Imperial College London

Detection of Civil Unmanned Aerial Vehicles by Sound Processing

EE2-PRJ E2 Project
Interim Report

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1. Abstract

The scope of this project is to develop an economical, precise, reliable and legal detection system to locate the position of a nearby drone. The need for drone detection systems has risen steadily as incidents continue to highlight how these aerial devices can be manipulated for dangerous and malicious tasks. The team has attempted to develop such a proposed system through processing the sound signals a drone produces. The system will detect sound through various microphones, filter the signals to 'single out' drone sound then process these signals via a detection algorithm, locating the drone's position relative to the system. Three design concepts were developed: a microphone that spins and scans the sky for a drone's sound signal, a flat microphone array using delay and sum beamforming, and a 3-D microphone array that analyses the maximum delay of signal between microphones. After a discussion comparing the advantages and disadvantages of the concepts alongside set design criteria, the team decided to pursue the development of the flat microphone array utilising beamforming, as it proved to be the most cost and performance efficient.

2. Introduction and Background

Unmanned Aerial Vehicles (UAV), commonly referred to as drones, have become widely used devices, serving both military and commercial purposes. Spawning a £8.5 billion global market[1], the drone's popularity is only continuing to grow as the technology rapidly develops. Showcased by the myriad of uses found for the drone, such as a means of providing surveillance for authorities, a tool for traffic control, and as an asset in military operations, the drone has proven itself as a valuable tool not only for recreation purposes, but for also increasing efficiency of various tasks. However, with almost uninhibited access to these powerful devices, society may expect dangerous consequences as result of careless, or even intentional misuse.

This issue can present itself in several forms that range from petty disturbances to severe crimes. Over the past three years, drone related calls to the police have risen by over 2000% in England alone[2]. This demonstrates not only the growing presence of drones but also the accompanying threat. Prominent examples of civilian misuse stem from breaches in privacy as users usually adopt drones equipped with wireless video cameras which they can manoeuvre with ease to a location of their choice. Such cases have also escalated into users flying drones into world leaders' residences, sometimes dropping hazardous material. A recent example exists where an individual in protest landed a drone carrying radioactive substances on the Japanese Prime Minister's roof [3].

Drones can also offer terrorists and criminals a new dimension to circumvent existing defence systems. Most recently, drones have been used to drop contraband into prisons, as evidenced by a case at a high security prison in Manchester, England [4]. Drones have also been increasingly used to enter restricted airspace, such as airports, causing aviation authorities serious concern. As reported by the US Federal Aviation Administration (FAA), drone sightings by pilots have trebled since 2014 [5], highlighting the rising misuse of drones.

In a bid to limit the negative impacts of drone use on society, legislation is being drawn up in several countries to combat these various issues. For example, today in the United States, all purchased drones weighing more than 227g must be registered with the FAA before use or owners may face serious penalties [6]. However, despite increasingly present regulation combatting these issues, drone misuse remains a big problem. Such recorded cases of commercial drone misuse have inspired this project to develop a system with the aim to deter future incidents by locating the drone mid-flight and then alerting individuals of an imminent threat.

3. Design Criteria

The detection system will be designed to adhere to certain criteria that make it optimal given the social, economic, and environmental context. Below is a discussion of the five most important criteria that the product must satisfy, taken from the product design specification (PDS) (for the complete PDS refer to appendix 1).

Economics

The design needs to be economical as the product is targeted for widespread commercial use. This necessitates an affordable design which by extension results in a trade-off between performance and cost for the choice of components such as computers and microphones. High-cost techniques such as radar are therefore ruled out as possible solutions. Cost minimization can also be done by avoiding superfluous computer and user interfaces to display the results, or by keeping the physical design of the system modest.

Performance

The basic requirement of the system is to determine the direction (azimuth and the elevation angle) of the drone relative to the detector. The level of precision in the results is expected to be in the order of 0.1° with respect to the device. Refresh rate is also a very important characteristic. As the drone may not be stationary, the system must be able to track it and update the results in real-time. A result of this is to minimize the computations involved in processing the sound signals by devising intelligent algorithms.

The system is expected to detect a drone above its own location, and suppress other noise that may be below it. This might require the use of unidirectional microphones that are only sensitive to the sky above the system.

Ethics and Safety

The system must not conduct, or have the capabilities to conduct, any illegal activity. This includes the jamming of the drone's operation, shooting at it, or any other activity that is deemed illegal by the most current standards of legislation. The latter part of the project may involve developing a drone disabling device to complement the detector, therefore rendering the adherence to this particular aspect of the design criteria crucial in the scope of project.

Reliability and Repeatability

The system must be reliable and able to repeat high quality results consistently despite external conditions or variation in drones. This renders image processing and video detection solutions challenging in this regard due to their struggle to detect the difference between small UAV's and birds[7]. Thermal energy also falters here due to the inability to differentiate many small, electric powered drones that don't produce much heat relative to background radiation[7]. Sound analysis is therefore the most suitable design choice for the device due to the fact that all drones emit a similar type of propeller noise.

Ergonomics and Consumer Interface

The entire system should be enclosed in a casing that will be aesthetically pleasing to the consumer, and can stand alone without support. A screen/monitor is also necessary to display the results of the drone detection to the consumer.

4. Concept Design

4.1. High Level System Outline

The **high level** design of the system is as follows:

1. The drone generates sound waves, due to its propellers and motors, at certain frequencies.
2. These sound waves are detected by microphones with a suitable directionality and sensitivity.
3. The signals received by the microphones are conditioned through circuits that convert output microphone current to signal level voltages.
4. The signals are sampled by a dedicated sampling device and transferred to the Single Board Computer (SBC).
5. The signals are filtered on the Single Board Computer and processed.

6. The SBC then displays the direction of the drone to the user via a suitable interface.

4.2. Pre Design Testing and Assumptions

The scope of this project is limited to commercial drones with battery powered motors and propellers. The project will hold some assumptions that the drone will be flying above the detector and that the drone is significantly far away enough so that the sound waves it generates will be planar by the time they reach the system (far field approximation).

Every drone will generate sound at frequencies unique to its physical design and propellers. To analyse the expected range of frequencies, testing was carried out by downloading recordings of drones and processing them in *Matlab*. The processing relied on analysing the frequency spectrum of the sound signals and identifying the relevant frequencies (refer to appendix 2.1 for the *Matlab Code* used to determine this).

At least five different recordings were tested and compared which resulted in the group finding consistent peaks at approximately 1000 Hz. In order to accommodate the design criteria for functioning over a 1 kHz range, the frequency range of operation was chosen to be from 500 Hz – 1500 Hz.

