Active Noise Cancellation System for UAVs

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The aim of this Project is to complete a first study of *Active Noise Cancellation* systems applicability to *Unmanned Aerial Vehicles*. The main motivation to this research is the EASA request to minimize noise from UAVs in populated areas, besides all other possible applications. At first, a brief introduction to the issue and ANC systems is made. Then, a physical model of propellers soundwaves is carried out so that an estimation of noise cancellation levels is possible. Next chapters are focused in the system employed. An algorithm is selected, modelled, and studied. Same steps are made with microprocessor, microphone and speakers. Principal research conclusions are discussed within the last section: this first study corroborates the feasibility of using ANC systems in order to reduce noise generated by UAVs. Finally, future work lines are proposed.

Nomenclature

A	Amplitude
c	Speed of noise, m/s
d	Desired signal
e	Error
f	Frequency in Hz
log	Logarithm to base 10
N	Sound power, W
p	Pressure, Pa
r	Distance, m
SPL	Sound pressure level, dB
T	Period, s
t	Time, s
x, y, z	Cartesian coordinates, m
w	Weights
y	Predicted signal
λ	Wavelength, m
ν	Step parameter
ρ	Density, kg/m^3
ω	Frequency in rad/s
φ	Phase, rad

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I. Introduction

The principal aim of this research is reducing the noise generated by UAVs *(Unmanned Aerial Vehicles)* during its normal use.

Noise generated by UAVs may be an important issue in several situations, as the following ones:

- Concerts and speeches recording.
- Animal care, fishing, wildlife observation.
- Military purposes.
- So many others uses we can't still even imagine.

But, above all, the motivation for this research is the European Authority EASA instructions[1] : *"The current framework foresees regulatory limitations on noise for unmanned aircraft subject to type certification. Noise even from unmanned aircraft in the open category should be abated as much as possible"*. There is an increasing number of UAVs being used in suburbs, so noise may disturb inhabitants' normal life. According to this, practical measures are needed in order to reduce the noise.

The principal line of research is designing propellers modifying parameters such as chord, thickness, blade numbers, etc. in order to control the noise produced. Good results are being obtained, however, noise can't be highly reduced this way. The proposal presented in this paper is the introduction of ANC *(Active Noise Cancellation)* to UAVs, and its combination with current research projects in order to improve results.

ANC is based in the physical principle that can be observed in picture I. We have a noise represented by a sinusoidal signal. If we are capable of detecting its frequency and amplitude, then, we can emit another signal with same characteristics but with opposed phase (180 degrees), which will cancel the first one. In order to do that, we need three components:

- A microphone that captures the noise.
- A control system that calculates the new signal.
- A speaker to reproduce the new signal.

In section III an in depth analysis of this system nature is made. Also, speaker and microphone selection is discussed in sections IV.

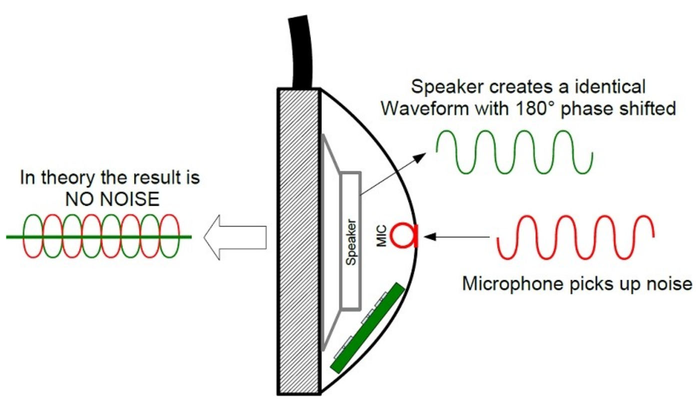

Figure 1. ANC physical concept

ANC technology is well developed nowadays, as it is commonly used in medicine electronic devices, such as electrocardiographs, or in smartphones to reduce the noise of our voice. It is also already used in aeronautical applications. In private aviation there are some luxury aircrafts that include a system like these in order to reduce the sound of the engines inside the cabin. Also some crew members use noise-cancelling headphones in order to speak the rest of the crew or the traffic management.

