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Echolocation as Acoustic Form of Relative Positioning

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ABSTRACT: To introduce order in the movement of many objects, they need to avoid collisions with their neighbours by knowing their position and reacting to it. This paper proposes using sound localisation, which can be used for short distances because of its limitations. The study is focused on implementing small distance echolocation for the relative positioning of objects by comparing the time difference of arrival to microphones used by the same object. Unlike previous works that rely on communication or external infrastructure this method allows each autonomous system to localise neighbour using only passive sound signals and on-board microphone array. The research aims to develop a navigation system for mobile objects moving in a swarm without communication between the objects. The study develops an alternative for GPS and visual navigation with limitations in specific environments. The software created showed the effectiveness and weakness of echolocation as the choice for different environments, increasing the need to use more types of navigation for drone swarms. This work contributes and early-stage lightweight approach to relative positioning in UAV swarms and provides insight into integrating acoustic sensing into hybrid navigation systems.

1 INTRODUCTION

Sound localisation has been present since the dawn of time and is a fundamental aspect of spatial orientation for humans. Alongside visual localisation based on the sense of sight, it is a key skill for humans to determine the direction from which a sound originates.

Sound localisation has contributed to the development of humanity by facilitating communication and spatial orientation. By recognising the direction of sound, humans can avoid dangers or efficiently carry out their activities. Survival in a hazardous environment would be limited without this ability.

Modern technological solutions draw inspiration from natural echolocation, which animals utilise. Examples include radars and sonars used in maritime and aviation industries. These systems are based on principles similar to those employed by bats and dolphins, enabling the determination of the position of objects in space even if they are beyond visual range.

Currently, the most commonly used navigation tool for unmanned aerial vehicles (UAVs) is the GPS, which functions well when available. The challenge arises when this system becomes unavailable for various reasons (e.g., in urban areas with dense buildings, in tunnels or when the signal is being jammed) or when multiple UAVs operate in the same area. In such cases, an alternative could be visual navigation, sup-ported by acoustic navigation. This work lays the foundation for building a hybrid navigation system based on images and acoustic signals for UAV swarms.

However, both GPS and vision-based systems face limitations in environments with high occlusion, limited lighting, or intentional interference. This raises the need for robust, low-resource navigation alternatives. Echolocation-based positioning, inspired by biological systems, offers such potential, especially for swarming UAVs operating without central coordination or communication.

This study introduces a lightweight echolocation-based approach for relative positioning by implementing and evaluating a passive acoustic method using Time Difference of Arrival and signal strength, demonstrating the potential of echolocation as a complementary technique in hybrid navigation systems for GPS-denied environments.

The remainder of the article is structured as follows. Section 2 discusses the literature on acoustic navigation. Section 3 presents the physical phenomena that can be used to develop a system for the acoustic localisation of mobile objects. Section 4 presents the concept of the laboratory setup and the results of studies on the suitability of acoustic signals for determining object positions. Section 5 provides concluding remarks.

2 RELATED WORKS

An example of sound localisation is the Simultaneous Localisation and Mapping (SLAM) algorithm [1]. This solution is designed to localise a drone indoors and calculate its position based on direct and reflected signals. The drone is equipped with four microphones and a siren. The siren emits sound at a specific frequency received by the microphones at two moments: right after emission and after reflecting off the walls. By analysing the variability of the sound's amplitude and phase and filtering the results, the positions of obstacles and the objects relative to them are calculated. This approach enabled the drone to move within a room without colliding with obstacles.

A similar solution to the audio localisation problem is using a phone to map a room [2]. Using the built-in devices in the phone, a microphone and speakers emit inaudible sounds. The microphone registers the echoes reflected from objects. The difference between these solutions lies in mapping: in the first example, it was performed in real-time from the drone's perspective, while in the second case, locations were assigned features during mapping. Such an approach allowed for error correction during localisation by comparing features. Research into localisation methods used by bats is a base for both solutions.

