an error of 2.5% of range. The two outliers have an accuracy of 20% of range. All localisations have a 0.2 degree accuracy in bearing.

At the ASK shooting camp four sensors are used in a somewhat rectangular configuration. 81mm mortars are fired (POO, shown in Fig. 7 the lower-left) towards the array. The maximum error of the POO is 2% of range and maximum DOA error is 0.5DEG. The DOA accuracy is lower than the Meppen scenario due to the different sensor configurations. In Meppen the sensors are positioned in a line and at ASK in a square.

The line configuration is better to reach lower DOA errors if the detections are perpendicular to the array. The square configuration is better if detections can be expected from all directions.
**Sniper localisation**

In this context a sniper is defined as a single shot with a small calibre rifle and a supersonic bullet. Because the bullet travels faster than the speed of sound, its shock wave is detected earlier than the muzzle blast. The range between the sensor and shooter can be calculated out of the time difference of detection, the difference of direction of arrival (DOA) and signal properties of the shockwave. This procedure is known in literature and is not discussed here.

For the localisations only particle velocity signals are used, the sound pressure microphone is not required.

All localisations are pre-recorded and analysed in post processing with the same algorithm and no special signal processing is done to smooth or upgrade the signals.

The capability to locate a sniper with a single AMMS is proven in the last years in various scenario's and various R&D programs in the US and Europe. In this paragraph some examples of the single AMMS sensor system are given. It is also possible to locate the sniper with a network of AMMS. This method is explained in the next paragraph "SAF localisation".

A typical time signal of a single shot is given in Fig. 8. The acoustic vector sensor signal (that is sound pressure plus three particle velocity signals) is represented in a time-frequency-DOA format. In this graph the colour indicates the direction of arrival (DOA) and the brightness of graph indicates the signal strength.

The results of a test with a prototype R&D sensor at the Dutch shooting range ASK ‘t Harde is shown below. A series of shots are fired with various types of small calibre rifles. The positions of the sensor, the shooter and the target are measured in accurately.

In Fig. 9 a representation for a shooter localization is depicted. The blue line shows the direction of the shooter (accuracy 1.5 degree CEP80) and the blue box (in this case a size of 36 by 100 meters) indicates that the shooter is in that box with a probability of 80%. These results can still be improved with the AMMS sensor.

![Fig. 8: Acoustic vector sensor signal of a sniper shot represented in a time-frequency-DOA format.](image)

![Fig. 9: Graphical interpretation of the SAF localization results with an R&D sensor. Top: localizations of each shot. Bottom: 80% probability that the shooter is in the box. Red line is the trajectory of the bullet. Red dotted line: DOA of shock wave.](image)

After these tests the AMMS sensor was used for SAF localisation, it has a better DOA accuracy than the R&D sensor resulting in a better range accuracy.

Some examples of typical scenario's are presented below.
The most simple scenario for SAF localisation is a single shot and relatively open environment (no mountains, buildings etc.). Three AMMS are fielded, see Fig. 10, the results are presented separately for each sensor (results are not networked). The distance from sensor to shooter is 240m; 10 shots are fired with AK47 (7.62mm) and 5 shots with .50 cal. ammunition.

Because of the limited number of shots (15) the maximum error and the mean error is noted. These errors are usually larger than the CEP but the latter is not valid for such a small number of shots.

For AMMS number 1 the closest point of approach (CPA) is 20m. The maximum muzzle blast DOA error is 0.9DEG and the absolute mean DOA error is 0.5DEG. The range estimation error is maximum 17% and has an average 14% (all underestimated, i.e. closer to the sensor).

For AMMS number 2 the CPA is 38m. The maximum muzzle blast DOA error is 0.6DEG and the absolute mean DOA error is 0.3DEG. The range estimation error is maximum 7% and has an average 6% (all underestimated).

For AMMS number 3 the CPA is 120m. The maximum muzzle blast DOA error is 0.7DEG and the absolute mean DOA error is 0.3DEG. The range estimation error is maximum 9% and has an average 4% (all underestimated).