However, this technology has not been used in UAVs yet. ANC has a good performance when noise main components are low-frequency. We believe that designing propellers in order to produce low frequency noise and combining this effect with ANC is a powerful weapon to fight noise.

II. Study of the applicability of ANC to UAVs

Due to the high impact that the relative position between the noise sources and the loudspeaker of the noise cancellation system has on the level of noise reduction, an analytical model has been developed in order to study the effectiveness of ANC when applied to the specific dimensions and configuration of UAVs. In particular, this paper focuses on propeller driven UAVs, like the popular quadcopters.

A. Analytical model

According to different studies,[?,?] the noise in UAV operation is mainly produced by the propulsive system, that is, the engines and their propellers.

For this study, each engine and its propeller are modelled as a punctual sound source emitting an omnidirectional harmonic pressure wave. Loudspeakers are considered in the same manner. According to this, the pressure change produced by the source i at a point that is located at a distance r of the source is given by

$$p_i(r) = A_i(r)\cos(2\pi\frac{r_i}{\lambda_i} - \omega_i t + \varphi_i) \tag{1}$$

where p is the sound pressure, A is the amplitude, λ is the wavelength, ω is the frequency in radians per second, t is the time and φ is the phase.

The dependence of the amplitude A with the distance r represents the drop in sound pressure when moving away from the source. For a spherical (omnidirectional and isotropic) propagation its given by

$$A_i(r_i) = \sqrt{\frac{\rho c N_i}{4\pi(r_i + \sqrt{\frac{\rho c N_i}{4\pi p_i^2(r=0)}})^2}} \tag{2}$$

where ρ and c are, respectively, the density and the speed of the sound for the medium where the wave is propagating and N is the sound power emitted by the source

The sound pressure produced by the different sources is summed for each point and time. Then, the effective pressure, p_{ef}, and the sound pressure level, SPL are calculated using,

$$p_{ef} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt} \tag{3}$$

$$SPL = 20\log\frac{p_{ef}}{p_0} \tag{4}$$

where p is the sum of all the pressure waves and $p_0 = 20\ \mu Pa$ is the threshold of human hearing.

B. Parameters of the analysis

Two different configurations have been considered initially: one with a loudspeaker for each engine and one with a single loudspeaker for the whole system. The use of multiple loudspeakers enables the system to cancel noise better and in a bigger volume, since each loudspeakers can be tuned to cancel a noise source and can be placed closer to it.

However, the employment of a single loudspeaker has several advantages. In the first place, the system is inherently simpler and more flexible (it can be applied to a wider variety of platforms with less changes, because parameters like the number of motors have no significant effect). Additionally, the greater simplicity can imply a reduction in weight and failures, which are very important aspects in aeronautical applications. Because of this benefits, the single loudspeaker configuration has been selected for the study, which will determine its possible performance.

The analyses have been done considering four noise sources. This noise sources are the corners of a square of 0.5 m. They are contained in an horizontal plane at 20 m of height (the flying height considered for the UAV). All of them are identical, with $\varphi = 0$, $f = 125\ Hz$, $N = 0.1\ W$ and $p^2(r = 0) = 0.1\ Pa$. These values has been estimated as representatives of a medium size drone[?,?,?]

The properties of air needed are the density $\rho = 1.225\ kg/m^3$ and the speed of sound $c = 343\ m/s$.

The values of the wavelength, the frequency in radians per second and the period can be obtained using the relations

$$\omega = 2\pi f = \frac{2\pi}{T} \quad ; \quad \lambda = c/f \tag{5}$$

The loudspeaker is in the vertical of the centre of the square, 0.20 m under the noise sources. Since an only loudspeaker is being used, it has to be tuned to cancel the noise perfectly (in this model) in just a single point. This point is situated in the vertical of the loudspeaker, at a height of 1.7 m. Therefore, the phase and the amplitude of the wave emitted by the loudspeaker have to be chosen adequately. In the configuration described before, since all noise sources are equidistant from the objective point, all their pressure waves are in phase at the objective point and their amplitudes are identical. Then, the phase and amplitude of the loudspeaker can be obtained from the following relations

$$\varphi_L = 2\pi\frac{r_M}{\lambda} + \varphi_M - 2\pi\frac{r_A L}{\lambda} + \pi \tag{6}$$

$$A_L(r_L) = 4A_M(r_M) \tag{7}$$

where the subscripts L and M make reference to the loudspeaker and the noise sources (engine and propeller), respectively, and r_L and r_M are the distances from them to the objective point.

