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Designing for Calmness: Early Investigations into Drone Noise Pollution Management

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Abstract— **Drone use is increasing rapidly within civil society, making their sound profiles - and potential contribution to noise pollution - increasingly relevant. Noise pollution has been demonstrated to be a public health risk including contributions to hearing impairment, hypertension, heart disease, dementia, sleep disturbance, decreased school performance, and annoyance. High-frequency and tonal noise has been identified as being particularly annoying to humans. In this work, early investigations into designing drones for calmness are explored, inspired by ethical considerations and empirical evidence about human perception of drone sounds. Experiments conducted in an anechoic chamber on a small (250 gram) quadcopter drone using one, two, and three-bladed propellers showed sound pressure peaks with fundamental frequencies at 116 Hz, 178 Hz, and 316 Hz respectively and sound pressure levels of 77.4, 76.6, and 76.4 dB(A) respectively at a distance of one meter. Therefore, in this case-study, less annoying lower-frequency sound can be achieved using single-bladed propellers. When designing for calmness, explicability should also be considered - a drone that is still audible can prevent spying and enhance trust. In the future, designers and manufacturers could increase public acceptance and reduce public health impacts by designing drones for calmness.**

I. INTRODUCTION

A. Background

Drone use is increasing rapidly within civil society [1], making drone sound profiles - and potential contribution to noise pollution - increasingly relevant. Noise pollution has been demonstrated to be a public health risk including contributions to hearing impairment, hypertension, heart disease, dementia, sleep disturbance, decreased school performance, and annoyance [2] [3] [4]. The World Health Organization states that ”at least 1.6 million healthy years of life are lost as a result of road traffic noise”in western Europe alone [5]. Many prior studies utilize traffic noise as a common form of noise pollution in an urban environment, but one study found the psycho-acoustic properties of small drone noise to be unique compared with traffic noise [6] meaning that a new form of noise pollution could be added to urban and rural environments.

This work contributes by providing early investigations into drone noise pollution management, addressing the following research questions: 1. What is the context and what are some relevant considerations in drone noise pollution management? 2. What are some relevant considerations about the objective measurement and subjective experience of drone noise and annoyance to humans and animals? 3. What are some relevant ethical considerations, including calmness and explicability? 4. Could single-bladed drone propellers potentially enhance calmness and explicability? 5. What is the sound profile of a small quadcopter drone using one, two, and three bladed propellers?

This work is exploratory in nature and more focused on understanding the drone noise pollution problem than providing complete solutions - although single-bladed propellers show potential. One area of novelty is in the criteria by which drones are designed: for calmness and explicability. Key limitation to this work are the small data-sets and challenges related to isolating the drone noise during in-situ testing. The aim is to provide early investigations into designing drones for calmness and establish directions for future work.

B. Drones

Drones, or unoccupied aerial vehicles (UAVs) are flying robots with varying levels of sensing and autonomy. Often associated with military use, civil applications of drones are growing quickly. These include hobbyist activities, journalism, wildlife monitoring, agriculture, public health and safety, law enforcement and surveillance, entertainment, social movement advocacy, commercial data collection, emergency response, and scientific research [1]. Operators include individuals, intergovernmental organizations, governments, businesses, social groups, and academia [1].

Fig. 1. Three types of smaller drones under 25 kg: a fixed-wing drone (left) [7], a multirotor drone (center) [8], and a hybrid vertical takeoff and landing (VTOL) drone (right) [9].

There are three main configurations of drones: fixed-wing, multirotor, and hybrid or VTOL (vertical take-off and landing); these are shown in Fig. 1. The most common configuration for industrial applications is the fixed-wing drone which resembles a small aircraft. The multirotor drone, such as the four-rotor quadcopter and six-rotor hexacopter, are outnumbered by fixed-wing drones two-to-one in industry [10] but multirotors are the most common in hobby use

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[1]. More recently, hybrid or VTOL drones which take off and land using propeller thrust like a multirotor but then transition into forward flight like a fixed-wing drone are being developed. These craft provide flexibility in operations as they can be launched and landed from small areas, but have a higher weight than pure multirotors meaning they need to produce even more thrust to take off, land, or hover - likely increasing noise levels produced. The sound profile and sound pressure levels (SPL) of the two configurations vary significantly as fixed-wing aircraft fly on large wings while multirotor drones spin smaller rotors quickly to produce the lift necessary to remain airborne.

Drones are highly heterogeneous in size, weight, power, and configuration. One of the smallest drones, the Black Hornet Nano used for military surveillance weights 18 grams and measures 10 cm in length [11]. Some of the largest drones include passenger-carrying models like those from Volocopter [12] and EHang [13] which are around the same size and weight of a small piloted helicopter. In principle, any flying vehicle can be made into a drone by replacing the pilot with remote control and sensing capabilities. However, the most common types of drones currently poised to make their way into urban and rural spaces are smaller drones (or ”sUAS”) under 25kg [14]. In addition, a smaller drone was chosen for the current study as they are legally permitted to operate closer to people, and have a higher-pitched (i.e. more annoying) sound profile compared with larger drones.

C. Drone noise

Drone noise has unique characteristics which make it particularly challenging to manage [6], yet as of this writing the sound profiles of only a few specific drone models have been investigated. In one study, the sound recordings of four small quadcopter drones (the DJI Tello, Phantom, Mavic, and Matrice [15]) were presented to thirty-seven participants; a strong correlation was found between SPL and annoyance [16]. Another study utilized psycho-acoustic metrics including loudness, fluctuation strength, roughness, sharpness, and tonality together with psycho-acoustic annoyance models, but applied these to counter-rotating propellers [17] which are uncommon in currently-available drone systems.