The described solutions were applied indoors, where the objects in the environment were fixed. The situation changes when multiple objects, such as drones, move in open spaces. Besides accounting for static obstacles, the relative positioning of mobile objects in open space must be introduced. In both cases, mobile objects must be equipped with microphones and speakers that transmit and receive sound signals. These signals allow objects to locate each other using differences in signal delay times and signal strength.

Solution presented in this article replaces echo as the main localisation method with direct signal transmission and reception between different components of the navigation system. As a result, it enables smooth transitions from indoor to outdoor environments and significantly shortens localisation time by avoiding the need to wait for reflected sound signals. The developers focused on relative positioning, intentionally leaving out absolute localisation due to the system's specific application.

Although echolocation is not most commonly used as method for swarm localisation, recent surveys[3] highlight need for diverse navigation solutions. Making it more reliable in different environments and resistant for various external factors. Current methods rely on vision, LiDAR and wireless communication, each with own specific limitations. In this context acoustic localisation could emerge as complementary or alternative approach. This study explores potential of echolocation to fill gaps in scenarios where traditional sensors may fail.

3 SOUND AND ECHOLOCATION

Animals use sound far better than humans to determine their position relative to other elements in their surroundings. Echolocation, also known as biosonar, allows them to navigate, search for food and hunt. To locate objects in space, they use sound reflected off the surfaces of objects or other animals. Among the animals that utilise this navigation method are well-known bats, dolphins, whales, some bird species and hedgehogs. Interestingly, some blind individuals have developed the ability to echo-locate.

The reasons why this skill has evolved include:

- navigating in environments with limited visibility, such as darkness, murky water or fog;
- detecting prey;
- identifying obstacles along a path.

All these reasons connect to localisation and navigation. Therefore, it can be concluded that echolocation is a practical navigation method. Despite many years of evolution and change, many organisms still use it as a fundamental method.

Marine animals such as dolphins and whales [4] use high-frequency sounds produced by forcing air through their nasal passages. These sound waves travel to the forehead and are focused into a beam. When the signal reflects off an object, it is received by the animal's jaw and transmitted to its ears. This process allows the animal to determine the object's size, direction, speed and distance.

Echolocation in the air works somewhat differently. Bats produce sound in their larynx and emit it through their mouths. These sounds can reach up to 140 decibels, but their frequency is too high (ranging from 20–80 kHz [5]) for humans to hear. Bats use reflected sound to identify the size and hardness of objects, and they can detect small insects at distances of up to about 5 meters. To avoid deafening themselves by producing such loud sounds, they deactivate their middle ear just before emitting the sound and restore their hearing just before the echo returns.

Sound is a physical phenomenon involving the creation of a longitudinal acoustic wave that represents a disturbance in the density of a medium. These waves propagate through gases, liquids and solids. Based on frequency, acoustic waves are divided into four types, as described in Table 1.

Table 1. Types of acoustic waves

Type of wave	Frequency
Infrasound	Under 0,016 kHz
Sound	From 0,016 kHz to 20 kHz
Ultrasound	Over 20 kHz
Hypersound	Over 10^7kHz

Humans can hear acoustic waves, referred to as sounds, while others are inaudible. The speed of such a wave is a key factor in determining the distance from the sound source and its position relative to the receiver.

For gases like air, the speed of sound at a temperature of 15ºC (288 K) can be calculated using the formula:

$$v=\sqrt{\frac{y\cdot R\cdot T}{M}}=\sqrt{\frac{1,4\cdot 8,314\cdot 288}{0,029}}\approx 339,99\frac{m}{s} \tag{1}$$

where:
γ - adiabatic coefficient (for air ~ 1.4)
R - universal gas constant (8.314 J/(mol*K))
T - temperature in Kelvin
M - molar mass of the gas (for air ~ 0.029 kg/mol)

Sound frequency offers opportunities to improve research and utilise filtering to detect only sounds of interest. Various filters exist, and the band-pass filter is the most relevant for limiting frequency ranges. This filter allows frequencies within a defined range between two boundary values to pass through.