4.3. Low Level System Design

Following extensive technical research, the team developed three different physical structure concepts, each with a unique method of detecting of the drone. However, enough of the system stages overlap between them to layout the system design in order of signal flow from input to output as below:

4.3.1. Microphone Hardware and Positioning

This section incorporates the hardware and physical structure of the part of the system that contains the microphones used to detect the sound from the drone. The role of this stage is to be able to scan the entire upper half of the sky above the location of the system, and pick up the sound signal generated. This 'scanning' of the sky for sound signals can be done via the three proposed concepts below. The microphone of choice for each concept is a unidirectional electret microphone. This microphone will enable the group to ignore noise incoming from below the system, and possesses very good sensitivity while adhering to a low cost [8].

Option 1: Singular Spinning Microphone

The first option is to install a single unidirectional microphone on a base that rotates by 360°. The microphone then moves on the surface of the hemisphere from an elevation angle of 0° to 90°. These mechanical movements are driven by two servomotors, with one motor rotating the base by 360°, and then the other motor incrementing the elevation angle of the microphone by 1° for every 360° rotation of the base. By iterating this 90 times, the microphone will be able to scan all the angles in the sky.

Figure 1 *Created using draw.io*

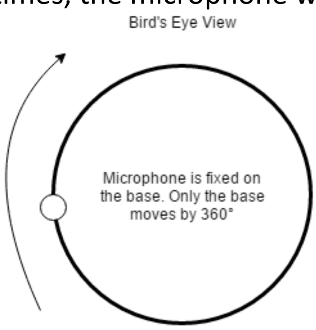
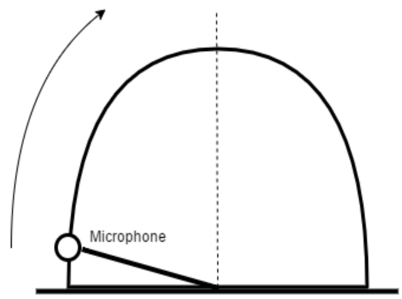


Figure 2 *Created using draw.io*



Option 2: Flat Multiple Microphone Array using Delay and Sum Beamforming

The first alternative is to install eight stationary unidirectional microphones in fixed positions along an octagon on a flat 2-D plane. Three is the minimum needed in order to determine sound directions in the sky, but with more microphones, sensitivity and noise rejection improves. Due to this, a planar array of microphones in an octagon configuration has been chosen, giving a reasonable amount of microphones and a simple geometry.

The microphones will detect sound from all directions in the sky at all times, unlike the spinning singular microphone. The methodology here then relies upon measuring the time difference between the microphones in receiving the same sound signal from the drone. Setting one microphone as the default with no delay, each microphone will receive the sound signal at a time different to the default microphone. The location of the drone can then be determined by analysing the phase difference between the recorded signals from each microphone. However, this method can be prone to error as a delay of one wavelength of the recorded signal could look exactly like the un-delayed signal. In order to accommodate this, the largest spacing between the microphones will have to be at least half the wavelength of the highest frequency of signal.

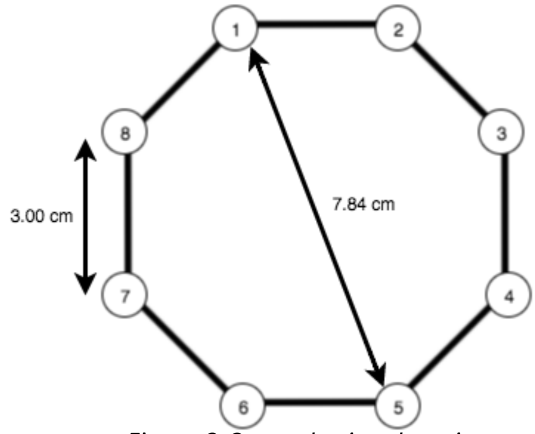


Figure 3 *Created using draw.io*

Highest frequency of incoming signal: 1500 Hz
Speed of Sound: 340.29 m/s

$$\frac{340.29}{1500} = 22.7\ cm\ smallest\ wavelength\ of\ signal$$

Therefore, the largest distance between microphones (1 and 5 on diagram) will have to be less than about 10 cm (refer to appendix 2.2 for justifications for given dimensions).

Option 3: 3-D Multiple Microphone Array using Maximum Delay Algorithm

Due to reasons explained below in the maximum delay algorithm (refer to 4.3.3 option 3), the third option is the same as the second array, but will have an additional microphone on a plane parallel, but above the flat plane of the other 8 microphones. The height of this microphone above the others is arbitrary as long as its distance from the furthest microphone is again 10 cm. This microphone is responsible for locating the drone's elevation angle, while the flat plane microphones will detect the drone's azimuth angle.

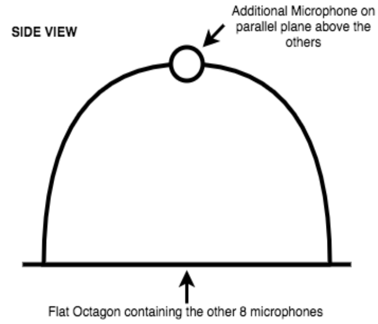


Figure 4 *Created using draw.io*

4.3.2. Microphone Signal Conditioning

The microphones receive the analogue signals and generate a proportional current output. This stage is responsible for the analogue circuitry that bias the microphones to operate as specified in datasheets, and that condition the signals output from the microphone for processing.

The analogue circuitry will first bias the microphone by supplying a current of approximately 0.5mA through it by using R1. This is slightly less than required in the datasheet to accommodate for variance in the supply voltage. C1 enables a high pass filter with R1 that lets through signals above a corner frequency of

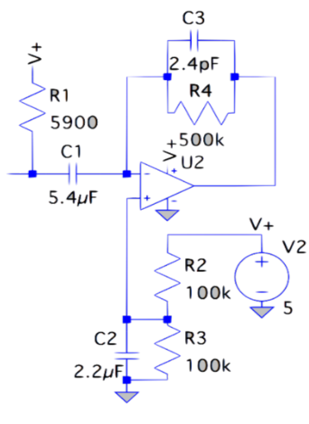


Figure 5 *Created using LTSpice*

5 Hz. Capacitor C2 filters thermal noise from the components and noise from the power supply. Resistors R2 and R3 are chosen to centre the operational amplifier input and output at the midpoint of the power supply. These are the pre-amp bias specifications.

The final step is the trans-impedance amplifier which will convert the microphone output current into a signal level voltage. The electret microphone will have a certain sensitivity level, dictating how much output current will flow per Pascal (Pa) of input signal. An estimate for the input signal was determined by comparing the dB SPL level of common everyday noises to the noise of a drone to be about 0.006 Pa. In order to output the signal as a voltage line level signal at 1.3V RMS, the typical voltage used for audio signals[8], from the given output current of the microphone, the feedback resistor R4 of the operational amplifier is chosen to be 0.5MΩ. The feedback capacitor, C3, compensates for the parasitic capacitance at the negative input terminal and alleviates instability. The capacitor also forms a low pass filter with R4, and so the value of C3 is appropriately chosen to produce a corner frequency well above the frequency range required for operation. A full detailed explanation of the calculations and motivations for each result is displayed in appendix 2.3.