Most smaller drones currently in operation utilize relatively quiet electric motors for propulsion. This means that the sound pressure levels produced are not high enough to risk hearing damage as seen in piloted aircraft or industrial machines. However, the unique sound profile - especially of multirotor drones with their multitude of high-speed propellers - creates an additional audible annoyance.

Some drone operations consist of transportation of items from fixed locations. For example, the most prolific drone operation in the world is the company Zipline which ships blood for transfusions via drone from a hub in Rwanda to surrounding clinics [18]. This means that drone noise pollution will recur on a consistent basis around the launch site and to and from the surrounding clinics (the drone does not land at its destination, but drops the cargo via parachute and returns to the launch site). Consistent noise pollution could be compared to wind turbine noise which causes frustration and irritation to those living nearby [19]. One study showed that paying residents for the annoyance, as well as allowing them to invest in the wind turbine and reap some of its rewards, increased satisfaction with the technology [19].

Some drone operations will occur from varying locations with varying destinations. For example, a drone used by hobbyists or journalists to capture aerial photos or videos for fun or for a news story could operate from a different location each day, and therefore create noise pollution at unpredictable times and places.

Most drone operations take place during the daytime, but some use-cases require or are aided by flying at night. For example, drones carrying thermal cameras are being used in Aalborg, Denmark to look for leaks in buried district heating pipes [20]; flying at night when it is colder makes the leaks easier to identify. Noise pollution at night can be particularly acute, which is reflected in noise ordinances being more strict during nighttime [21].

Drones will operate at varying distances and execute varying flight paths relative to those on the ground. Drone noise is usually highest during take off when the drone is at ground-level and using a high power setting to climb. Drone flights typically take place between ground level and 100 or 120 meters altitude [14], so they are at some distance from people on the ground - but not so far away that they will necessarily be inaudible. The flight path may be between two destinations such as in cargo transportation, or it may be near an object of interest such as a high-rise building or wind turbine during inspection. The former constitutes noise of a drone passing by, while the latter encompasses a more persistent noise. A participant in a Danish study stated ”if it (the drone) just flew by, I wouldn’t mind, but if it’s like, several times a day, or if it flew around for some time, that would annoy me”[22]. Another typical flight path is one used to cover a certain area of ground, such as for map-making or farm monitoring. Here, the drone flies straight paths with turns at the end and overflies the area of interest in a back-and-forth pattern. Relative to an observer on the ground, this flight path constitutes a series of increasingly and then decreasingly close fly-bys.

A final consideration in drone noise pollution management is the purpose for which the drone is operating. Evidence shows that the public is much more tolerant of drones operated for what they view as good uses [23]. ”Participants...would accept drones practically regardless of where and how they fly if they knew that they were being used to help saving lives”[23].

D. Noise laws

Noise laws vary by country and sometimes municipality, so the context in which this testing took place will be taken as an example. The legislation concerning noise in Denmark is handled by the Danish Environmental Protection Agency under the Danish Ministry of the Environment. For establishing new industry or installations the expected noise should be compared to the recommended noise limit and normally be arranged to comply with the relevant limit. For new wind turbines the limits are mandatory – no environmental permits are issued without compliance with the legal limits [21].

Industrial noise with clearly audible tones is penalized 5 dB on top of the measured equivalent SPL due to the additional annoyance associated with pure tones. Recommended limits depend on the area with the highest limits in industrial areas. In areas for open and low residential dwellings the limit is between 35 dB(A) at night (averaged over 30 minutes) and 45 dB(A) at daytime in weekdays (averaged over 8 hours). At night no single noise event can exceed the limit by more than 15 dB in residential areas [21].

Road traffic noise is measured in terms of the day-evening-night level, L_{den}, which is an average over a full day in which an extra 5 dB is added during the evenings and an extra 10 dB during the night in order to reflect the extra annoyance of noise in these periods. The recommended limit for L_{den} concerning road traffic in housing areas is 58 dB(A), but authorities have no general duty to reduce noise if this limit is exceeded [24].

Currently, there is no Danish legislation specifically directed at drone noise pollution management. Outside of Denmark, the World Health Organization has created environmental noise guidelines with a focus on minimizing harm to public health. There are guidelines for road traffic, wind turbine, and aircraft noise, but no guidelines for drone noise are included [5].

E. Objective measurement of drone noise

Drone noise pollution can be characterized in two ways - objectively and subjectively. Objective measurements include capturing quantitative data on variables such as SPL and sound frequency profile. These measurements are important in understanding the actual noise produced by drones.

F. Subjective experience of drone noise

The subjective experience of drone noise depends on factors related to the psycho-acoustic interpretation of objective noise. Human hearing is bounded by the ear's ability to detect sounds of different frequencies, with audible frequencies typically ranging from around 20 Hz to around 20 kHz [25]. In addition, human hearing has varying sensitivity across the sound spectrum, with low sensitivity especially at low frequencies and maximum sensitivity around 2-5 kHz. Fig. 2 show the equal-loudness-level contours for pure tones according to the international standard ISO226:2003 [26]. An equal-loudness-level contour relates the frequency and the objective level (in terms of the sound pressure level) so that tones on a specific contour is perceived as equally loud. The loudness level is measured in phones, and by definition the loudness levels equal the SPL (in dB) at 1000 Hz. Note that loudness levels do not directly translate to annoyance - although an annoying sound certainly is more annoying the louder it is. Hearing varies across individuals, and hearing loss as seen in old age constitutes an additional variable to the subjective experience of noise - also if enhanced with the use of hearing aid(s) [25].