Because the AMMS can localize each audio sample it is not sensitive for reflections. The localisation algorithm shows to be robust in this scenario.

The signature of a single shot in an urban scenario is shown in Fig. 11. Because of the high dynamic range, the absolute values of the time signals are shown on a Decibel scale.

As can be seen in Fig. 11, the velocity signals have a better signal to noise ratio (approx. 50dB) than the sound pressure signals (approx. 30dB). The noise is caused by background noise and the (omnidirectional) sound pressure signal is more susceptible to this than the particle velocity signal.

The urban setting causes a reverberation time of approx. one second, see Fig. 11. The shockwave is the first maximum of the signal, the muzzle blast is the second. In comparison the signals of a single AK47 shot in the open field is shown in Fig. 12. Here the reverberation time is about 0.1s and because of the lack of background noise the signal to noise ratio difference between particle velocity and sound pressure is about 10dB (in the urban scenario this was 20dB).

Fig. 10: Simple scenario for the localisation of snipers.

Fig. 10: Simple scenario for the localisation of snipers.

The urban scenario is more difficult because of the reflections on buildings causing reverberation. This example is not the most difficult because only a single shot is observed. A salvo of shots in an urban environment is more difficult to localize because the shock waves and muzzle blasts mix making it difficult to separate and combine each signature.
In this example three AMMS were fielded, see Fig. 13, the results are presented separately for each sensor (results are not networked). Three single shots are fired with an AK47 at close range (91m).

For AMMS1 the CPA is 8m. The muzzle blast DOA errors are 0.1, -0.1, -0.1 DEG. The range estimation error is 4.5%, 3.5% and 2.3%.

For AMMS2 the CPA is 26m. The muzzle blast DOA errors are -0.3, 0.7, -0.5 DEG. The range estimation error is 5.8%, 5% and 9.5%.

For AMMS3 the CPA is 53m. The muzzle blast DOA errors are 0.2, 0.9, 0.4 DEG. The range estimation error is -2.3%, 2.7% and 1.9%.

Fig. 13: Urban scenario, single sensor localisation, single SAF shots.

Another issue in the urban scenario is that in some cases the SAF signatures are located beyond line of sight for the sensor position. In a test with the Dutch police, a 9mm pistol with blanks was fired on a courtyard. AMMS1 is positioned 3 meters from a wall and AMMS2 is placed on a box elevating it 1 meter above the ground, see Fig. 14).

Remarkably, the blanks that are fired beyond line of sight could still be localized. The accuracy is less than with line of sight localisations (In this example 3DEG). It is believed that this is possible because the DOA is determined for each audio sample. The first samples of the detection are in the direction of the shortest path, in this case over the 4 meter high roof.

Long range sniper localisation with high CPA.

A .50 cal. sniper is located 731 meters from the sensor (AMMS4, Fig. 15) and a shot is fired with a CPA of 327m. The sniper is located with an accuracy of 5% of range and 1.1 degrees in DOA.

In this scenario it is difficult to give a clear definition of signal to noise ratio (SNR). If one only observes the raw signals the SNR is larger than 20dB. This means that automatic detection and direction finding is straightforward. It also means that this range is not the maximal range that a sniper can be localized.

The time difference between shockwave and muzzle blast is large if the shooter is far away and the CPA is small. As the CPA becomes larger the time difference becomes smaller. However if one keeps the CPA constant and the shooter distance smaller, the time between shockwave and muzzle blast also becomes smaller. It is therefore impossible to get range information from the time difference alone.
Fig. 15 is a special case. The shock wave is only observed in front of the shooter (with approx. 140 degrees, depending on bullet velocity). AMMS2 is exactly on this limit. Due to this the shock wave and muzzle blast coincide. The muzzle blast therefore cannot be detected automatically. When the signals are processed manually, the range estimation was exact and the DOA error is 0.3DEG.
SAF localisation

In this context small arms fire is defined as anything that shoots in a flat trajectory with a limited calibre, can be subsonic or supersonic, fired in single shots or bursts, and both incoming and outgoing fire.