4.3.3. Signal Processing and Hardware Control

The output from the signal conditioning stage is multiple 1 kHz signals (one for each microphone) with amplitudes proportional to the sound pressure incident on the microphones. These signals need to be sampled for processing. The role of data processing and data collection is divided between a Single Board Computer (SBC) and an additional microcontroller respectively. This was done to prevent transient problems that arose from previous designs that required the control of multiplexers by the SBC. It is also very important to know the time between each sample of data and to ensure that this time is constant, otherwise this can distort analysis of time delays between microphones. Therefore, the SBC, which has to process data and is prone to several interrupts which cause unpredictable time delay, will not be used to do the sampling. The sampling will instead be conducted by the independent microcontroller.

The sampling rate for each microphone must be at least twice the maximum signal frequency of 1500Hz to prevent aliasing. One ADC will take samples from each microphone and move between them until each signal from each microphone has been recorded into respective data vectors, rather than sampling one entire mic vector at a time. This reduces worst case time delay from [length of sampled data vectors]*sampling time to [number of microphones]*sampling time, where number of microphones < length of vector. Before the data vectors are passed along to detection algorithms, the data is passed through a digital band pass filter, controlled by the SBC, to only allow signals in the 500-1500 Hz frequency range to be processed by the SBC. The different algorithms used to process the data for each design option are described below.

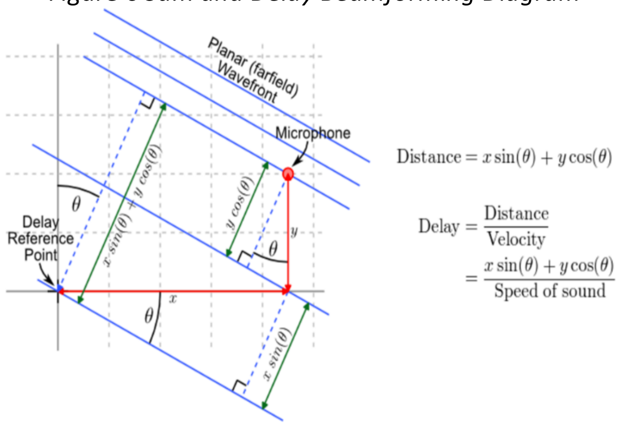
Option 1: Algorithm for Singular Spinning Microphone

Due to the mechanical rotations, the microphone will scan the entire sky above the system. The simple algorithm is designed to detect when a sound level in the required frequency range (500 – 1500 Hz) is present and above a threshold noise value. As the microphone scans each azimuth and elevation angle combination in the sky, the SBC will read the signal from the microphone and test to see if the amplitude is larger than the threshold noise level (value will be developed in testing by measuring ambient noise levels). If above the threshold, the drone's location corresponds to the given angles; otherwise the system will continue to scan the sky.

Option 2: Delay and Sum Beamforming Algorithm for Flat Microphone Array [9, 10]

The first step is to declare one of the microphones as the default reference microphone. As the sound wave is received by the array, all the other microphones will receive the signal with either a negative or positive time delay compared to the reference microphone. Since the array is designed with the maximum distance between microphones as less than half the wavelength of the highest frequency, for every direction in the sky, there will be a unique delay for each microphone (in reference to the default microphone). Consequently, if the microphones' signals are added together after being delayed by their unique delay, maximum constructive interference will occur when compared to summations of other possible delays corresponding to different directions.

Figure 6 *Sum and Delay Beamforming Diagram* [9]



By exploiting this fact, one can discern the location of a sound wave (a drone) by conducting several summations of the microphone signals over a unique set of predetermined time delays, and then choosing the direction with the corresponding delay that yielded the maximum result, as the direction of the sound wave. This unique set of time delays, each corresponding to a single direction, can be calculated with simple geometry as shown in figure 6 (illustrates 2-D, but exact same concept is extended for the elevation angle). Knowing the distance between the microphones and the speed of sound, a time delay value can be calculated for each microphone relative to the reference for each unique direction.

Upon start of the system, the single board computer (SBC) will perform the geometric calculations to produce the unique set of time delays and store them in memory. This will save lots of time from calculating the angles for each scan separately. The SBC will then perform all the summations for different time delays, corresponding to all possible directions, and collect the results. Finally, the SBC will compare all the results to see which summation led to the maximum amplitude. Consequently, the drone is inferred to be approaching from the corresponding direction that resulted in the maximum amplitude. Note that with this algorithm the resolution can adjusted, as the time delays can be calculated for every 1°, 0.1° and so on.

Option 3: Maximum Delay Algorithm for 3-D Microphone Array

This algorithm is based on locating which two microphones have the greatest time delay difference between them in receiving the incoming sound signal, to find the direction of the drone. The processor will run through all the collected data of the lower plane microphones', comparing each one of them with each of the other seven microphones. The result will be to find the pair of microphones that have the greatest time delay difference of receiving the incoming sound signal. The azimuth direction of the drone sound source is the straight line connecting the two microphones, pointing outwards in the direction of the microphone that received the sound signal first. The elevation angle can then be found by measuring the time delay difference between the microphone on the top with each of the other microphones on the octagon. Using the same geometrical equations given above in option 2, the angle of elevation of the drone sound source can be calculated from the measured time delay with each microphone.

4.3.4. Output to User

For the purposes of the initial prototype, the location of the drone will be displayed on a screen controlled by the SBC. This screen will output the position of the drone using a radar-like display. Further work may involve sending messages with the position of the drone when the system is placed away from the user.

5. Discussion and Concept Selection

The team discussed the relative advantages and disadvantages for each concept in the context of the design criteria. This led to the group assigning marks for each concept's ability to adhere to each of the five categories in the criteria. These marks were compiled on a concept selection matrix which was used to choose a concept to ultimately pursue for the remainder of the project.

Option 1: Singular Spinning Microphone

The advantage of this concept is that it is very simple to design, debug and has a simpler algorithm for detection than the other two concepts. However, the mechanical rotations of the microphone makes it more prone to failure and damage, as well as necessitating more expensive long-term maintenance. The mechanical feature in the concept also means that this method of scanning the sky is slower than the other two concepts. The scanning speed is limited by the speed of the mechanical rotations, while option 2 is able to scan the entire sky just by changing the set of delays used for summation by the computer. In this concept, there also exists a trade-off between speed and resolution. As a scan is done faster, the microphone has less time to process the information received from a particular direction in the sky. Despite choosing a very directional microphone, the concept will inherently have a lower resolution than an array of multiple microphones. Reliability can also be hindered by the fact that the motor and linear actuator controlling the microphone sweep will produce noise to the microphone. This concept is also less cost efficient than the other options because even though it utilizes only one microphone (compared to 8 or 9 in the other options), its cost is significantly augmented due to the stepper motors required to allow rotation. Furthermore, extra material such as plastic and mechanical components will be needed for the construction only further driving up the cost.