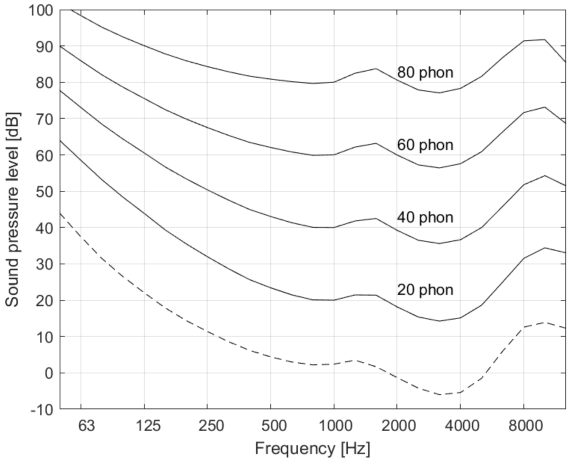

Fig. 2. Normal equal-loudness-level contours for pure tones (human hearing) according to the international standard ISO226:2003 [26]. The dashed curve is the threshold of hearing and the solid curves are for the phon levels indicated. Loudness levels in phon equal SLP levels in dB at 1000 Hz per definition. Graphic by the authors.

G. Noise and annoyance

Empirical evidence on human perception of drone noise and annoyance is limited, but previous work found that lower-frequency sound profiles were preferred over high-frequency ones [27]. In the study, 26 participants were given a 5-point 'just about right' questionnaire. Stimulus material in the form of audio recordings of the sound of a Cumulus fixed-wing drone (shown on the left in Fig. 1) were presented to the participants. Three drone sounds were played: one modified to be lower-pitched, the unaltered sound, and one modified to be higher-pitched. Lower frequency sounds were preferred, with high frequencies being considered ”shrill”. Another study found a correlation between lower SPL and annoyance ratings in both road vehicle noise and drone noise [6]. Interestingly, ”sounds which appeared to 'loiter' were judged more harshly than those that didn't”, meaning that relatively fast-moving cars were more acceptable than distant and slower-moving drones - especially those that were hovering rather than passing by [6].

Anecdotal evidence of drones annoying humans and animals appears often in the news. For example, residents of the Bonython neighborhood in the outskirts of Canberra, Australia have formed a ”Bonython against drones”alliance with the mission ”to stop the drones and their intrusiveness on the peace and quiet of our suburb and environment”[28]. One of the drones that has caused controversy, operated by Google's subsidiary Wing [29], is a hybrid VTOL configuration with twelve small motors and four-bladed propellers used to hover while delivering baked goods or coffee. These small, fast-spinning, multi-bladed propellers give the drone a high-pitched noise which residents find particularly irritating and caused a crow to attack the drone in one video clip; still images from the video are shown in Fig. 3 [30].

Ambient sound conditions will likely play a role in the subjective interpretation of drone noise and in levels of annoyance [6]. In the Danish countryside the ambient noise level has been measured at 37 dB(A) [27] meaning drone noise will be much more apparent than in a busy city with higher ambient noise levels.

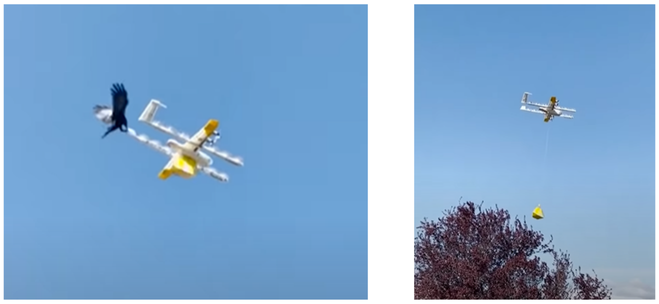

Fig. 3. A crow attacks a Google Wing [29] drone while the drone attempts to deliver coffee in Australia [30].

H. Animals' subjective experience of drone noise pollution

The impacts of drone noise on animals has been the subject of some study. Animals experience noise differently than humans and have hearing ranges that can be significantly different than humans. For example, elephants can hear lower frequencies than humans, but their high frequency range ends around 10 kHz [31]. Bats can hear frequencies between 10 kHz and 100 kHz [31], and use echolocation to navigate in the 20 to 60 kHz frequency range [32]. In one experiment it was found that a drone's noise was characterized by the propellers' rotation speed of 6,000 RPM producing noise at 100 Hz, and by the switching frequency of the electronic speed controllers (ESCs) at around 20 kHz. The latter caused interference with bat's echolocation and disturbed them [33]. However, the switching frequency of the ESCs could be modified to 8 kHz, removing the sound from the bats' perceptible hearing/echolocation range. It has been observed that elephants show signs of discomfort if a drone is audible, even if the drone is not visible [34]. The researchers hypothesized that drone noise had a similar characteristic to another annoyance to elephants - honey bees. They found similarities between the noise produced by the four drones studied and honey bee noise, particularly at higher frequencies which elephants are most sensitive to.