Basic navigation for humans is visual navigation. However, sound navigation has supported survival for thousands of years by helping detect danger. It allowed for the detection of threatening objects before they became visible. Therefore, it can be stated that it is essential to support the primary form of navigation.

M. Gröhn, T. Lokki, and T. Takala conducted a study comparing sound, visual, and combined audio-visual navigation [6]. Participants in the study had the task of moving from point to point along a specific path in a virtual environment while controlling the direction and speed of movement. They were equipped with a controller that set a motion vector when pressed and moved, whose length and direction corresponded to the speed and direction of movement in the virtual space. Three experiments were conducted: the first involved navigating using sound alone, the second using only vision and the third using both sound and vision.

The study showed that visual navigation outperformed sound navigation, but the combination provided high precision and speed in task completion. The researchers noted that when participants used both the eyes and ears, sound was initially employed to determine the path, while vision was used for greater precision in the final phase. These observations suggest that audio navigation is faster but less precise.

The comparison of visual and sound navigation can also be considered in the context of their use by humans and animals and their influence on environmental adaptation. Both senses play key roles but differ in their mechanisms, advantages and limitations. Table 2 presents the properties of visual and sound navigation.

Table 2. Comparison of visual and sound localisation.

Visual navigation	Sound navigation
Operating principle	
Based on the detection and interpretation of light reflected from objects. Vision enables the perception of shapes, colours, depth, and motion	It relies on the interpretation of sound waves reflected from objects or emitted by the surroundings Uses sound signals, which are then interpreted by the brain to create a "sound image" of the environment
Allows direct perception of the surroundings in real-time and precise assessment of the position and distance of objects	In real-time, it allows for the determination of the direction of a signal with the ability to approximate the distance from its source
Range and accuracy	
Wide field of vision and detailed determination of the distance to an object. Limited in challenging visibility conditions such as at night, in fog, or underwater.	The ability to determine direction and range significantly surpasses visual navigation but is more susceptible to interference, such as noise or other nearby sounds.
Very accurate and rich in details, such as obstacles on the route	Approximate distance estimation without detailed information about the surroundings
Adaptation to environment	
It provides the best performance in environments with good lighting; in open spaces, it provides immense capabilities	Despite its limitations in accuracy, it is much better suited for nighttime, underwater or enclosed spaces where obstacles obstruct vision.
It is accurate and rich in details, such as obstacles on the route	Approximate distance estimation without detailed information about the surroundings
Related Technology	
Cameras, spatial analysis technologies, object recognition	Sonars, radars, ultrasonography

4 LABORATORY SETUP AND RESEARCH DESCRIPTION

Ultimately, each UAV in the drone swarm will have acoustic sensors and cameras. This study will examine the potential of using acoustic signals to approximate the mutual positions of UAVs during flight. The objective will be to determine the distance to the sound source and the direction from which the sound originates in the local coordinates of the UAV station. For this purpose, each drone should have an acoustic signal source and microphones arranged in an array. This approach allows the TDOA (Time Difference of Arrival) algorithm to determine the direction of the sound and the received signal strength to calculate the distance from the source. Based on the data from the microphones, the drone can estimate the position of a neighbour with decent precision over short distances. Each UAV has its reference frame and changes its position without requiring direct communication or GPS navigation. Figure 1 and Figure 2 shows an example of installing microphones and a sound source on a drone.

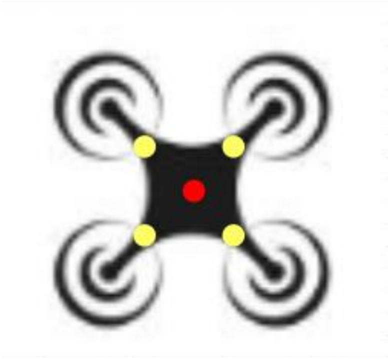

Figure 1. Example of the construction of a drone for acoustic navigation (microphones are marked in yellow, and the sound source is marked in red)