Option 2: Flat Microphone Array with Delay and Sum Beamforming

The flat microphone array requires less construction material and mechanical components than the other options, making it more affordable. To further reduce the cost, efforts will be made to purchase components without unnecessarily high performance, thus keeping costs low without sacrificing the quality of the product. The flat microphone array also benefits from a very efficient algorithm that is able to scan the sky faster than option 1 as the scan speed is no longer dependent on the mechanical rotation speed. Furthermore, the resolution of the array can be designed to be significantly higher than the others options and is easily adjustable. This extra adjustability means that the concept design is flexible, catering to a myriad of operating environments. Additionally, the adjustability infers that time delays can be designed such that the direction of the drone is known within 0.1° or 0.00001° of an angle from the device, providing a high degree of precision for the location of the drone when in flight. Even though higher degrees of precision implicate longer operating periods for scanning the entire sky, the extra time taken is negligible due to the extremely high initial functioning speeds of the microcontroller (component used to collect data). This concept incorporates the most complicated detection algorithm, but is the most precise and cost efficient.

Option 3: 3-D Microphone Array

The design of the array is very similar to option 2, but it has an additional microphone and dome structure to support it, which cost more and is more effort to construct. The main disadvantage with this concept's detection method is the lack of high resolution and speed. The method of determining the azimuth angle in this option only gives a rough approximation of the source's angle and isn't as accurate as the previous option. Also, determining the elevation angle requires calculating the angle from recorded time delay measurements for every scan separately. This lowers the speed of the sweep.

Table 1: Concept Selection Matrix – marks given on a scale from 1 (worst) to 5 (best)

Criteria	Option 1	Option 2	Option 3
Economics	3	4	2
Performance - Speed	1	5	3
Performance - Resolution	3	5	3
Ethics and Safety	5	5	5
Reliability and Repeatability	1	5	3
Maintenance and Construction	1	5	3
Simple to Design, Analyse, and Debug	5	1	3
Total Marks	**19**	**25**	**22**

6. Conclusion and Future Work

In conclusion, an analysis of all three concepts based upon the design requirements set out above illustrate that option 2, an eight microphone array that utilises beamforming for detection, is the most suitable option for development and prototyping. It satisfies the design criteria best with a fast scan speed, a variable and high precision, relatively cheap construction, and a reliable and steady state design. This design is also innovative compared to already existing drone detection technologies. The team's research has found that no other technology being developed for the same purpose uses beamforming as a method for detection. It is also considerably more affordable than competition that is able to deliver with such precise results, an innovation that opens such anti-drone products to large, personal consumer markets.

Although quite promising, the chosen concept has to overcome several challenges to proceed to successful development. One of these challenges is how the system will react if there are two or more drones in the range of detection. Under the currently designed detection algorithm, the device will only be able to detect the closest drone out of the possible multiple in flight. The group hopes to modify the current algorithm so that the device can detect and alert individuals about any number of drones posing a threat, not just the closest one. A possible solution to this problem is to modify the algorithm so that instead of only identifying a drone as one from the direction that produces a maximum result (refer to 4.3.3 option 2 algorithm), it identifies a drone as any direction that produces a result above a certain predetermined threshold. Therefore, any number of directions that produce a value above the threshold will be identified as a drone, thus allowing multiple drones to be detected. Furthermore, another challenge the group hopes to address is that sound signals from drones may be distorted from surrounding buildings or reflected off walls. This effect can be mitigated by altering the algorithm such that signals below a certain amplitude are ignored, as reflected sound signals have a lower amplitude than those arriving directly from the drone. Another challenge requiring attention, is that the designed concept is run on power from the mains. This can be an issue if the user prefers to place the device in an area that does not have access to a mains outlet (an open field, roof of a building), and so future work can be dedicated towards supplying power from a battery or some other portable power source.

Additional future work will be undertaken in assembling the different modules of the device, such as the microphone array and its bias analogue circuitry, the program running the detection algorithm (via delay-sum beamforming), and the user interface to deliver the results. Successful completion and integration of these tasks into one working device will enable the team to pursue the second stage of development for the device, which is developing an innovative disabling technique that can be used in tandem with the developed detection technology to completely and legally eliminate a drone threat.

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Appendices

1. Complete Product Design Specification

Product Design Specification

Project : Detection of Civil Unmanned Aerial Vehicles **Date:** 14/01/16
Author: Group 11 **Version:** 1

1. Performance

The product must satisfy a very high speed scan. This must mean that the product will have to minimize computations with intelligent algorithms and component design choices. A minimum criterion is for the system to be able to update its results 30 times a second. This is the minimum rate to provide a fluid flow of the drone's position on the display screen.

Resolution is another important factor of performance. The product must be able to deliver precise results to an order of at least 0.1°.

2. Environment

Product must not directly release any substances that are harmful to the environment (greenhouse gases for example). The system must also conduct its detection without sending out any signals (for jamming purposes) into the environment as jamming this way is illegal.

3. Life in Service

System will work for about 95% of the average quadcopter drones. But as new drone technologies are developed such as glider drones that do not emit any noise, the product will not be of any service and will have to be modified to adapt.

4. Maintenance

Product must be designed in a manner, in which the user cannot accidently cause damage that requires maintenance. This pertains to fitting a wooden casing that encloses the electronic components on the strip board, the single board computer, and other required components. This means that any maintenance should not be done by the consumer, and this also avoids the risk of them damaging any openly placed components.

5. Target Product Cost

The team estimates the product to cost about £50. This includes the purchasing of material as plastics to construct the casing, strip board to mount microphone, mechanical components if needed, microcontroller, SBC, and output display screen. This still makes the product considerably cheaper than its competition.

6. Competition

The competition of sound processing to detect a drone usually lies in the realms of radar, sonar, thermal, video imaging, and even detecting via radio frequency analysis.
The concept needs to be cheap enough so that even domestic consumers can purchase it, rather than just well-funded government entities. This in turn rules out radar and sonar, as they are high performance, but quite expensive technologies. Thermal processing involves looking at the specific heat energy generated by the average drone, and then analysing the heat waves being received into the system. This is sometimes

quite unreliable with small, electric powered plastic drones that do not generate the amount of heat expected by the system. Also, video or image processing detection methods employ certain algorithms that look at the fight paths of drones in the sky so as to not mistake them for other things, but they are frequently known to yield false alarms by detecting birds.

7. Shipping

The product will be manufactured in one location, but it may have a global reach, requiring shipping of the entire assembled product.

8. Packing

The product will come ready for use, assembled and constructed by the team. The packing will be a small, sealed cardboard box that is packed with Styrofoam on the inside to protect the system from damage.