As an example of burst fire 11 rounds of 5.56mm are fired 394 meters from a single AMMS sensor (number 1 in Fig. 14) with a CPA of 60 meters in hilly terrain.

The absolute mean error in the DOA of the muzzle blast is 0.5DEG and the absolute maximum error is 1DEG. For each bullet the range estimation can be done. The maximum range error is 5% with a mean of 1.9%.

The difficulty with a burst signal is that the (reverberation of the) shockwaves might mix with the muzzle blasts. The complexity of the problem is dependent on the environment (reverberation), the range of the shooter (low sound level muzzle blast) and the CPA (in case the shockwaves mix with the muzzle blasts). This mix of variables makes it difficult to predict the robustness of the method to handle burst signals.

The ability to detect and locate SAF signatures with a single sensor is interesting but in order to detect and localize the shooter, the bullet needs to pass the sensor with a certain limited closest point of approach (CPA). The maximum CPA is in the order of 500 meters.

Since the sensors can easily be separated by more than 1km this relative large CPA restriction may not always be sufficient for compound protection as it may be possible to shoot between the sensors without being localized.

Another method to locate the shooter is by using multiple, networked AMMS. The SAF signature (either muzzle blast or shock wave or both) detected by multiple AMMS is now combined to a shooter localisation and a bullet trajectory.

The advantage of the networked solution is that the localisation becomes more accurate but more importantly, the system also becomes more reliable. This makes it possible to increase the complexity of the scenario and still accurately locate shooters.

RPG localisation

For a test, RPG’s were fired at the infantry shooting camp (ISK). Multiple AMMS were fielded, ranging from 10 meters up to 500 meters from the RPG location. The signals of the RPG being fired were recorded for analysis.
The emitted sound power of an RPG is higher than e.g. a 81mm mortar shot, but the effective range of the RPG is much lower than the mortar. The signal to noise ratio (SNR) of a relevant RPG detection is therefore much larger than the expected SNR of a mortar. It is therefore concluded that RPG's can be detected, classified and localized with the standard AMMS localization software.

RW localisation

The detection, classification and localisation of rotary wing aircraft (RW) has been investigated for several years and in several R&D programs. The localisation of RW is supported by the Dutch MoD.

In contrast to the impulsive signals RAM, SAF and RPG, the acoustic signature is harmonic. This makes the methods for detection, classification and localisation different than the impulsive signals.

At this stage of the R&D it is possible to detect and classify a helicopter and discriminate between main and tail rotor making it possible to classify the type of helicopter.

The localisation is now based on triangulation in 2D (no elevation).

A test with a sensor spacing of 100 meters showed that any helicopter could be localized up to 200 meters and up to 50 knots speed with an accuracy better than the actual helicopter dimensions, see Fig. 18. Because of these promising results, the test will be repeated with larger sensor spacing, higher speeds and distance.

![Fig. 18: Localisation of RW. Blue: On-board GPS, green: raw data, red: localisation that includes history of localisations. (Units are meters).](image)

The localisation in 3D is a research topic in the near future as well as the detection range estimation.

Other platforms

The AMMS is a sensor that is designed for static use on the ground. The first AMMS based applications are sold. RAM-SCORE for RAM target practising and shooting range safety. The same sensors are sold for a compound protection system that where the acoustic localisations are fused with the battlefield management system with RADAR and electro optical camera's.

Apart from static AMMS ground sensors the use of Acoustic Vector Sensor (AVS) technology is used on other platforms.

A lightweight version of the AMMS is in development as a man portable system. In cooperation with the several European MoDs the AMMS is adapted to be used on a ground vehicle.

With an aerodynamic packaging the AVS is made suitable to be used on a 2kg class UAV. The AMMS is being upgraded to be used on a rotary wing aircraft.

Man Portable AMMS

A lightweight version of the AMMS is in development as a man portable system. The man portable AMMS is similar to the AMMS but to reduce the mass lightweight materials are used. Two versions are in development. One is powered with the USB port of a toughbook computer that is used by for instance the forward observer. The other is powered with 4 AA batteries for a day use.

