Unmanned Aerial Vehicle Detection via Acoustic Feature Extraction

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Abstract

The recent proliferation of the inexpensive unmanned aerial vehicle (UAV), or drone, has escalated perimeter security concerns. The ability to detect the presence of a UAV over a protected area is now of interest for law enforcement and other security personnel. Acoustic signal processing is a promising detection modality because rotary UAVs emit significant propeller noise. We measured the acoustic signature of the popular DJI Phantom 3 drone in order to develop a detection methodology. The major features found in the Phantom's audio signature were the harmonics of its fundamental 177 Hz blade passing frequency and a 40 kHz ultrasonic altitude rangefinding signal. Techniques using this information to detect a drone's presence and proximity were designed. A prototype detection system implementing these algorithms in the Python programming language was developed to prove the concept. This system correctly detects the Phantom up to a maximum of 50 feet away with a single microphone, and evidence implies that further refinement could improve this distance to at least 100 feet. This suggests that an acoustic detection system is optimally used for confirmation of a nearby UAV presence when used in tandem with a longer-ranged technique.

Introduction

In recent years, the economical Unmanned Aerial Vehicle (UAV), or drone, has flourished and proliferated due to advances in manufacturing and computational technology. These fully functional, sub-3-foot scale aerial platforms are within the budget of hobbyists and amateurs. As a result, drones present a foreboding problem to perimeter control. For example, earlier this January, a drone crash-landed in the White House lawn, evading security forces. Furthermore, this July, a teenager demonstrated the ability to remotely fire a handgun mounted to a similar drone. Although neither of these events were nefarious in nature, they reinforce the inability of current defensive measures to provide protection against drone-based threats.

This project conducts an initial evaluation of audio analysis techniques in order to determine their utility as the first stage in any system for the detection and denial of UAVs over protected areas. While multiple drone manufacturers exist, particularly DJI, Parrot, and 3D

Robotics, the Shenzhen-based company DJI estimates it owns a full 70 percent of the worldwide commercial UAV market. Thus, a “Phantom 3 Professional” drone, as the newest DJI model, was measured and characterized by its acoustic signature. The Phantom (see Fig. 1), about 2 feet in maximum diameter, is a “quadcopter,” i.e., driven by four fixed-pitch propellers mounted to independently controlled brushless electric motors. Directed flight is accomplished by individually varying propeller rotational speed. A myriad of sensors, including an accelerometer, gyroscope, compass, GPS receiver, and ultrasonic rangefinder, enable the on-board computer to control the UAV with high precision. The ultrasonic rangefinder determines altitude by emitting a pulse and measuring its time of flight, à la sonar. Finally, the Phantom mounts a 3-axis gimbal and high resolution camera. The drone and camera are controlled remotely by a 2.8 GHz transmitter (see Fig. 1). Live footage from the camera is streamed back to the transmitter to assist control and photography.

Figure 1 (Left): The Phantom 3 drone and its remote control.

Figure 2 (Right): Audio recording equipment. From left to right, the data collecting laptop, oscilloscope, microphone power supply, and microphone itself, mounted on a ring stand. The entire setup is completely wireless.

Project Description

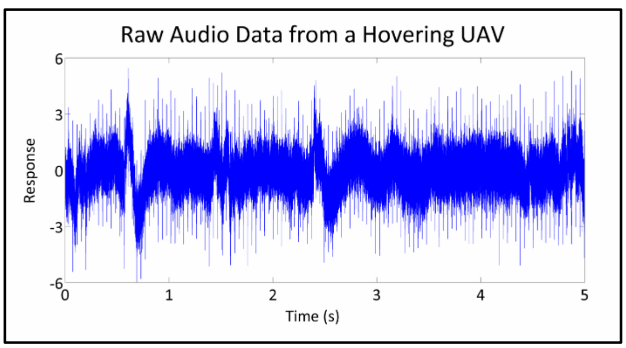
Data Collection

Acoustic measurements of the Phantom UAV were taken in a variety of configurations. In order to detect a potentially wide range of frequencies, a microphone sensitive up to 100 kHz (1/4” GRAS model 40BF) was used. The microphone was driven by a power module (GRAS model 12AA) wired into a digital oscilloscope (PicoScope model 4824). The resulting data was collected and logged on a standard portable computer. The entire setup (see Fig. 2) could be run on battery power alone for field tests. Additional equipment used included a red laser pointer and optical switch (PASCO model ME-9259A) to construct a photogate for accurate measurement of the Phantom's propeller rotational speed.