9. Quantity

One system is delivered for every purchase. This system is a combination of the all the electronic components, the single board computer, microcontroller, and the display screen.

10. Manufacturing Facility

Manufacture of the product is rudimentary, and will be done at only one site by team members for the prototype. Manufacturing will only include wiring up the third-party electronic components onto a strip board, 3-D printing out the plastic casing, and connecting the display screen onto the outside of the casing.

11. Customer

The target customer for this project is an average consumer who may not be backed by large funds as government entities. Therefore, an emphasis has been made to keep the cost of the product low. The customers can be general individuals, prisons, football stadiums, government agencies to protect important figures or to track terrorist activities.

12. Size

The size of the system is not strictly restricted to any bound size, although keeping a minimal size will allow us to reduce the cost on materials. Having the entire system placed in a cube casing of sides of length of about 1 foot keeps the system small enough to be placed in any suitable location for detection, but also is large enough to encapsulate the electronic components, wiring, and single board computer.

13. Weight

No restriction on weight of the system. Nevertheless, the team is not expecting a heavy product (as electronic components are light and the casing will be constructed from light plastic). Consumers will be able to hold the system in their hands with ease.

14. Materials

Materials used will depend on the specifications of how the system will perform the detection. However, there are some general materials that will be needed regardless of the method of detection. These include a single board computer for processing the received sound signals, microcontroller to sample the analogue signals, a strip board to mount microphones and to produce bias circuitry for the microphones, electronic components (resistors, capacitors, op amps, wiring, etc.), a screen to output results to the user, and plastic to construct the casing for the system.

15. Product Life Span

Will run for as long as the third-party electronic components will function.

16. Aesthetics, Appearance and Finish

As mentioned before, a wooden casing will be used to enclose all the electronic wiring and components. All the user will be able to see will be a screen used to display the results, and the microphones used to detect the sound.

17. Ergonomics

The system should be enclosed in a cube-like casing that will protect it from damage that may be accidentally inflicted by the user. This will hide the complex electronic wiring and components from the user's view.
A cube will also provide a flat bottom surface, allowing the system to be placed on surfaces without external support.

18. Standards and Specifications

Standards set out are that the system will deliver results to angles of 0.1 degrees, and that results are updated 30 times a second.
Other standards are that the system must oblige with health and safety standards for every country that the product is sold to.

19. Quality and Reliability

System must be able to function over a decent range of drone sound frequencies. It is impossible to cover the range of each and every drone, but a bandwidth of approximately 1kHz can be used as leverage. Sound analysis of a variety of drones can be conducted prior to determine this bandwidth. Reliable functioning is needed, despite external conditions or variation in drones. This includes minor bad weather conditions; if the average quadcopter can function in the given external weather condition, so should the system.

20. Shelf Life (storage)

Not applicable

21. Testing

Two stages of testing are conducted. Pre-design testing is carried out to find the range of frequencies of the average quadcopter drone's sound wave. This is required, as the system will only want to detect sound signals in this given frequency range. The testing comprises downloading sound clips of quadcopter drones and running them through a Matlab function that analyses the sound's frequency spectrum and highlights the peaks corresponding to the frequency of sound made by the drone. At least five such samples are taken and a range is created.

Testing is then done again once the prototype has been constructed. This will comprise of testing all the functions outlined in the concept design section of the report, and making sure the concept adheres to any performance design criteria laid out above.

22. Processes

The process will begin with manufacture of the system as described above. As a customer purchases the system from wherever in the world, the team will then transport the product via air freight, and then by truck to deliver at the consumer's doorsteps.

23. Time Scale

Once a working prototype has been developed, further systems sold to consumers will be able to be manufactured within a week.

24. Safety

The product must pose no physical harm to the user. This involves using materials and components that are not hazardous, toxic, and by ensuring safe connections to the mains power supply.

25. Company Constraints

There are no constraints laid out yet. However, if the team chooses to pursue a disabling feature in the future, the main constraint is to develop a system that is perfectly legal. Lots of disabling techniques can be developed by shooting down the drone or by radiating noise at it, however none of these are legal.

26. Market Constraints

The main constraint to the market is the cost of the product. Usual drone detection systems are very expensive and are unable to cater to the general personal consumer market. This constraint is the key for the product to surpass competition and cater to a new market of consumers who are not backed by large funds (as government agencies).

27. Patents, Literature and Product Data

Not really applicable. Detection of drones via sound processing has been attempted before and so no new inventions are used in the product. The innovation in the product lies in providing a low cost solution and in using already existing technology in ways that have not been done before.

28. Legal

The system must not conduct, or have the capabilities to conduct, any illegal activity. This includes the jamming of the drone's operation, shooting at it, directing noise at it, or any other activity that is deemed illegal by the most current standards of legislation.

29. Political and Social Implications

The system will have lots of positive implications. The system will allow users to monitor their privacy very well by being aware of any presence of drones spying on them. It will also allow consumers to remain alert of drones that may carry a physical threat or that may be trespassing (or conducting any other illegal activities). Also this will allow government agencies to use the system to monitor prisons, government owned sport stadiums, residences of important figures for any sign of drones. The system can even be used by rescue services to prevent drones from interfering in rescue efforts.

The system itself will only display the location of the drone, and does not **yet** contain any disabling features. Therefore, there are no such negative implications of the device. It only can give user knowledge over the drone's location, but no power over taking any action (that can be done independently of this system or the team may develop a legal disabling feature in the future).

30. Installation

No installation will be needed on the part of the user. The product will come ready, and all the user has to do is to connect the system to the mains and switch it on.

31. Documentation

Documentation given with the system to the consumer will contain brief information on how to use the system, how to interpret its results, and who to contact if the system malfunctions and needs maintenance.

32. Disposal

No waste is left behind by the system and so disposal is not applicable.

2. Technical Analysis and Testing

2.1. Matlab Code for Drone Frequency Range

//reads audio .mp3 file
//takes the fourier transform of the audio signal to analyse its frequency spectrum
//creates a plot of magnitude of the signal vs frequency, illustrating peaks at certain frequencies
//sound(y,Fs) sends the audio signal to the speaker at sample rate Fs to hear the input audio signal

```
[y,Fs] = audioread('quad (mp3cut.net).mp3');
fourier = fft(y);
amp = sqrt(fourier.*conj(fourier));
plot(amp);
sound(y,Fs)
```

2.2. Microphone Array Dimensions Specifications

The furthest distance between two microphones (as between 1 and 5) needs to be at least half the wavelength of the highest frequency of the sound signal to avoid distorted delay calculations.

Highest frequency of incoming signal: 1500 Hz
Speed of Sound: 340.29 m/s

$$\frac{340.29}{1500} = 22.7\ cm\ smallest\ wavelength\ of\ signal$$

For ease of calculations, we will use 10 cm instead of 11.35 cm as the maximum distance between the two furthest microphones. The diagram below illustrates two triangles, A and B.