The main purpose of the USB powered version is to assist the forward observer / forward air controller. The acoustic localisations are communicated trough the USB port and are displayed on a separate application that runs on the toughbook. Main focus is an acoustic situation awareness for SAF and RAM.

The battery powered system can transmit up to 10km line of sight. It can therefore be left behind when troops are moving in order to cover their back.

Ground Vehicle AMMS

In cooperation with multiple MoD's (the Dutch MoD has the lead in this) the ground based AMMS is upgraded to be used on the ground vehicle. It is now possible to demonstrate this technology in a realistic environment for a single sensor on a single ground vehicle, see Fig. 19.
The AMMS is able to localize SAF with a CPA of 500m. This means that a shooter is localized if the bullet passes the ground vehicle within a radius of 500m. Dismounted soldiers in the vicinity of the ground vehicle are therefore protected by the vehicle. After localizing the hostile shooter its location can be pointed out by radio and the vehicle can provide fire support.

If the SAF / RAM / RW localisations are fused with the local aria network the SAF / RW localisations become more robust. The wide area network is used to fuse the RAM and RW localisations with other users (e.g. compounds, police posts, forward observers and other convoys).

**AVS on UAV**

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 (rough order of magnitude, ROM, is around 250), as can be seen below.

![Field of regard comparison acoustic (ROM 80km², in orange) versus camera (ROM 0.3km², in yellow).](image)

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.
Fig. 21: A foam Skywalker with an AVS mounted on the nose, just before landing.

In the figure below 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.

Fig. 22: Signals from the AVS on the UAV of 81mm HE mortar launch (approx. 500m distance) and impact (approx. 3km distance).

**Sense and avoid**

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.

An AVS is capable of localizing distant, fast-moving air vehicles. 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 the figure below 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.

Fig. 23: 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. In the figure below 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.

Fig. 24: Time-frequency signals of an AVS on a flying UAV during a passing Cessna. Colour indicates a DOA.

The previous results are obtained by flying the UAV, recording the data and post processing this data to results. Recently the UAV is upgraded in such way that the localisation results can be displayed in real time. Fig. 25 shows the time signals of an AVS on a flying UAV when a propane test cannon is fired. The left graph shows...
the unfiltered data, in the middle one the propeller noise is removed and in the right one the wind noise is cancelled. This processing can be done in real time at the UAV. The localisation relative to the UAV is transmitted to ground station and georeferenced.

Fig. 25 left: unfiltered time signals. Middle: the propeller noise is removed. Right one the wind noise is cancelled.

Fig. 26 shows the output of the electro optical camera that is seen on the ground in real time. Upper-right a person is seen. This is the position of the propane cannon. The red dot that is seen close by the person is the acoustic localisation of the event.

Fig. 26: Electro optical camera real time view of the camera in the UAV. The red dot is the acoustic localisation of the propane cannon.

**AVS on a rotary wing aircraft**

In the recent conflicts in both Afghanistan and Iraq, a reported 70 helicopters have been shot down by a combination of Rocket Propelled Grenades (RPGs), Surface-to-Air Missiles (SAMs) and small arms fire (SAF). It is expected that the actual number of rotary wing craft brought down by hostile fire is greater than that reported as many of the incidents do not report the cause. Out of the reported 48 hostile fire incidents where the type of hostile fire is known 20 involved RPGs, 18 involved small arms, and 10 involved SAMs.

Much importance is placed on self-defense systems based on optical sensors, which protect aircraft from large projectiles with a thermal signature, such as shoulder launched SAMs or man-portable air-defense systems (MANPADS). Such self-defense systems are available and in operation today, as sensors have been developed to detect that specific type of threat. The statistics show, based on data from Iraq and Afghanistan, that most aircraft are engaged by small arms and RPGs, compared to SAMs (38-10). However, there has not been a suitable sensor capable of detecting, classifying and locating small arms and RPG threats. Microphones have been experimented with and are available in ground based systems for detecting supersonic bullets and muzzle blasts.