Some species of birds seem to be particularly disturbed by the presence and sound of drones. In California, a drone crash-landed at the Bolsa Chica Ecological Reserve causing 2,500 nesting terns to abandon their nests and rendering around 1,500 eggs left behind unviable [35]. ”In my 20 years of working with wildlife and in the field, I have never seen such devastation,” said the manager of the park Melissa Loebl. However, experiments performed on mallards, flamingos, and greenshanks found that 80% of the time a drone could approach within 4 meters of the birds without visibly disturbing them [36]. Still, it should be noted that animals may experience high levels of stress without visible changes in behavior. ”A study of bears tagged with cardiac biologgers that monitored their heart rate showed that while a UAV circled around them at 20 m altitude, changes in their physical behavior were minor, but there were magnitudes of heart rate spikes correlated with wind and proximity to the UAV”[34].

Therefore, for both the practical aim of gaining acceptance to operate drones around humans, using drones to observe natural animal behavior, and for ethical reasons, the impact of drone noise on humans and animals should be an important drone design consideration.

II. ETHICAL CONSIDERATIONS

A. Calmness

The importance of calmness as an ethical consideration in technological design has been a staple in the ethically-informed value sensitive design methodology [37], and has been included as one of the ”twelve human values with ethical import often implicated in system design”[38].

Indeed, capturing the attention of people - such as for presenting advertising to them - has been described as highly valuable [39]. Drones could be especially effective at this task, adding a moving object - which humans tend to focus on over static objects - into the visual range. Taken to the extreme is a scenario where advertising drones clutter the airspace and occupy human perception - both visually and audibly - reducing calmness in urban and rural contexts.

In some cases, however, drone use may be able to enhance calmness significantly. For example, using a small drone instead of a medical helicopter to transport medical samples between hospitals could greatly reduce noise pollution - especially to those living near the hospitals. For search and rescue operations over homes, using a small drone instead of a helicopter could reduce disturbance to residents and destruction to property below caused by the powerful rotor downwash (i.e. to greenhouses).

It might seem reasonable that a completely silent drone would be the best way to enhance calmness, and that minimization of drone noise should be pursued (as in [40]). Researchers at the Massachusetts Institute of Technology have built a prototype electric model aircraft which flies without any moving parts making it near-silent in flight [41]. However, a very quiet or near-silent drone would limit explicability [27], considered in the next section.

B. Explicability

Explicability encompasses accountability - the ease at which the person or organization responsible for a technology can be seen (”who is behind it?”), and intelligibility - the ease at which the operation of the technology can be understood (”how does it work?”) [27]. Near-silent operation would ease the use of drones for spying or covert operations. Although this capability is useful in a military context, it is problematic in a civilian context where transparency of operation and trust are important design considerations [42].

The chilling effect - where "individuals assume that they are all the time monitored and thus would change their behaviour in order to avoid...repercussions"[43] - could be exacerbated by silent drones. "The chilling entails the inhibition or discouragement of legitimate exercise of civil liberties and rights... [43]"Stress would likely increase if people fear they could be observed by a drone at any time. "The possibility of near-constant surveillance raises significant concerns related to the chilling effect this is likely to have on public life and individual freedom"[44].

There are safety and fairness implications of silent or near-silent (i.e. less explicable) drones as well. Electric cars, with their quieter operation, are around 40% more likely to hit a pedestrian [45]. Blind and partially-sighted people are particularly vulnerable; one study found that over 90% of respondents had experienced problems with them [45]. Drone safety can be enhanced if people on the ground can hear the drone, making them aware that a drone is operating nearby. If the drone comes too close or is crashing, this situational awareness will give them time to move or find shelter [46].

C. *Environmental sustainability*

Drones could be used for a variety of tasks that could either directly or indirectly enhance environmental sustainability. For example, using a 1.5 kg fixed wing drone to transport urgent blood samples rather than by car and ferry would reduce the CO2-equivalent produced by an order of magnitude [47]. Yet direct comparison of different types of transportation are not possible as each method offers differing capabilities, benefits, and risks - including noise pollution. In the blood sample transportation case, unique types and occurrences of noise pollution will be generated - either from road vehicle noise and ferries, or from drones.

As mentioned earlier, drones could be a useful tool in enhanced environmental sustainability via wildlife observation and conservation. However, the presence and noise of drones could interfere with the animals' natural behaviors.

D. *Opportunity costs*

It has been pointed out that not utilizing a potentially beneficial technology leads to opportunity costs as the potential positive outcomes are not fully utilized [48]. Similarly, there exists an imperative "to develop new technical options that more adequately meet the values of ethical importance than do current options"[49]. Therefore, if drones are underutilized in applications where they could produce positive outcomes and enhance human flourishing, and if the drones could be designed in such a way that they give capabilities not previously possible with better ethical impacts, then these drones should be built.

E. *Summary of ethical considerations*

Based on the likely risk of drones contributing to noise pollution, and the aim to develop a less annoying but still audible drone which maintains explicability, this work proceeds with initial investigations into designing drones for calmness starting with the propeller design and continuing with a case study of a small quadcopter drone.

III. DESIGNING PROPELLERS FOR CALMNESS

A method for designing quiet propellers for small fixed-wing electric drones - including consideration of noise, power efficiency, and structural efficiency of the propeller - has been developed [40]. The analysis showed that reducing rotation speed lowers the harmonic frequency of the noise profile, and that for a fixed number of blades, reducing the propeller's rotational speed is the main way to reduce noise. Sound level decreases with increasing number of propeller blades and can reach up to 10 dB(A), but harmonic frequency is reduced with reduced number of blades and a lower number of blades require less power for a given thrust [40]. A single-bladed propeller could potentially maintain explicability by being audible, but enhance calmness by lowering the harmonic frequency of the resulting noise and reducing annoyance to humans. Single-bladed propellers are examined in the next section.