In the first of three experiments, multiple 10-second audio samples (see Fig. 3) of the Phantom, hovering approximately 6' above the ground and 6' from the microphone, were taken along with background noise. Additional samples, wherein the drone simply sat on the floor, were taken inside of an anechoic chamber to reduce ambient noise. All samples were taken at 200 kHz in order to achieve the desired 100 kHz frequency resolution.

Second, to determine the true blade rotational speed, a laser mounted 10' above the ground formed an unbroken beam to a floor-mounted optical switch such that the Phantom could be flown in between the two. The Phantom was kept in the beam for approximately 20 seconds, during which time the speed of a propeller was continuously monitored.

Finally, in order to determine whether the interval between the ultrasonic pulses is related to altitude, additional 50-second audio samples were collected at various altitudes. For each sample, the Phantom was flown at a single predefined height above the ground from 2.5 through 40 feet.



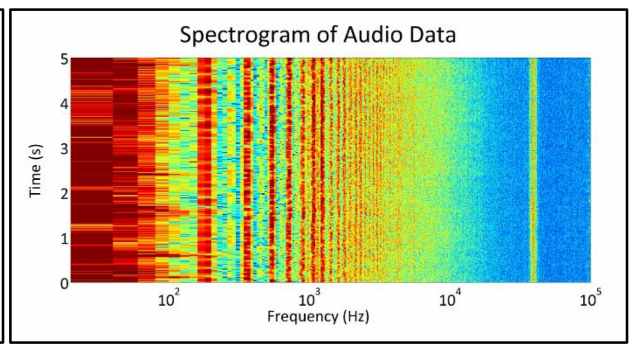
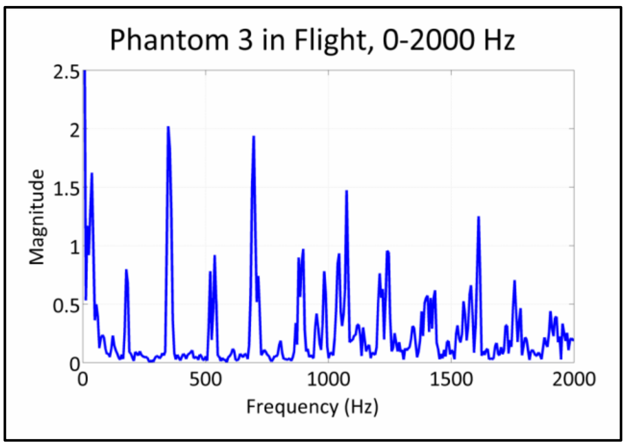


Figure 3 (Left): A sample of raw audio data. Irregularities, such as the wavers at 0.5 and 2 seconds, may be due to external vibrations or wind, but negligibly affect the resulting frequency distribution. The units of the vertical axis are not determined due to undefined characteristics in the microphone's electrical response, but are not necessary for a relative frequency analysis. Indeed, this ensures any techniques derived from the data will be more portable. Figure 4 (Right): A spectrogram of the same audio data where warmer colors indicate a greater signal magnitude. Notice the pronounced band at approximately 177 Hz and the sequence of multiples afterwards, as well as the signal around 40 kHz. The former is the sound generated by the Phantom's propellers, the latter, that of its altitude rangefinder. Noise occupies the region below 100 kHz.

Analysis

The data was imported into MATLAB for in-depth analysis. Spectrograms of data recorded with the Phantom airborne (see Fig. 4) show that its acoustic signature contains two main features: multiples of approximately 177 Hz and a separate 40 kHz spike. Both are constant. Furthermore, samples taken with the drone in the air and idling on the ground demonstrated vastly different sub-kHz signatures (see Figs. 5 and 6), while the 40 kHz signal remained identical. The 177 Hz signal and harmonics were generated by the propellers, while 40 kHz is the frequency of the pulses emitted by the ultrasonic rangefinder. Additionally, the photogate-based measurements determined the average rotational rate of the propellers was 88.4 Hz. The blade passing frequency, defined as rotational speed times blade number, is the expected 176.9 Hz. This confirms the source of the harmonics.