A helicopter is a very noisy environment and crewmen have little or no acoustic situational awareness of the outside environment. Small arms fire directed at a helicopter is often not detected until damage occurs, and even then the crew often doesn’t know where it’s coming from. If hostile fire could be detected and located immediately, then the crew could be informed of the source. It would allow either more rapid evasion and/or response with well-directed suppressing fire.

As a first step the AMMS sensor is mounted on a small rotary wing, see Fig. 27. The data was captured and in post processing it showed possible to detect the SAF muzzle blast and locate the bullet passing UAV.

Fig. 27: Electro optical camera real time view of the camera in the UAV. The red dot is the acoustic localisation of the propane cannon.

Fig. 27 AMMS on a UAV.

After these encouraging results a test was done with a propane gun as sound source on the ground and the AMMS on a Cougar rotary wing hovering, see Fig. 28.
Fig. 28 upper: the propane cannon is used as sound source to be detected by the AMMS on the steps of a Cougar hovering.

Some typical signals are shown below. The time signals are shown in Fig. 29. Left the raw signals are shown and right the processed signals. As can be seen, it is possible to reduce the platform noise substantially.

Fig. 29 Left: raw time signals, right processed signals detecting SAF.

Discussion

The AMMS sensor that is used by the Dutch MoD on a daily basis shows to be robust and stable. The sensor is now used for the localisation of RAM signatures, for optimal accuracy 6 to 10 sensors are surrounding the target area (expected point of impacts) and the current software purposefully filters out SAF signatures.

In the study that is discussed in this paper 4 to 6 AMMS were used in a compound protection scenario where the acoustic localisations were facing outwards and were used to fuse with RADAR data and to steer an electro-optical camera to get eyes on target.

The AMMS localisation software is upgraded for the outward localisation of RAM signatures and shows to reach the accuracy requirements to cue the electro-optical camera. The software reports to a local graphical user interface as well as the Dutch Battlefield Management System (BMS) making it possible to share the acoustic localisations by the military network.

The software to support the AMMS localisation is developed in close cooperation with the Dutch MoD. The software is upgraded if it serves a certain scenario. The localisation of RPG's is directly possible but not included in the current software. A minor system upgrade will make this possible.

In this study it shows that the sniper localisation with a single AMMS sensor works well (also in complex scenario's) and that a networked system enlarges the area where SAF signatures are localised.

All SAF localisation results in this paper are post processed with the same software and it is therefore directly possible to upgrade the AMMS and their localisation software to handle SAF signatures. At the moment it is possible to demonstrate SAF localisation in real time and in a relevant environment (shooting range).

The detection, classification and localisation of rotary wing aircraft has been studied thoroughly and the algorithms work well. In a separate study it shows that the rotary wing detection, classification and localisation software may easily be upgraded to propeller fixed wing and UAV's. The capability to detect, classify and locate rotary wing aircraft will be integrated in the man portable AMMS.

The acoustic vector sensor provides a multi-threat detection and localisation capability as it can be used to locate all relevant acoustic battlefield signatures on a variety of platforms. The developments on platforms are on different technology readiness levels. The acoustic localisation of RAM and SAF from a UAV and ground vehicles are in TRL 6: prototype demonstration in relevant environment. The acoustic localisation of RAM and SAF from a rotary wing platform is in a lower TRL.

Conclusion

The acoustic vector sensor provides a multi-threat detection and localisation capability as it can be used to locate all relevant acoustic battlefield signatures on a variety of platforms. The developments on platforms are on different technology readiness levels. The acoustic localisation of RAM and SAF from a UAV and ground vehicles are in TRL 6: prototype demonstration in relevant environment. The acoustic localisation of RAM and SAF from a rotary wing platform is in a lower TRL.
The ground based AMMS sensor is at the highest TRL. It is sold to the Dutch MoD for various applications. The topic of this paper is ground based systems for compound protection.

The AMMS sensor is a ground based vector sensor that is capable of detecting and classifying RAM, SAF and RW acoustic signatures. With a single sensor it is possible to locate SAF even in acoustic difficult scenario's, i.e. urban, bursts, long range.

With a networked solution it becomes possible to accurately locate RAM, SAF and RW acoustic signatures for a compound scenario.