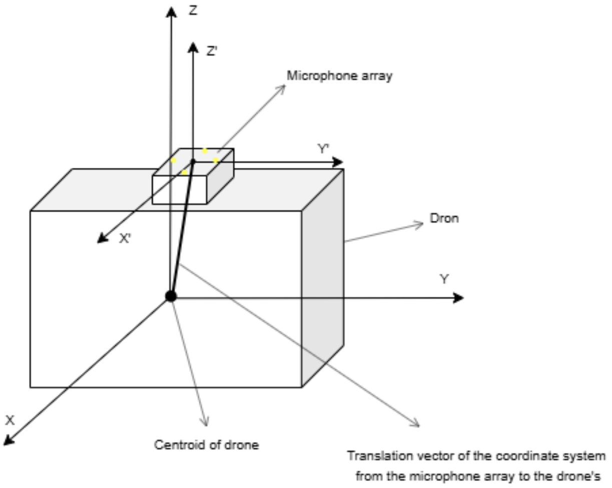

Figure 2. Coordinate systems for a drone and microphone array

Figure 3 illustrates a situation where one drone transmits a sound signal while another receives it using microphones. Assuming that the acoustic signal sources emit signals with the same power, the strength of the microphone's signal allows the distance determination. In such a situation, the position is relative to the coordinate system of the drone receiving the signal. The position of the signal-transmitting drone is determined based on the distance and the direction from which the signal arrives. Figure 4 illustrates the method for determining the position of the sound source on a surface.

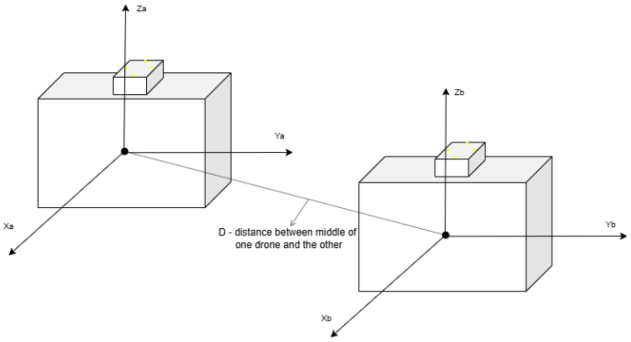

Figure 3. Relative position of drones in their coordination systems

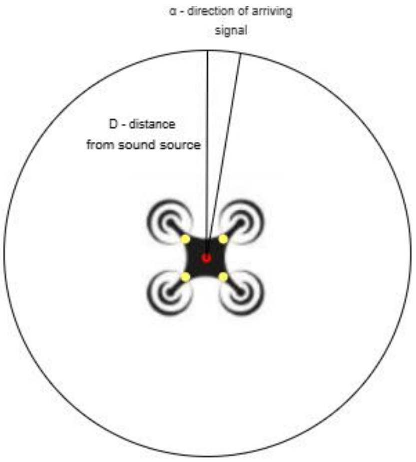

Figure 4. Determining the position of the sound source on a surface

Sound propagates evenly in space. Individual microphones in the microphone array receive the signal at different times. Based on the measured time difference of signal reception by individual microphones Δt_n and the speed of sound, as well as the azimuth from which the sound arrived, can be determined. Firstly, the distance is calculated as it is used to calculate azimuth based on the time difference of arrival.

$$d_n = v_d \cdot \Delta t_n \tag{2}$$

where:
d_n - distance of the n-th microphone,
v_d - speed of sound,
Δt_n - time difference for the microphone.

Assuming that in the coordinate system of the microphone array, the microphones have coordinates (x1,y1), (x4,y4), and the sound source has coordinates (x,y), the actual distances of individual microphones from the sound source is calculated using the following formula.

$$d_{dn} = \sqrt{(x - x_n)^2 + (y - y_n)^2} \tag{3}$$

where:
d_{dn} - distance of the sound source from the n-th microphone,
x, y - coordinates of the sound source,
x_n, y_n - coordinates of the n-th microphone.