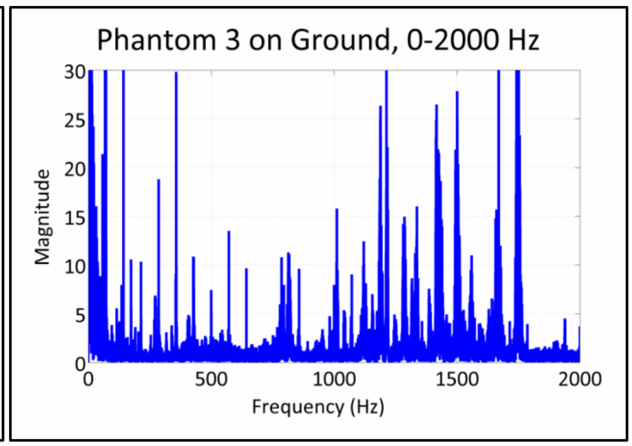


Figure 5 (Left): the Phantom's typical frequency spectrum in between 0 and 2000 Hz when hovering in air. Harmonics are visible at multiples of 177 Hz as also visible in Fig. 4. However, they quickly devolve and lose consistency after approximately 1000 Hz, making analysis of the higher frequencies difficult.

Figure 6 (Right): A typical frequency spectrum of the Phantom when resting on a surface with propellers still spinning. Note the lack of clear harmonics as seen in Fig. 5, possibly due to slower and uncoordinated blade rotational speeds. Because of this difference, further analysis focused solely on the cleaner data produced by the Phantom while airborne.

The results' consistency led to the design of a detection technique. As the harmonics were the audible result of the blades, not only the presence of the basic blade passing frequency (i.e., 177 Hz) but also the presence of harmonics must be present in order to avoid false positives from spurious noise emissions. Furthermore, the absolute magnitude of a signal may vary with microphone, sample length, signal quality, and a host of other factors that contribute to unreliability. We developed an algorithm to take these factors into accounts. First, an audio sample is taken in approximately 200 ms, or 5 Hz. This fast rate allows for rapid, real-time analysis. Second, the FFT is taken of the data with a Hann window applied to increase the final signal-to-noise ratio. Next, the result is truncated to the band below 1000 Hz (see Fig. 7), as anything beyond contains at best a garbled signal (see Fig. 5). The filtered and processed audio signal is autocorrelated, where the autocorrelated signal is the series of dot products of the original and incrementally offset input data vectors from the FFT.

The resulting 1D signal spikes at the interval between the blade harmonics, or not at all if the drone is not present. One may find the peak inside of a certain window in order to determine the exact blade passing frequency at that moment. For example, in Fig. 8, a peak was found inside of the window 177 ± 30 Hz at 177.02 Hz. The height of this peak is significant when compared to its mean value without a UAV present; i.e., the noise floor, as it determines drone proximity to the microphone. This method, with accurate calibration, can determine the presence, proximity, and blade passing frequency of the Phantom 3.