The frequency of the loudspeaker will be set equal to that of the noise sources.

As final part of the study, the interferences between two different drones equipped with ANC systems have been analysed. The two UAVs are considered identical, in regard to the sound produced, and are placed at an horizontal distance of 10 m, flying at altitudes of 20 m and 24 m. Also the influence of the first two harmonics of the main frequency ($f = 125Hz$) of the noise sources has been studied.

C. Results

Graphics for the SPL with the ANC system being inactive and active have been obtained, as well as graphics for the difference in SPL and the relative difference between the two situations. The position of the drones has been marked as D1 and D2 and the relative difference has been calculated, using effective pressures as,

$$Relative\ difference = \frac{p_{ef_{inactive}} - p_{ef_{active}}}{p_{ef_{inactive}}}$$

1. Results for a single UAV

Figure 2 shows that, even when considering sound dropping with distance and no having into account reflections, the SPL at ground (or human height) level is around 80 dB in a wide area. This SPL can be compared with that produced by a car. The effect of the ANC system when it is active is clearly noticeable and the SPL at those same heights become lower than 60 dB, which can be compared with the noise level of a casual conversation.

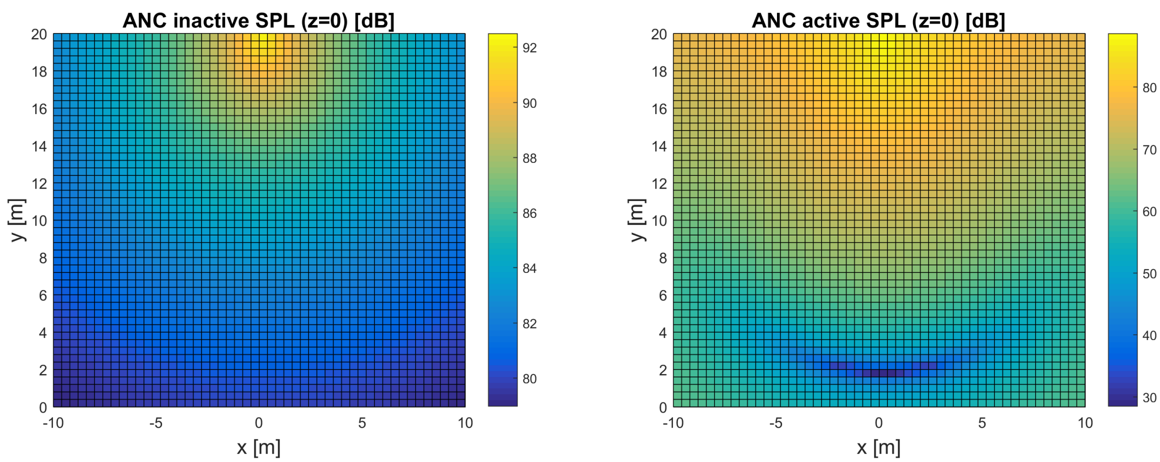

Figure 2. Comparison of SPL with ANC active and inactive

Figures 3 and 4 give a clearer and more precise idea of the noise reduction achieved. It decreases when moving away from the objective cancellation point, but is greater than 75% in almost all the 30m x 30m area analysed in the horizontal plane, which is a great result for a flying altitude of 20 m.