For each microphone, a distance difference equation can be written relative to the sound source:

$$d_{dn} - d_0 = d_n \tag{4}$$

where:
d_{dn} - distance of the sound source from the n-th microphone,
d_0 - distance of the sound source from the beginning of the system of coordination

$$d_0 = \sqrt{x^2 + y^2} \tag{5}$$

d_n - distance difference for the microphone.

Taking into consideration formulas (2), (3), (4) and (5), the following system of equations is determined.

$$\begin{cases} \sqrt{(x-x_1)^2+(y-y_1)^2}-\sqrt{x^2+y^2}=v_d\cdot\Delta t_1 \\ \sqrt{(x-x_2)^2+(y-y_2)^2}-\sqrt{x^2+y^2}=v_d\cdot\Delta t_2 \\ \sqrt{(x-x_3)^2+(y-y_3)^2}-\sqrt{x^2+y^2}=v_d\cdot\Delta t_3 \\ \sqrt{(x-x_4)^2+(y-y_4)^2}-\sqrt{x^2+y^2}=v_d\cdot\Delta t_4 \end{cases} \quad (6)$$

In order to determine the position of the sound source (x, y), it is necessary to find the solution of the system of equations (6) using, for example, the least squares method. The direction of sound ∅ can be determined using the following formula.

$$\phi=\begin{cases} \arctan\left(\frac{y}{x}\right) & if\ x>0 \\ \arctan\left(\frac{y}{x}\right)+\pi & if\ x<0\ and\ y\geq 0 \\ \arctan\left(\frac{y}{x}\right)-\pi & if\ x<0\ and\ y<0 \\ \frac{\pi}{2} & if\ x=0\ and\ y>0 \\ -\frac{\pi}{2} & if\ x=0\ and\ y<0 \end{cases} \quad (7)$$

where:
∅ - azimuth of the sound source relative to the centre of the coordinate system given in degrees,

The ReSpeaker USB Mic Array microphone is the core element to conduct the experiments. Figure 5 shows the arrangement of the device's microphones after removing the cover. This device contains four microphones. To operate the ReSpeaker, the ODAS (Open Embedded Audition System) library software can be used to detect the direction and distance of the sound source relative to the device.

The ODAS library software provides the ability to determine the following parameters [7]:

Determining the time difference of arrival of signals – analyses the time differences at which sound signals reach individual microphones. These differences allow for estimating the direction from which the sound is coming.

Selecting the direction of the signal – enables focusing on the sound source and ignoring noise or other sounds from other directions.

Determining the angle of the sound source – the ReSpeaker Mic Array, thanks to its microphone configuration, can determine this angle in the horizontal plane and within a limited range in the vertical plane.

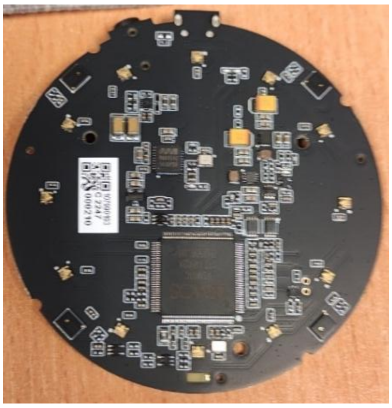

Figure 5. The ReSpeaker USB Mic Array device with the four microphones labelled

The approximate distance to the sound source can also be estimated using an algorithm based on signal strength. This distance is calculated based on the decrease in signal amplitude and the time difference of signal arrival.

The experiment involved the microphone array acting as a receiver of acoustic signals with a frequency of 1500 Hz generated from a mobile phone(The phone played the role of the sound source and corresponded to the drone's distance and azimuth). The experiment was conducted in two environments: indoors and in an open space.

In each experiment, the direction of the signal origin and the distance to the signal source were determined. The direction of the signal origin was determined using the ODAS library software, while the author prepared a custom program to calculate the distance. Figure 6 illustrates the laboratory setup used for the experiments. The studies were conducted in environments where various natural sources of sound interference and phenomena that complicated calculations were present. This approach aimed to simulate real-world conditions that might occur when determining the relative positions of flying drones. In the open space, sound disturbances were generated by wind, rustling trees and a barking dog. While indoors, the primary factors affecting results were echoes of the reflected signal and noise from a running laptop.