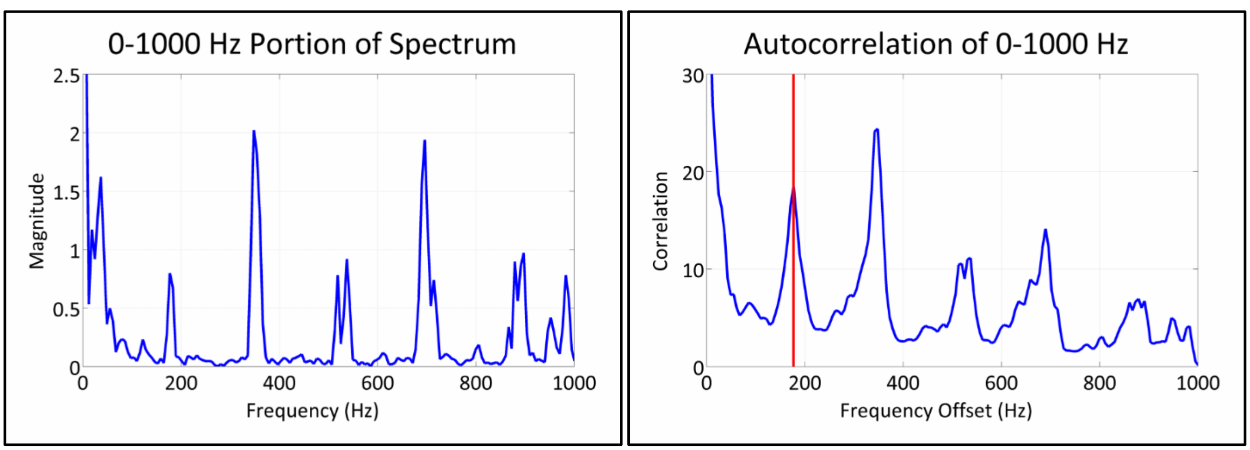
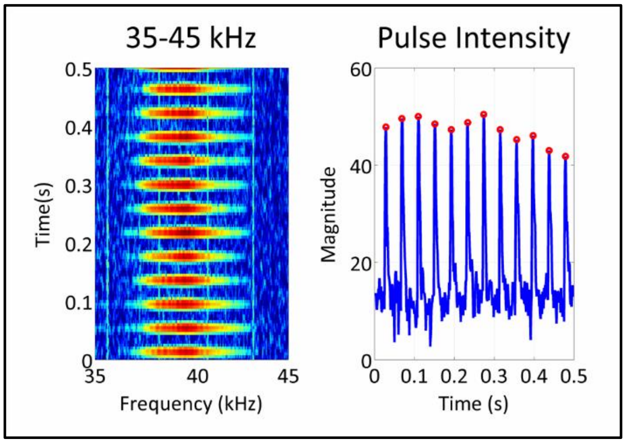


Figure 7 (Left): An example of the truncated 0-1000 Hz portion of the audio frequency spectrum. The clear harmonics lend themselves well to analysis.

Figure 8 (Right): The autocorrelation of the same data with the 177.02 Hz peak denoting blade passing frequency marked with a vertical red line.



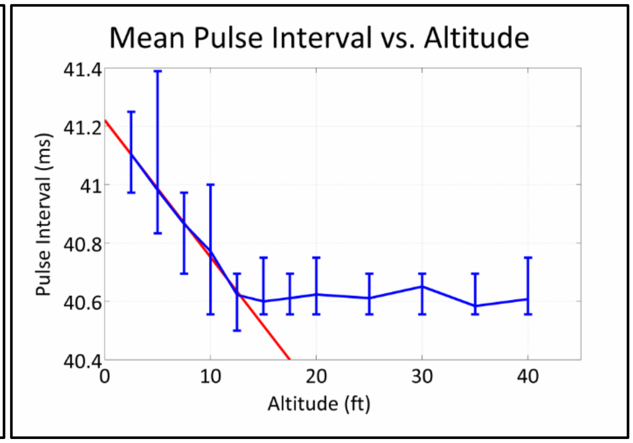


Figure 9 (Left): An example spectrogram showing the pulsed ultrasonic signal and a plot graphing the corresponding 1D sequence extracted from the spectrogram, with peaks automatically identified and marked in order to calculate the average pulse interval.

Figure 10 (Right): The relationship between pulse interval and altitude. Blue represents the minimum, maximum, and mean intervals measured during tests; red is a least-squares fit line. This relationship is only useful when the drone is less than 10 feet above the ground.