A. *Single-bladed propeller*

A single-bladed propeller's geometry is similar to standard two or three-bladed propellers, except it utilizes a counterweight instead of another blade for dynamic balance. Propellers are rotating wings which spin around a central axis (i.e. the motor's axis or gearbox axis). They are characterized by two main attributes: diameter and pitch [50]. The diameter of a propeller is the diameter of the circle described by the tip of the propeller when it is rotated; the diameter of drone propellers are traditionally measured in inches. The pitch of a propeller is determined by the positive angle of the blades, and is defined as the forward distance the propeller would travel during one rotation with zero slip. Propeller blades have airfoil cross-sections at decreasing angles along the blade length towards the tip. Typically, the airfoils along the blade length follow a helical pitch. Again, drone propeller pitch is usually given in inches.

The single-bladed propeller produces thrust in a similar way to multi-bladed propellers. A propeller can be described as an actuator disc, with lower-pressure and velocity air ahead of the disc described by the propeller arc [50]. The propeller's pitched blade(s) imparts rotational and rearward energy into the airstream, resulting in higher pressure and velocity air behind the propeller disc. The rearward-accelerated air creates an equal and opposite reaction which propels the aircraft forward or the multirotor drone upward. In a one-bladed propeller, there is only one lift force created compared with two for a two-bladed propeller. This means that there is a moment applied to the motor or gearbox shaft, whereas in multi-bladed propellers these moments are cancelled out by the balanced forces created by the other blade(s). However, in practice the centrifugal forces in a drone's propeller blade(s) are high due to the high rotational speed, and the smaller magnitude moment is therefore easily resisted by the motor or gearbox shaft. The result is a net thrust force upward. This is shown in the free body diagram in Fig. 4.

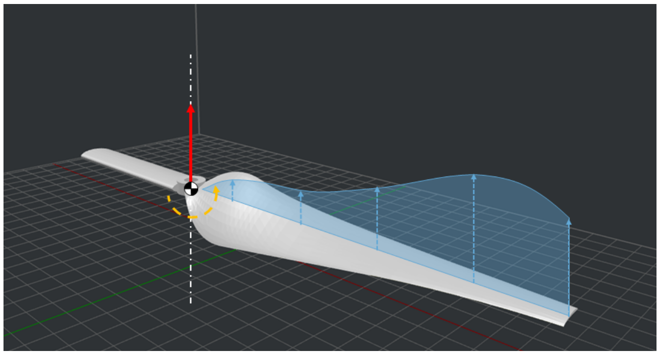

Fig. 4. Free body diagram of a single-bladed propeller during clockwise (as viewed from the back) rotation around the axis shown in white. A counterweight (left side of hub) opposite the blade (right side of the hub) keeps the system dynamically balanced. The distributed lift force (blue) along the blade length creates an upward force which results in a net thrust force (red) at the axis of rotation along with a bending moment at the blade root (yellow). In practice, the bending moment is relatively small compared with the internal centrifugal forces in the blade due to the high rotational speed, and standard propeller materials are suitable to resist the bending moment. The relatively small aerodynamic drag forces on the blade and counterweight are ignored for clarity. Graphic by the authors.

IV. CASE STUDY: SMALL QUADCOPTER

A 250 gram Leora [51] electric quadcopter drone utilizing an Autoquad flight controller [52], shown in Fig. 5, was utilized for the exploratory testing. The drone's carbon fiber frame was modified slightly to extend the arms from 200 mm to 240 mm so that the larger propellers would not hit the body; otherwise, the drone was un-modified. The equipment list is shown in Table I.

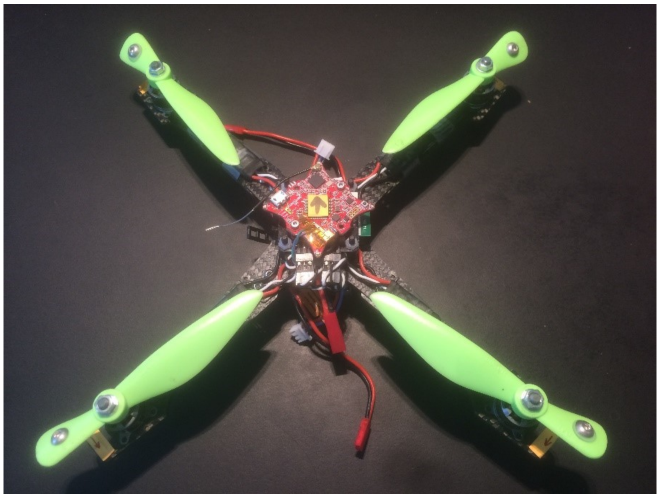

Fig. 5. The Leora quadcopter with four single-bladed propellers mounted. Image by the authors.

Three sets of propellers were utilized as shown in Fig. 6, and the drone with single-bladed propellers is shown in Fig. 5. The three types of propellers tested were all DAL 'regular' models [53] and sizes were 6X4, 6X4, and 5X4.3 inch (1,2, and 3-bladed respectively). The single-bladed propeller is a modified two-bladed propeller with one blade removed and counter-weights added for balance. Notably, the drone did not need any adjustments to the flight controller to be operated with one, two, or three bladed propellers.