We know that:

- all of the interior angles in the octagon are 135°
- line connecting microphones 2 and 6 needs to have length < 10 cm

Since all interior angles are 135°, all sides of the octagon are equal, and the lines joining microphones 6-8 and 8-2 are the same length, then B is a right angle triangle with the line connecting microphones 2-8 = $\sqrt{2}$*length of either other side of the triangle. Knowing the length of the line 6-8 and that the angle between the sides of the octagon is 135°, we can calculate that the sides of the octagon to have to be less than 3.826 cm. For convenience of construction, we choose this value to be 3.00 cm. Back tracking the same calculations used to find the length of the side, the length of line 2-6 (furthest distance between any two microphones) is 7.84 cm.

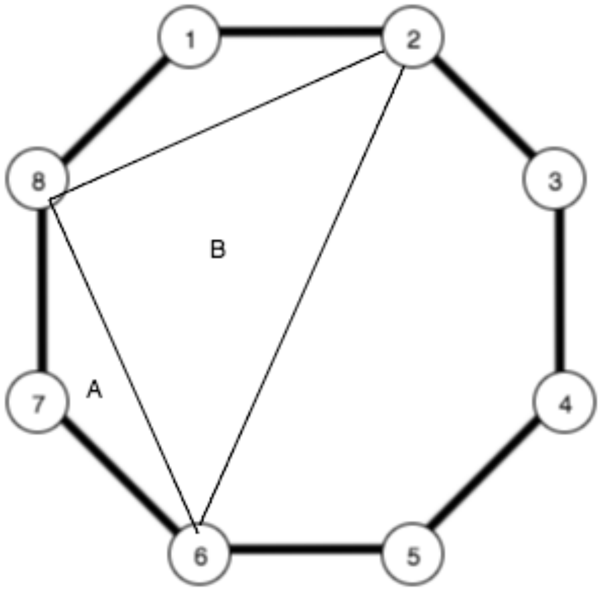


Figure 7 Created using draw.io

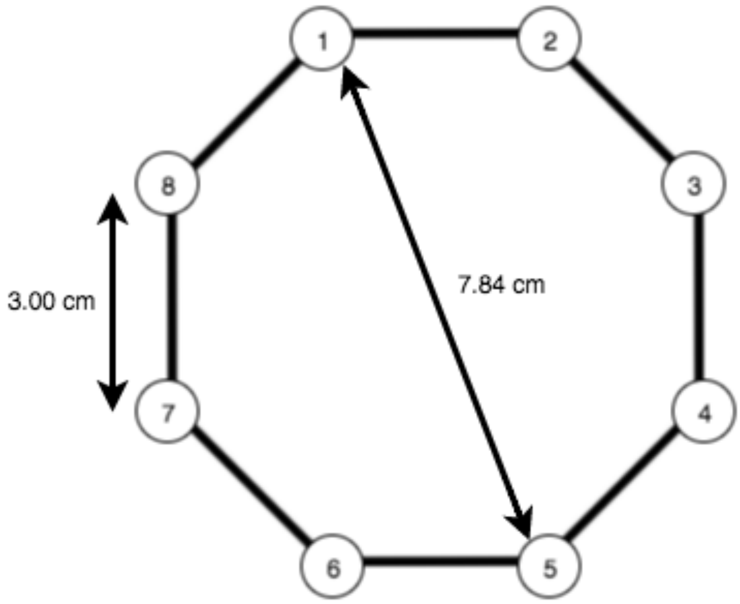


Figure 8 Created using draw.io

2.3. Microphone Output and Bias Circuitry Design Choices

Design Choices using http://www.ti.com/lit/ug/tidu765/tidu765.pdf as a guide.

Microphone Bias Resistor and Coupling Capacitor

Resistor R1 chosen as 5900Ω to give a 0.5mA current through the microphone as specified in the data sheet (slightly less is chosen to accommodate variance in the supply voltage)

C1 and R1 form a high pass filter giving $C1=12\pi R1fc$. Thus $C1$ is calculated to be 5.40uF for a corner frequency $fc=5Hz$.

Opamp biasing

Two 100k R2 and R3 resistors are used to centre the opamp input and output at the midpoint between the power supplies. The capacitor C2 was chosen in order to filter thermal noise created by the resistors and any noise which may be present on the power supply.

The corner frequency of the low pass filter formed by R2,R3,C2 was chosen to be well below the frequencies in use. A 2.2μF capacitor was used in order to create a corner frequency of fc=1/2(100kΩ||100kΩ)2.2µF=1.447Hz.

A bigger capacitor would give an even lower corner frequency and better noise rejection.

Gain Calculation

If we expect the maximum input to the microphones to be the noise of a drone far away, this is comparable to approximately 50dBSPL when compared to the approximate dbSPL level of common sounds 1

The sensitivity of the microphone chosen is -47dBv (this is measured when compared to a 94dBSPL source), therefore the microphone gives 4.5mV/Pascal (94dB SPL = 1 Pa).

Maximum sound level expected at microphone: 50dB SPL=0.006Pa

Calculated volts per Pa = 10−4720=4.47mV/pa

Output current per Pa =4.47$mVpa$2.2kΩ=2.03$\mu A/pA$

Output current at 50dB SPL = 2.03$*$0.006μA=12.18nA

We want to map this to line level of 1.228Vrms using our trans impedance amplifier, therefore $R2=VOUTIIN$=1.228V12.18nA=100MΩ

In order to automate this process for calculating the required components with different specifications, below I have created an equation that takes as

Input:

microphone sensitivity (dBV)

output impedance (Ohms)

maximum expected sound level (dB SPL)

line level RMS required at this sound level (V)

Outputs:

Required value for the feedback resistor (Ohms)

Required value for the feedback capacitor (Farads)
$Rfeedb(micSens,outImp,maxSound,lineRMS)=lineRMS10micSens20outImp\times10maxSound20\times(20\times10-6)$

Calculated value for feedback capacitor: $C=12\pi133725(Rfeedback)$

During testing, take the maximum sound input expected at the microphone input and adjust the feedback capacitor R4 in order to create a line-level voltage of approximately 1.8v p-p.

Capacitor C3 compensates for parasitic capacitance at the opamp inverting input which may cause instability.

Recalculating the gain required:

(using MATLAB implementation of function above feedbackResCalc())

In order to get the line level signal of 1.3v RMS that we chose before, from a 50dB SPL signal we would require a 95MOhm feedback resistor. This is excessive, and will introduce significant amounts of noise.