Figure 6. Laboratory setup view (laptop, microphone array, and phone as the acoustic signal generator).

The microphone array and the acoustic signal source were located on the same surface in each experiment. When determining the distance to the signal source, the source's distance was changed every 0.5 meters, ranging from 0.5 m to 3.0 m (see Figure 7) the signal source was located at an azimuth of 220 degrees. Each measurement was repeated ten times.

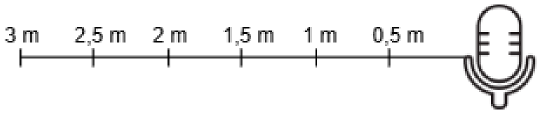

Figure 7. Illustration of distance measurement.

Obtained results of the sound source distance test are shown in Table 3. The columns containing the distance values present the arithmetic mean of the results obtained in each of the ten measurements.

Table 3. Summary of calculated distances for 10 measurements.

Actual Distance [m]	Calculated Distance Indoors [m]	Error Indoors [m]	Calculated Distance in Open Space [m]	Error in Open Space [m]
0,5	0,995	0,495	0,58	0,08
1	2,623	1,623	0,84	0,16
1,5	2,581	1,081	1,827	0,327
2	1,864	0,136	1,619	0,381
2,5	2,611	0,111	2,248	0,252
3	2,75	0,25	2,87	0,13

After analysing the obtained results, it can be concluded that determining the distance to the acoustic signal source using the described indoor method does not yield satisfactory results. The likely cause is the insufficient selectivity of the microphones used in the experiment, which prevents the original signal from being distinguished from its echo reflected off objects in the room. The distance measurement results obtained in open space are much better and promising for the approximate determination of distances between drones flying in a swarm.

During the second experiment, the acoustic signal source was placed 1 m from the centre of the microphone array to determine the direction. The source's angle relative to the array was changed in increments of 90 degrees (Figure 8), starting from an arbitrarily chosen angle of 70 degrees. Also, for each angle performed 10 measurements.

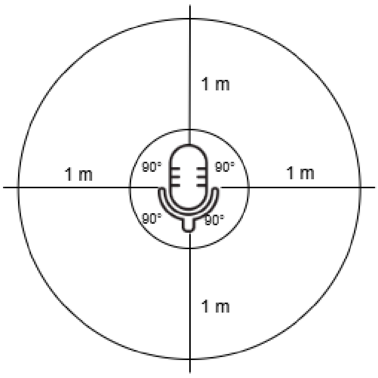

Figure 8. Illustration of azimuth measurement.

The results of the azimuth measurements of the sound source are presented in Table 4. The columns containing azimuth values show the arithmetic mean of the results obtained in each of the ten measurements.

Table 4. Summary of calculated angles.

Real angle [°]	Calculated angle indoors [°]	Calculated angle outdoors [°]
70	221	70
160	220	140
250	144	236
340	244	325

Similar to determining the distance to the source, the results of determining the azimuth of the sound source obtained indoors are significantly worse than those obtained in open spaces. The reason is similar and lies in the inability to separate the original signal from its echo.

5 CONCLUSIONS AND FUTURE WORK

The presented results are one of the first steps in developing a hybrid dead reckoning navigation system based on images and acoustic signals without relying on GPS. The primary goal of this approach is to ensure awareness of the position of a drone moving within a swarm relative to other members of the swarm. Since drone systems usually have limited energy and computational resources, solutions with low resource requirements are needed.

The results obtained for acoustic signals are not entirely satisfactory but are promising. Upcoming research will focus on reducing the impact of signal echo on the results. This research will include the application of better sound filtering, more precise analysis of received signals and work on frequency ranges and microphone sensitivity.

In the next stage, efforts will concentrate on developing an AI-based system to determine the direction and distance of the sound source using acoustic signals. We anticipate the system's design will operate within the limited energy and computational resources available onboard the drone.

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