TABLE I

EQUIPMENT LIST FOR THE SMALL QUADCOPTER DRONE.

Equipment	**Make/model**
Electric motors X 4	T-Motors MT1306-10 3100 kV brushless AC
Electronic speed controllers X 4	KISS 30 Amp
Battery	DualSKY ECO 400 Li-Po, 3S
Flight controller	AutoQuad M4

Fig. 6. The three propellers tested with one (left), two (center), and three blades (right). Image by the authors.

A. *In-situ testing*

Testing took place in-situ at the edge of the city of Odense, Denmark with a two-lane roadway around 150 meters away - see Fig. 7. The drone was flown over a field with tall grass, likely reducing sound reflections from the ground. The ambient temperature was 7 degrees C, and the windspeed was 2 m/s according to the weather report [54].

Fig. 7. The drone being tested in-situ; the drone was hovered for around 20 seconds at an altitude of approximately three meters and at a distance of about three meters from the test equipment. Image by the authors.

The testing utilized the equipment listed in Table II. The video camera utilized an external microphone with wind damping cover, and was hand-held to keep the drone in frame and the microphone pointing at the drone. Concurrently, the handheld SPL meter - positioned at the same location as the camera - was manually pointed at the drone. The handheld SPL meter was set to fast dB(A) mode. A stopwatch was used to roughly synchronize the video/audio data with the decibel meter readings.

During the test, the drone was taken off and flown to approximately three meters away from the measurement

TABLE II

DATA COLLECTION EQUIPMENT WITH EACH ITEM'S MAKE AND MODEL.

Equipment	Make/model
Video/audio camera	Canon EOS M50
External microphone	BOYA BY-MM1 cardioid polar
Wind damping microphone cover	BOYA
Handheld sound pressure level meter	Radio Shack 3300099 digital sound level meter

equipment and three meters above ground level. It was then hovered for around 20 seconds and measurements were taken including the sound recording and the decibel levels. The drone was operated manually, but in "stabilized"flight mode which reduced the need for manual corrections which causes audible differences in propeller speeds.

B. Anechoic chamber testing

The laboratory measurements took place in the anechoic chamber at the University of Southern Denmark. A measurement microphone was connected to a combined power supply and data acquisition board; the microphone signal was then recorded to the solid drive of a computer using the acquisition board's software. The equipment is in Table III.

TABLE III

DATA COLLECTION EQUIPMENT WITH EACH ITEM'S MAKE AND MODEL.

Equipment	Make/model
1/2-inch free-field microphone	Brüel & Kjaer Type 4189
Microphone preamplifier	Brüel & Kjaer Type 2671
Microphone calibrator	Brüel & Kjaer Type 4231
90 mm diameter windscreen	GRAS AM0069
Data acquisition frontend	Brüel & Kjaer Type 3560C
Input/Output module	Brüel & Kjaer Type 3109

Prior to the measurements, which took place on the same day and within a few hours of one another, the microphone was calibrated with a Brüel & Kjaer Type 4231 calibrator. After the measurements had been carried out, the calibration was confirmed to still be valid.

The free-field microphone was mounted on a stand and directed towards the target position of the drone when hovering - the distance between the drone and the microphone was targeted to 1 meter, and the microphone was below the drone at an angle of about 45 degrees. The drone was operated by an experienced drone pilot, who kept a safe distance well behind the microphone in order not to interfere with the measurements; see Fig. 8. The drone was flown freely (i.e. not securely fastened to a test stand) in order to more accurately recreate the flight conditions of the in-situ testing.

V. RESULTS: SMALL QUADCOPTER

A. In-situ testing

The audio recordings of all three propeller configurations were extracted from the test data. The power spectrum of the sound from each configuration was estimated from the recordings using an implementation in Matlab® of Welch's method with a hanning-window and 50 % overlap (the sampling frequency was 44100 Hz and the blocksize was 16384 leading to about 100 spectra in each average) [55]. The results from 0-2000 Hz are shown in Fig. 9.

Fig. 8. The drone (left) being tested in the anechoic chamber; the drone was hovered in manual mode by the drone pilot (right) for around 60 seconds at distance of one meter from the test equipment. A B&K 4189 free-field microphone (center) was used. A string was tied to the drone and bolted to the grid floor to prevent the drone from damaging the walls of the chamber. Image by the authors, with consent granted by the subject in the image.

It was found that all signals have a periodic structure, shown as peaks in the data. The pitch of these signals can be identified by locating the frequency fundamental - the lowest frequency occurrence of a periodic, and by the spacing between harmonics. The frequency fundamental is often the first local maximum. Since the signal is not quite stationary, the sound peaks have some bandwidth, but are still to be characterized as tonal: at low frequencies the peaks are 10-20 dB larger in amplitude compared to the non-tonal noise. The power ratings in the figures are not in absolute scale, as the camera's microphone is not calibrated. In order to obtain rough estimates, absolute SPLs have been measured using a class 2 Sound Level Meter and are reported in the following subsections.

1) One-bladed propellers: The one-bladed propeller data is shown in blue in Fig. 9. The average fundamental is about 118 Hz, and there are seven or eight harmonics giving a tonal characteristic. There is also a prominent peak around 80 Hz of unknown origin. SPL levels averaged 53 dB(A), with a minimum of 52 dB(A) and maximum of 54 dB(A).