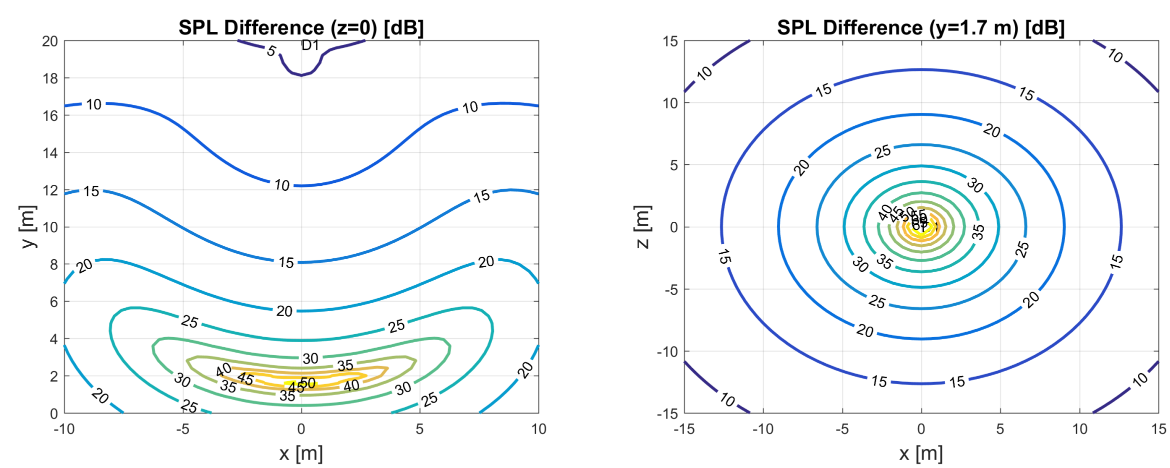

Figure 3. SPL difference with ANC active and inactive

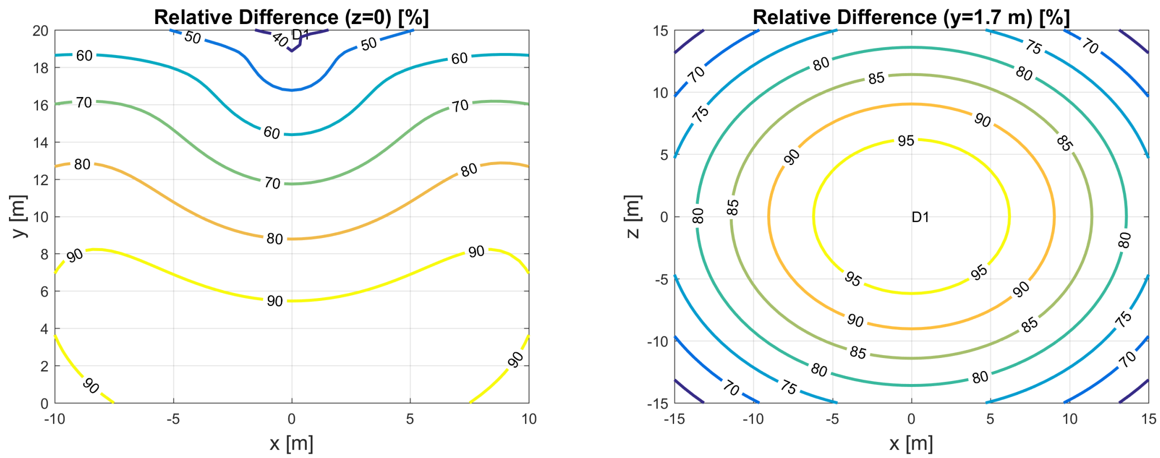

Figure 4. SPL relative difference with ANC active and inactive

2. Results for two UAVs

The presence of a second drone, that is, a different group of noise sources with their respective loudspeaker doesn't affect the efficacy of the ANC system. Comparing figures 4 and 5, it can be observed that the changes are noticeable only in the area where the reduction level is over 85%.