New specifications (Microphone changed to more sensitive version):

-37dBV Microphone, 1800 Ohm Output Impedance, 70DB SPL sound expected, 0.25v RMS signal output

MATLAB:

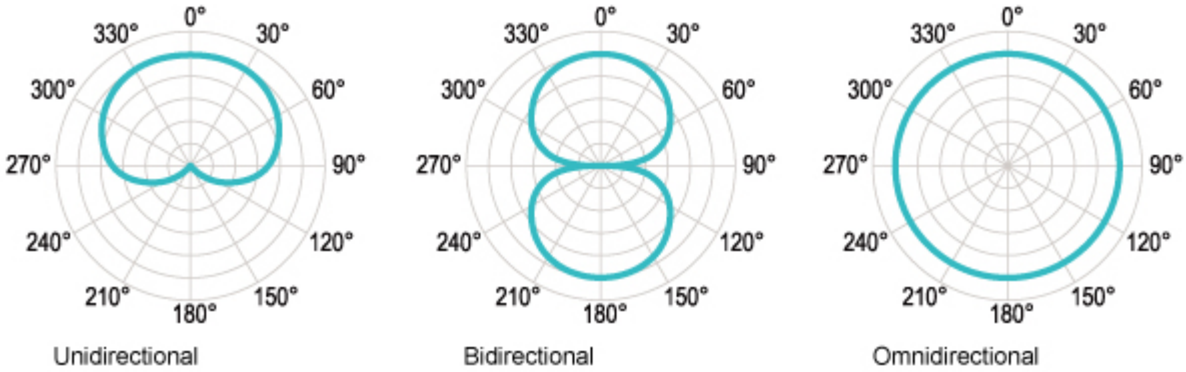
>> feedbackResCalc(-37,1800,70,0.25)

“Feedback resistor required is 0.503712 MOhms and feedback capacitor required is 2.362789 pF”

2.4. Microphone Design Choice

One of the key assumptions is that the drone will be coming from a direction above the system (in the sky).
In order to filter out other noises from the environment that aren't related to the drone, it is important to ensure directionality of the microphones. This ensures that the microphones will only have gain in the direction of the sky, and not below the system.
We have chosen to use a unidirectional electret microphone.

http://www.yamahaproaudio.com/global/en/Images/pa_beginners_microphone_6-4.jpg



By orienting the microphones with the surface of the microphone tangent to the surface of the earth, we will ensure that any noises from sources below the microphone are suppressed through using a unidirectional configuration. Electret microphones have very good sensitivity and are also extremely cheap. The one I have chosen will also help filter out unwanted frequencies. We estimate that the frequency range of the drones is to be in the range of 800Hz->4KHz. The microphone that I have chosen has a frequency response between 100Hz->10KHz

We have chosen the component below as it has a high sensitivity and a good signal to noise ratio.
KEIG4537TFL-N

http://uk.rs-online.com/web/p/condenser-microphone-components/7542104/

3. Minutes from Meetings

Monday, 26 October 2015

Present: Ben Chua, Guy Haroush, Vincent Leung, Aaditya Malhotra, Alexander Wilson, Victor Zhao, Pavol Olexa
Absent: /
Next meeting: Scheduled on 02/11/2015

1. **Discussion:**

   a. *Framework of the Project*

   It was agreed that this project would be focusing on detection of position of drones due to time constraint. It was proposed that audio processing would be the method of detection, rather than radar and sonar technology, due to limited budget. Image processing could be considered as assistance to audio technology.

   b. *High Level Design*

   To detect the position of drone, it was proposed to use microphone arrays. A brief initial design of having a 2-D array was done, which involves 8 microphones, forming a circle on the same plane. Direction would be determined by choosing the least phase difference between neighbouring microphones as well as largest amplitude among the 2-D array. Distance could be determined by knowing the drone's power output. Through power-distance relationship and the amplitude of sound wave collected by microphone, approximate distance could be obtained. Ways to extend it to 3-D would be discussed next time.

2. **Action Points:**

   a. *Algorithm*

   It was decided that Pavol would be responsible for the algorithm due to relevant researches done by him previously, which would be presented in next meeting.

   b. *Purchase of Drones*

   A small drone costing around £10 would be purchased for initial product development. Larger drone by Alex could be used at later stages for testing the prototype of the system.

   c. *Microphone Arrays Design - Beamforming*

   Everyone would do research on beamforming on microphone arrays in order to keep track of the target's position (direction and distance). This would be discussed upon meeting with supervisor, Mr. Mike Brookes, on 28/10/2015.

Monday, 02 November 2015

Present: Ben Chua, Guy Haroush, Vincent Leung, Aaditya Malhotra, Alexander Wilson, Victor Zhao
Absent: Pavol Olexa
Next meeting: Scheduled on 09/11/2015

1. **Issues from previous meeting:**
   a. *Algorithm*
   As Pavol was absent from meeting due to personal reasons, it will be discussed in next meeting.

   b. *Beamforming*
   Everyone came up with their own design of microphone arrays.
2. **Discussion:**
   a. *Microphone Array Design*
      i. *Resolution*
      There were doubts on whether microphones are mostly unidirectional (i.e. the sound coming perpendicularly with the microphone would be of less resolution) or omnidirectional. It was agreed that initially, microphones can be assumed to be omnidirectional, which we will do testing later and prove the assumption.

      ii. *Shape and Number of Microphones*
      It was agreed that 3 microphones would be required for detecting direction in a 2-D plane. However, for 3D plane, there were uncertainty about the shape due to the resolution problem aforementioned. It was proposed that the minimum number of microphones required is 4, as we have no need to sense sound below the device. Further discussion would be needed with our supervisor, Mr Mike Brookes.

   b. *Design Evaluation*
   Despite the fact that we have come up with ideas, there were no concrete benchmarks for evaluation of the design. Therefore, it was agreed that we have to come up with a standard to evaluate the effectiveness and feasibility of a design.

3. **Action Points:**
   a. *Criteria of the Design Evaluation*
   The criteria of design evaluation have to be concrete enough in order to proceed with a feasible design. This would be discussed upon meeting with supervisor, Mr. Mike Brookes, on 04/11/2015.

Monday, 16 November 2015

Present: Ben Chua, Guy Haroush, Vincent Leung, Aaditya Malhotra, Alexander Wilson, Victor Zhao, Pavol Olexa

Next meeting: Scheduled on 23/11/2015

1. Discussion:

a) Array Design

Upon meeting with Mr. Mike Brookes, it was confirmed the maximum distance between two microphones would be half a wavelength of the highest frequency wave. Hence, the maximum frequency emitted from the drones has to be found in order to design the distance between microphones.

b) Work Allocation

As the interim report approaches, it was decided that every team member would take up a part of it, and compile upon completion. It was agreed that the scope of the report would be focused on detection of drones. The allocation is shown below:

Topic Member(s) Responsible

Background Victor

Concept Design

a) Radar Pavol

b) Beamforming (Line, Sphere) Guy

c) Spinning Microphone Alex

Product Design Specification (PDS) Aaditya

Technical Development Ben, Vincent

2. Action Points:

a) Submission of Work

The deadline for every member to submit their part was decided to be two weeks after this meeting.