2) Two-bladed propellers: The two-bladed propeller data is shown in red Fig. 9. Here, the fundamental frequency is around 186 Hz, but here the level of the fundamental is less that that of the harmonics. Again, the sound has a clearly tonal characteristic with six harmonics. SPL levels measured by the handheld meter averaged 52 dB(A), with a minimum of 49 dB(A) and maximum of 54 dB(A).

3) Three-bladed propellers: The three-bladed propeller data is shown in green in Fig. 9. The fundamental frequency is around 326 Hz and the first 2-3 harmonics are clearly above the surrounding level. SPL levels averaged 50 dB(A), with a minimum of 48 dB(A) and maximum of 53 dB(A)

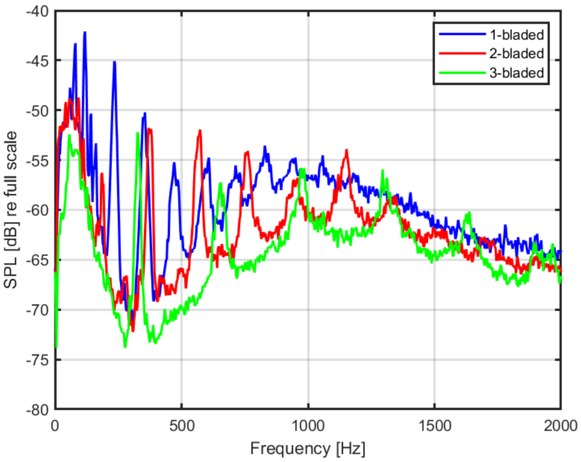

Fig. 9. The sound profile data from the in-situ tests.

B. Anechoic chamber testing

Around 60 seconds of sound from the drone flown manually in a relatively stable hover with each of the three propeller configurations were recorded, and the recordings were saved for analysis in Matlab ®. The power spectrum of the sound was calculated as described in the previous section with the following two changes: the sampling frequency was 65536 Hz, and the absolute level of the Sound Pressure Level is known and reported. Even though the spectra contain information to about 25 kHz, the plots that follow are limited to 2 kHz since the upper part of the spectra are flat or slightly decaying with no interesting peaks or dips.

1) One-bladed propellers: The blue plot in Fig. 10 shows the sound profile of the single-bladed propeller. The fundamental is at 116 Hz, and eight or nine harmonics are clearly visible up to about 1000 Hz. Above 1000 Hz the spectrum is flat and slightly decaying from a level of about 28 dB to about 26 dB at 4000 Hz. At higher frequencies this trend continues (not shown).

2) Two-bladed propellers: The red plot in Fig. 10 shows the sound profile of the two-bladed configuration. A fundamental at 89 Hz is visible and attributed to the rotational speed of the motor. However, the second harmonic at 178 Hz that correspond to the blade-passing-frequency, is much more prominent. At higher frequencies the even harmonics tend to dominate the uneven harmonics until about 1500 Hz, where the spectrum becomes flat and slightly decaying at levels comparable to the one-bladed configuration.

3) Three-bladed propellers: The green plot in Fig. 10 shows the sound profile of the three-bladed configuration. The fundamental at 104 Hz is due to the rotational speed of the motor (the diameter of the three-bladed propeller is smaller than the one- and two-bladed versions; see section IV). The third harmonic (corresponding to the the blade-passing frequency) at 316 Hz is more prominent than the second harmonic, and at higher frequencies integer multiples of the third harmonic clearly dominate. The tonal characteristic of the sound is present up to about 2500 Hz; at higher frequencies the level is relatively constant at 22-24 dB.

4) Ambient noise: The ambient noise of the anechoic chamber when unoccupied is shown in grey in Fig. 10. The background noise is at least 20 dB and typically more than 30 dB below the sound pressure due to the drone. Therefore, effects of background noise are negligible.

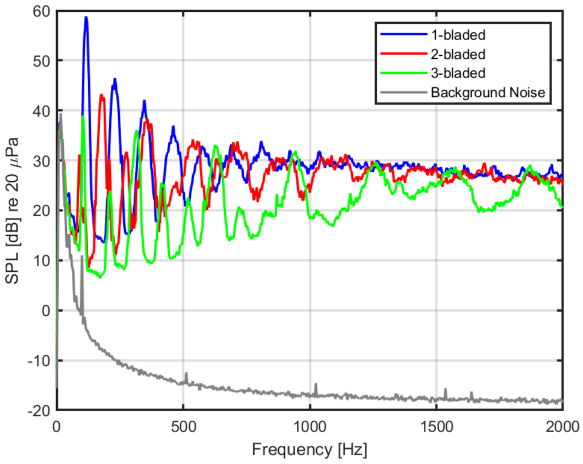

Fig. 10. The sound profile data from the anechoic chamber tests.

C. Summary of testing results

The objective measurement data from the tests in the anechoic chamber are summarized in Table IV. It was found that one, two, and three-bladed propellers produce prominent sound at their blade-passing frequencies of around 116 Hz, 178 Hz, and 316 Hz respectively with average SPL measured at 77.4, 76.6, and 76.4 dB(A) respectively. The equipment used in the anechoic chamber all comply with the requirements of a class 1 Sound Level Meter.

TABLE IV
SUMMARY OF RESULTS; THE SPL LEVELS LISTED HAVE BEEN CORRECTED FOR BACKGROUND NOISE.