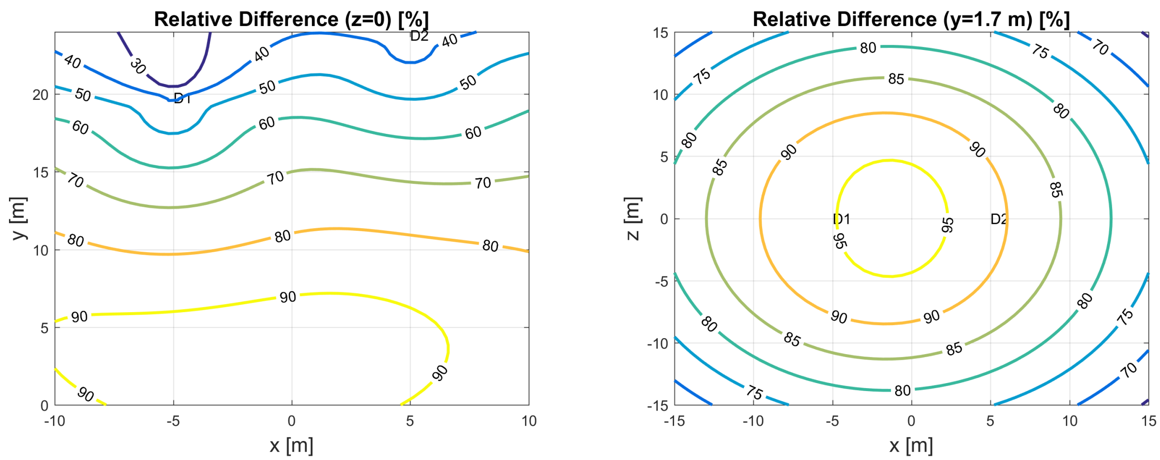

Figure 5. SPL relative difference with ANC active and inactive for 2 UAVs

3. Results for multi-frequency noise

When considering the main frequency of the noise sources together with its two first harmonics, the performance of the system becomes poorer, as can be seen in figure 6. The relative noise reduction achieved at 15 m from the objective point falls from around 80% to 40%. This shows that ANC is only effective for low frequency noise.

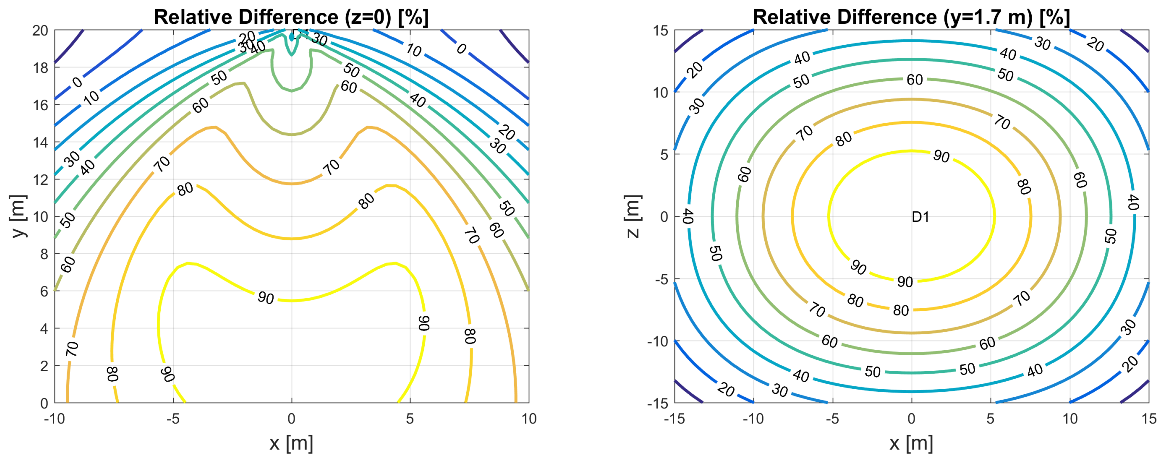

Figure 6. SPL relative difference with ANC active and inactive for multi-frequency noise

III. System control implementation

A problem appears when we try to cancel a noise because processing a signal takes time. It is not possible to take the noise received by the microphone, put it 180 out of phase and emit it instantly, so the sound emitted by the loudspeaker will not cancel the noise generated by the drone, which could have changed by that moment. Therefore, we need to find a way to predict the noise that the UAV will be generating at a given time basing our prediction on a sample or of the noise at a previous instant of time. This can be achieved using an algorithm with the structure shown in figure 7.