More information may be garnered from the ultrasonic signal at 40 kHz. There is a correlation between pulse interval and height for distances below 10 feet, which is consistent with the maximum operating altitude for the ultrasonic sensor given by DJI. In order to automatically measure this value, one may collect data over a period of time, preferably several seconds for higher accuracy, and generate a spectrogram with a 5 ms time resolution (see Fig. 9). The mean is taken of each time segment in between 39 and 40 kHz to generate a 1D signal, and the largest peaks at least 35 ms apart are kept (see Fig. 9). Of these peaks, the distance between the two furthest divided by one less than the number of peaks is the mean pulse interval. The relationship drawn between the pulse interval and altitude, given by a least-squares fit to the collected data (see Fig. 10), states:

$$A = 878.2 - 21.3 * I_P,$$

where A is the altitude given in feet above ground level and I_P is the pulse interval in milliseconds. Additionally, comparing the magnitude of the peaks to the noise floor, as with the result of blade frequency autocorrelation, gives a useful metric of drone proximity.

Finally, in order to observe the audio frequency spectrum in real time and test the algorithms presented here, a graphical application that interfaces with the PicoScope oscilloscope was developed in Python with the wxPython graphical user interface toolkit. Initial tests with this system indicate that its detection of the Phantom 3 functions up to approximately 50’, although the human ear’s detection range, closer to 100’, suggests room for further refinement.

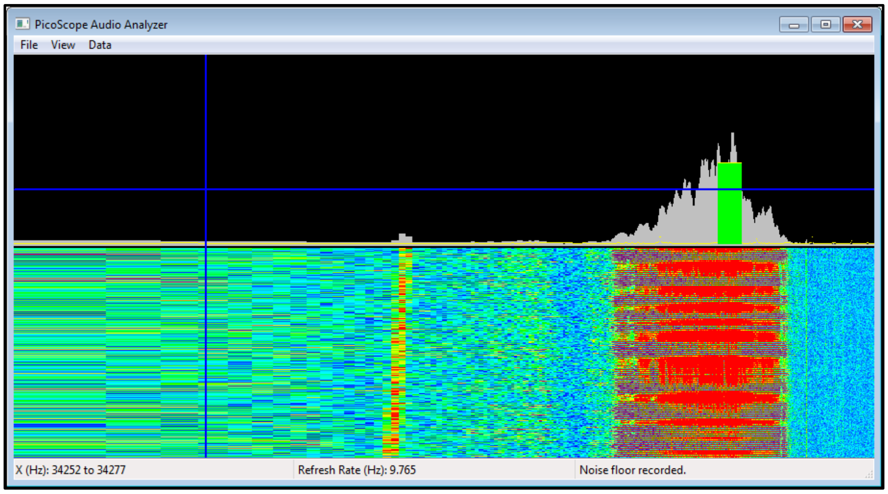


Figure 11: The Python real-time audio analyzer application developed for this project. A spectrogram occupies the bottom sector, while the top sector is zoomed in near the 40 kHz ultrasonic signal. The green bar indicates the difference between the median of the current signal and the noise floor.

Future Work

There is ample room for further research. While the Phantom was flown in its stock configuration for this project, it is of interest to know how it performs while bearing a load. Initial tests indicate that it is extremely difficult to strap a significant weight onto this particular drone, but the blade passing frequency should increase. Therefore, the described method of peak-finding in autocorrelated data may measure the blade passing frequency with enough accuracy to reveal the load. Additionally, if the drone strafes at high speed, there is a differential between the speeds of its sets of propellers, which may be reflected in the drone’s frequency spectrum. Determining the number of propellers (e.g. 4, 6, or 8) on multi-prop UAVs may be possible by further examination of the acoustic emissions. Beamforming techniques may be able to determine the position of the drone in space and provide additional range detection gains. Finally, other detection methods, such as radio frequency monitoring, radar, and video detection remain to be pursued.

Conclusions

The major features present in the acoustic signature of a Phantom 3 quadcopter are the harmonics of its blade passing frequency, nominally 177 Hz when idling in air, as well as its pulsed ultrasonic rangefinder 40 kHz signal. These signals can be extracted via a Fourier transform, autocorrelation, and a peak-finding routine. The relative magnitude of the blade passing frequency and ultrasonic signal to noise floor can determine UAV proximity, while the pulse spacing of the ultrasonic signal can determine altitude beneath then feet. Evidence suggests a maximum detection range on the order of one hundred feet for our given microphone setup. An audio-based detection technique is likely used best in tandem with a separate long-ranged system, but provides information intrinsic to the UAV itself.

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