No. of blades	**Fundamental frequency**	**Sound pressure level, average**
1	116 Hz	77.4 dB(A)
2	178 Hz	76.6 dB(A)
3	316 Hz	76.4 dB(A)

The sound pressure levels measured in the anechoic chamber are reported at at a distance of 1 meter; in free-field the SPL can be expected to decrease with 6 dB for each doubling of the distance between drone and listener. In practice, the flight path of the drone (i.e. flight elevation) will play a key role in the SPL that reaches people. In addition, the flight path will determine if the drone's noise is persistent - making it similar to fixed-location industrial noise, or transient - making it more similar to traffic noise. However, if drones are operated very far from people, audible explicability will be reduced since the drone's sound will blend in with the ambient noise. In this way, drones may be nearby but people will have no (audible) way of knowing which could facilitate spying or at least a feeling of uneasiness - that drones could be present anywhere at any time.

The objective measurements of the sound frequencies are consistent with the subjective and in-situ experience of the drone noise: there is a clearly audible tonal content in all signals, and the frequencies increase with increasing number of propeller blades. Despite the one-bladed configurations higher SPL at its fundamental, the A-weighted level of the three configurations are almost the same as the A-weighting emphasizes mid-frequencies where human hearing is most sensitive. Therefore, in this case-study, less annoying lower-frequency sound of similar SPL to two and three-bladed propellers can be achieved using single-bladed propellers.

VI. DISCUSSION

This work is exploratory in nature, with the aim to provide early investigations into designing drones for calmness. It has been performed in a Danish context, and relies mostly on empirical evidence gathered in Denmark. It is underpinned by norms and ethical considerations relevant in Denmark.

In-situ testing was included in this exploratory work so that relevant factors to consider during lab-controlled testing could be identified. For example, small wind gusts outdoors require the pilot to adjust pitch, roll, and yaw slightly which resulted in variations in the sound profile during maneuvering. These subtle adjustments were reproduced in the anechoic chamber.

The case studies both utilized single-bladed propellers as a means to reduce annoyance while still preserving explicability. Single-bladed propellers may not necessarily prove to be the optimal configuration for all drones, but early results are promising and this unique propeller design should be investigated further.

A key limitation to this work is the small data-set as limited testing of one small drone took place. Still, it is hoped that the in-situ and anechoic chamber testing in combination with the ethical considerations of drone noise pollution will facilitate future work and additional data collection.

A. Future work

A wide variety of drone types could be studied - including fixed wing, VTOL, and larger drones - which will likely have a more significant contribution to noise pollution. Additional objective measurement of drone sound could be gathered by isolating the drone in an anechoic chamber to separate its sound profile from ambient noise and identify the sources of the sound (i.e. propellers, electronic speed control switching, wind buffering against the drone's arms, etc.) Statistical methods could be utilized to check if there is a significantly different sound profile from various power system and design configurations. In addition, subjective measurements of the annoyance and explicability of drones could be gathered using in-situ experiments or using augmented reality simulations. Various sound profiles, flight patterns, approach speeds, and more could be assessed using augmented reality. These could be used to create psycho-acoustic models of f.x. drone noise annoyance.

It will be necessary to optimize the design of the single-bladed propellers proposed here. This must include determining the impact single-bladed propellers have on the drone's power system. Changes in the motor's rotational speed will have significant consequences on it's efficiency and the resulting flight duration and range of the drone system. This could be achieved using a combination of calculation, simulation, and physical testing.

Currently, there are no standards for measuring the noise level of drones; in the future, it would be useful to develop such standards. There are many relevant variables that will need to be considered in the establishment of these standards, and special attention should be paid to creating realistic scenarios that translate into real-world use-cases. Different standards may be required for different drone types; for example, it would be relevant to test multirotor and VTOL drones while they are hovering, but fixed-wing drones as they circle around a point of interest. Standards would make it easier to directly compare the sound profiles of different types of drones. Furthermore, an open database of the sound profiles of existing drones could be created.

Designing for calmness aims to minimize the negative impacts of drone noise pollution - creating less annoying sounds while still considering explicability. But perhaps drones could be designed to create pleasing, musical, or otherwise beneficial sound profiles. Then, rather than minimizing a harm, they would actively contribute to enhancing human and animal wellbeing.

VII. CONCLUSION

Designing drones for calmness is a complex and multi-faceted task, and much work remains to understand drone noise objectively and subjectively. In this work, several research questions (see Section I) have been addressed, and a number of indicative findings have been reached. Drones produce a unique noise profile compared with commonly addressed noise sources such as road noise and wind turbine noise, yet legal guidelines and testing standards are lacking. Both objective measurements of SPL, frequency, tonality, etc. of drone sound, and subjective/psycho-acoustic measurements of relevant properties such as annoyance are required in order to characterize drone noise. Humans and animals interpret drone noise differently, adding complexity to the design task. From an ethics perspective, designing for calmness as well as explicability is preferable for drones in a civil context. Single-bladed propellers may be a way to achieve both calmness and explicability, but the SPL could be slightly higher than that of multi-bladed propellers which may be in conflict with eventual legal requirements if these focus solely on objective noise level rather than annoyance. The approach to design for calmness and explicability applied to the small multirotor drone in this work and could be applied to other types of drones in the future. Much remains to be done, but hopefully the data and analysis herein contributes to the responsible development of drones and aids in drone noise pollution management in a pro-active way.

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