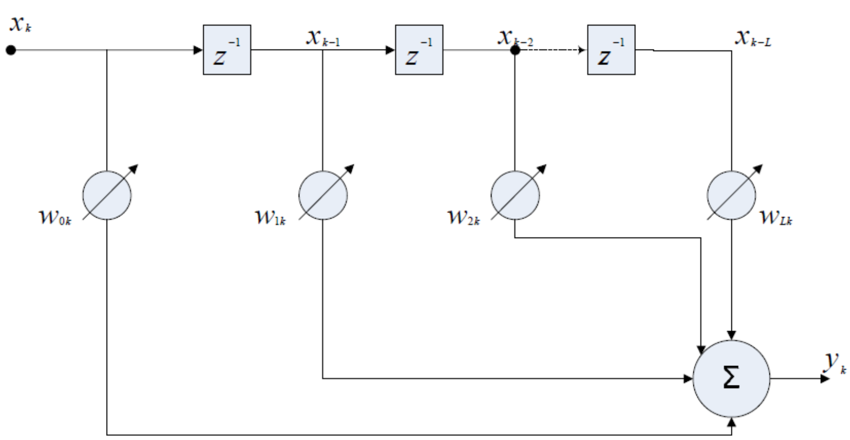

Figure 7. Diagram of the algorithm

Where x_{k+1} is the signal that we want to predict and x_k,x_{k-1},,x_{k-L} are our samples of noise at previous times and the w_{ik} are the weights that are being to multiplied by x_{k-i} . The prediction is y which is:

$$y = \sum_{i=0}^{L} w_{ik} \cdot x_{k-i}$$

We want y_k (our prediction) to be as similar as possible to x_{k+1} (the noise at the time when we can emit our prediction y_k). Therefore, it is necessary to find the weights that minimize the error between our prediction and the noise signal. LMS (Least Mean Square) is going to be used in order to find these weights.

LMS is an adaptive algorithm. This means that there are parameters in the algorithm that are going to change with time. Theses parameters are the weights. LMS algorithm tries to minimize the mean square error. This algorithm will adapt itself to the signal behaviour in each time. The advantages of this method are, mainly, the low operational cost of the algorithm and it simple implementation.

It can be demonstrated that the the mean square error, expressed as a function of the weights is a surface with a single minimum. The LMS algorithm computes the error uses its gradient to determine how to modify the weights in order to minimize the error (trying to descend on the error surface). This is done as shown in the following equations:

$$
\begin{aligned}
y(n) &= w(n) \cdot x(n) \\
y(n) &= \sum_{i=0}^{L} w_{ik}(n) \cdot x_{k-i}(n) \\
e(n) &= d(n) - y(n) \\
\nabla e(n)^2 &= 2e(n)\nabla e(n) = -e(n) \cdot x(n) \\
w(n+1) &= w(n) - \frac{\mu}{2}\nabla e(n)^2 \\
w(n+1) &= w(n) + 2 \cdot \mu \cdot e(n) \cdot x(n)
\end{aligned}
$$

In these equations, $d(n)$ is the signal that we want to predict and the μ parameter is the so called step parameter. The step parameter controls the speed of the convergence. If μ is very high, the inclination of the error surface acquires importance and the changes of the weights that the algorithm makes are bigger. But, if the μ is too high, it can cause instability and the solution could diverge.

Figure 8 shows an example of the results obtained with this method. The simulation was run taking 5 weights and the value of μ was 0.1. The reference signal was: $d(n) = 0.1 + 0.1 \cdot sin(\frac{2\pi \cdot 100000 \cdot n}{8193})$