Wednesday, 25 November 2015

Present: Ben Chua, Guy Haroush, Vincent Leung, Aaditya Malhotra, Alexander Wilson, Victor Zhao, Pavol Olexa

Next meeting: Scheduled on 30/11/2015 (Both General and Technical)

1. Issues from Previous Meeting

As Guy is away on 23rd November, the date of the original scheduled meeting, it is rescheduled to 25th November.

2. Discussion:

a) Principle of Finding Direction

In the previous technical meeting, it was decided that the detection would be based on time delays. By sweeping azimuth and elevation at a certain interval we would like, sets of delays on microphones would be stored in database.

Two methods have been raised to obtain the time delay. First method is through correlation integral, where the time delay is given when the phase difference is largest. Another method is to try sets of delay pre-calculated in database and sum the waveforms up. The one with highest gain/ amplitude would be the correct set of delay. Backtracking gives us the direction.

It was proposed by Alex and agreed by others that in the scope of our project, in which prototype would be made, the second method would be more suitable, due to the fact that the implementation would be much simpler than the first method.

It was also proposed that the interval for sweeping would be 1°. Moreover, successive approximation, e.g. binary search, would make our implementation faster and more efficient.

b) Specifications of Microphone Arrays

It was agreed that ten microphones would be used for accuracy in direction measurement. Microphones used can be a Low-pass Filter as the maximum desired frequency is at about 1kHz. A Bandpass filter around 1k-2kHz would also be added to mostly eliminate the effect of high frequency noise.

Single-Board Computer, e.g. Raspberry Pi, would be used as a main core of our design. Data processing would all be done within the single-board computer.

3. Action Points:

a) Work Submission

It was agreed that Alex would be responsible for the High Level Block Diagram, while Ben and Pavol would be responsible for Algorithms and Simulations, e.g. pseudocode. Deadline would be next meeting.

b) Array Design

It was agreed that we would come up with array design with 10 microphones in next meeting.

Wednesday, 02 December 2015

Present: Ben Chua, Guy Haroush, Vincent Leung, Aaditya Malhotra, Alexander Wilson, Victor Zhao, Pavol Olexa

Next meeting: Scheduled on 07/12/2015 (Tentative)

1. Issues from Previous Meeting

a) Block Diagram by Alex

Alex presented his block diagram to all of the group members. The actual sampling frequency should be higher than the Nyquist Rate $2*fsig$ It was agreed that as the samples are taken sequentially rather than parallel, the frequency of the single-board computer would be at least $2*fsig*n$, where n is the number of microphones.

b) Design Algorithm by Ben and Pavol

The Design algorithm is presented through MATLAB. To make the calculation more convenient, a cube is used for the microphone arrays, due to the fact that a cube is symmetric and the position vectors of each microphone could be easily derived. However, problems arise for finding the maximum peak of the sound source.

2. Discussion:

a) Shape/Layout of Microphone Arrays

As aforementioned, it was agreed that the shape of the microphone is a cube. Hence, the number of microphone used is 8 (vertices of a cube).

b) Principle of Finding Maximum Amplitude

To prevent the dominance by sudden noise other than the sound from the drone, it was suggested that using the mean might be a better choice.

c) Negative Time Delay

It was questioned that if negative delay matters, as it is equivalent to predicting future sound waves. It was explained by Ben that it doesn't matter, as long as we fix the time frame where we sum the samples (which is not immediately from the microphone input, but rather the input from the past). To know the data we have to store in our system, we have to know the worst case scenario. The total number of samples we have to store is $(Tdmax-Tdmin)*fsamp+n$, where n is the number of samples (frame) that we would like to sum them up.

d) Sampling Frequency

It was agreed that the higher the sampling frequency, the higher the accuracy of retrieving the original waveform. A compulsory requirement is that it must be higher than or equal to the Nyquist Rate. However, it is limited by the clock frequency of the single-board computer we will have.

3. Action Points:

a) Circuit Diagram

It was suggested that a detailed circuit diagram for the overall circuit would be done. The Block Diagram done by Alex would be used as a reference, where the variable gain amplifier would be a possible optional add-on to the circuit.

b) Work Allocation

The group is divided into various sub-groups. Each sub-group would have to come up a detailed design (e.g. circuit diagram, component, drawings). The work is allocated as following:

Topics Member(s) Responsible

Microphones, Multiplexer Alex

Filter Aaditya

Single-Board Computer and Display Ben, Vincent, Pavol

Physical Structure/Building the Microphone Array Victor, Guy

Note 1: The tentative time for meeting of group responsible for Single-Board Computer and Display is at 2pm, Sunday, 6th December.

Note 2: For the group on Physical Structure, please refer to the 1st technical meeting on setting the length between microphones.

c) Drone Sound Frequency

As measured before, the maximum drone sound frequency is around 1kHz. However, it was only based on the only recording that was available online. To ensure the accuracy of the frequency, it is suggested that more and longer soundtrack samples could be obtained, from which the maximum source frequency could be found. The related MATLAB file is already on SharePoint, which can be used to analyse the recordings. The frequency obtained would be a determining factor to the length of the cube microphone array.

It was agreed that Victor would be responsible for collecting more samples. The minimum number of samples is 5.

Friday, 11 December 2015

Present: Ben Chua, Guy Haroush, Vincent Leung, Aaditya Malhotra, Alexander Wilson, Victor Zhao, Pavol Olexa

1. Discussion:

a) Physical Design of the Microphone Arrays

After discussion at the Technical Meeting, it was decided that octagon would be preferred rather than cube, so the device would be more compact, as well as easier to implement.

b) Design of Bandpass Filter(BPF)

After collection of more sound samples, it was decided that we would mostly consider the sound around 1kHz. Hence, we would need a BPF with corner frequency at 710Hz and 1.4kHz. (3dB point)

c) Modifications of Block Diagram

Rather than having a single-board computer alone, it was agreed that another microcontroller, replacing the multiplexer due to transient problems, would be added for functions like selecting microphones, while the single-board computer would only be served for data manipulation (data processing center), in which delay would be found. Some choices of components were suggested by Alex, and would be uploaded to SharePoint for reference. It is expected that this method would enhance the sampling rate, which would be ideal for our purpose.

2. Action Points:

a) Work Allocation

As the end of first stage arrives, the work has been allocated for the implementation of the prototype. Ben, Vincent and Pavol would be responsible for the software for data processing on the PC, which would mainly be processed through Python. The part for the microcontroller (ADC, data transfer) would be done by Alex, while the report-writing and physical design would be done by Guy, Aaditya and Victor. Victor would also be responsible for the website. Everyone would need to do research on the components required for their parts, so that they can be purchased next term.