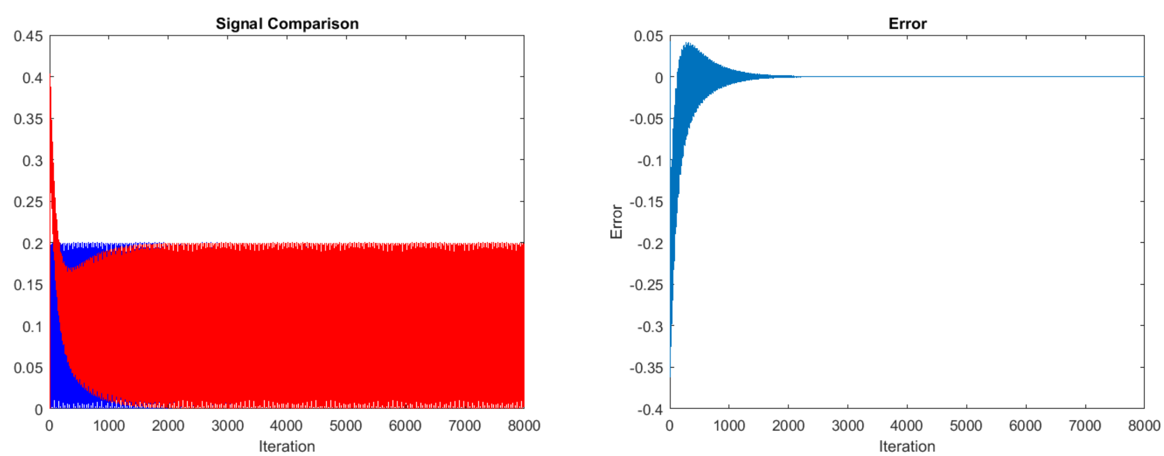

Figure 8. Signal comparison and error

As can be seen, our prediction (red signal) is not so good at first, but it improves with time. It can be seen, as well, that the error tends to zero with time. This behaviour is due to the perfect periodic nature of our reference signal. If our signal were not periodic, the error would be oscillating around zero. In order to see the weights behaviour in a real case, a simple script in Simulink was run (9).

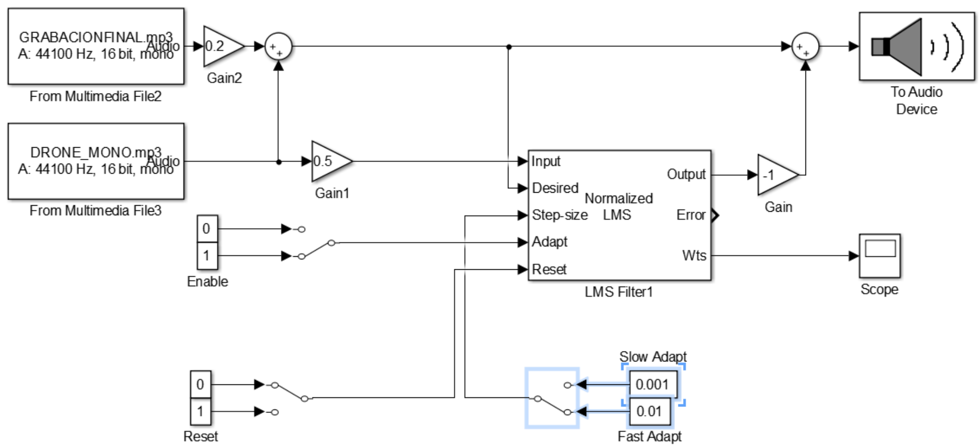

Figure 9. Simulink example

There are two signals. One is a voice recorded and the other one is the sound of a drone recorded. Our reference signal is the noise of the drone and our desired signal is the signal that we want to filter (the voice and the noise mixed).

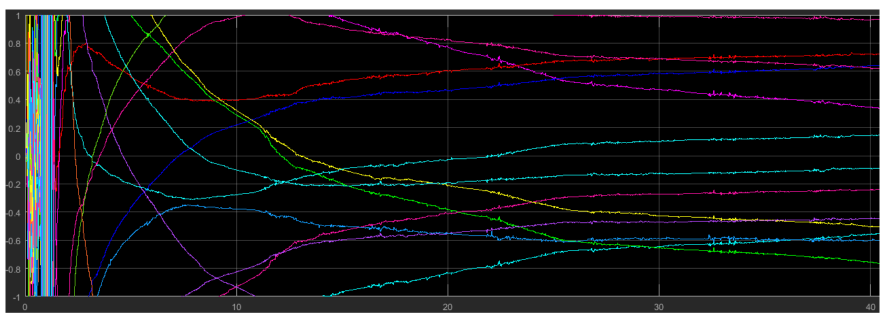

Figure 10. Evolution of the weights

In figure 10 it can be observed how the weights try to find the minimum square error, adapting and tending to a particular value. If the signal behaviour changes, the weights would adapt to the new signal behaviour.

Finally it can be concluded that with this simple algorithm very good results are obtained with a very low operational cost. Therefore a powerful processor is not necessary to cancel the noise.

IV. Integration of the system into UAVs

The ANC system is basically composed of a Microphone which inputs the noise generated by the engine, a Control System with the predictive model and a Speaker which will emit the generated wave.

The resultant system is modular (an interesting point because it makes easy for the user its incorporation into the UAV) and versatile (which allows the user to exchange the components quickly in order to customize it). This is shown in figure 11, where the block diagram of any conventional UAV including the noise cancellation system is represented.

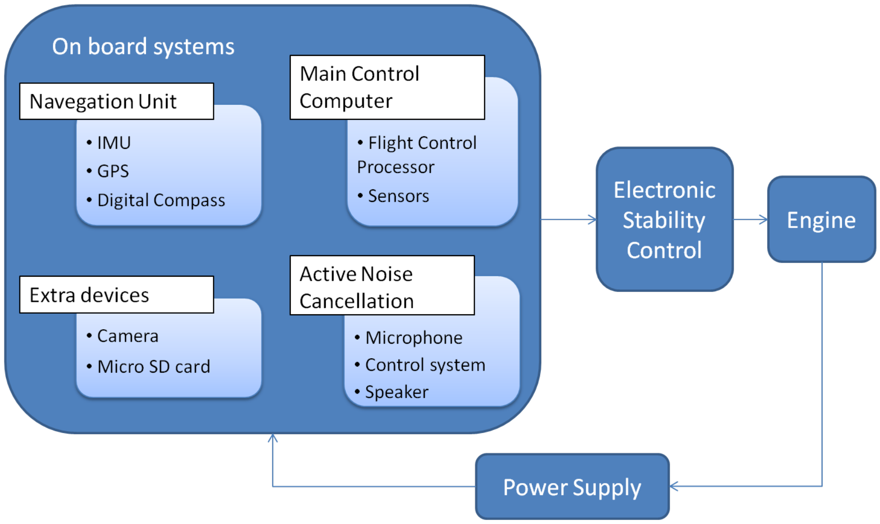

Figure 11. Block diagram of a conventional UAV with the ANC system installed

Once the system is onboard, it will require a connection with the Navigation Unit in order to receive the data collected by this system, and also with the Main Control Computer to verify the correct behaviour of the ANC.

A. Cost and weight increment

In order to give an example of the expected cost and weight increment of the system implementation, some typical devices which could be used have been chosen.

- Electret Microphone ($100Hz - 10kHz$) with a 60x mic preamplifier, it works from 2.7V up to 5.5V
- Arduino DUE microcontroller, based on a 32-bit ARM core microcontroller
- Grove - Speaker, a module which supply power amplification and sound outputs

The selection of the devices used as reference for the estimation of cost and weight has been based on the project attached in the point 9 of the bibliography, where an ANC system is implemented.

	Microphone	Control system	Speaker
Cost (€)	6.45	37.95	7.60
Weight (g)	16	36	68

Table 1. Estimation of the cost and weight of the ANC system

Considering the selected items the system's weight is about 120 g, which is a payload affordable for almost any medium UAV nowadays and the final price is of 52 €, being the control system the most expensive device and depending of the power needed by the speaker.

V. Conclusions

To sum up and collect the main ideas of the project, the team has come up with the following conclusions:

- As the result of the analytical model detailed previously, it has been proved that the ANC system performs very well on UAVs when it is cancelling low frequency noises
- Also as the result of the analytical model, it has been proved that the ANC system can be used on several vehicles flying close without causing interferences
- The ANC system has an easy implementation with an adaptive filter
- The ANC system has an affordable price and light weight, which can be considered as the payload of any medium UAV nowadays

A. Future work

As a result of the study the group have finally arrived at the conclusion that this system will be sooner required by the UAVs developers. It is only a matter of time before the UAVs are integrated into populated areas, so continuing developing this system would be a good sign of anticipating that moment.

This is the main reason why, in order to take advance to the project, it would be interesting to continue following these steps:

- To develop a more comprehensive study with more detailed models
- To complete a real implementation on an UAV and test the system

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