Project Quiet Quad: a Very Low Noise Multirotor System

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***Abstract* - In this paper we present the design for a very low-noise quadcopter, using off the shelf propellers and electronics. A novel optimization model is designed to converge parametric design and quantized component selection, producing a performance simulation of all possible systems in the problem space, and allowing for trends to be observed. The model is compared against experimental bench testing of propeller-motor combinations, and the method is analyzed. Our initial results highlight inaccuracy in our input dataset, leading to inconclusive evidence for our hypothesis. Direction for future research is also suggested.**

Introduction

Multirotor systems are becoming increasingly popular robotics platforms for a number of reasons: They are mechanically simple [1] and fairly low cost [2], can be enabled to perform autonomous functions for many unique applications [3], and can operate in areas other robotic systems or humans can't reach [4]. However, current multirotor technology falls short when used in areas shared with humans, mainly because of safety concerns [5] and being obtrusively loud [6]. Because of these restraints, multirotor usage today is limited in scope and in areas of application.

We set out to design the quietest possible quadcopter system using readily available components, with a flying weight under the 250g FAA registration minimum. Because we are working with a large but quantised set of available components, traditional continuous-space optimization techniques are not applicable. Our novel approach starts with a database of propellers,

Fig. 1: An Initial Low Noise Quadcopter Design

motors, batteries, and other components, and uses available performance data to simulate flying weight and efficiency, creating a locally optimal system design for each propeller. This system enables us to compare design options on an even playing field, where each possible system design is automatically populated with the correct components to minimize weight normalized to constant thrust to weight ratio.

In comparing the outputs of the design analysis model, we postulate that systems with high predicted propeller efficiency and low total thrust output will result in the lowest noise output. We also account for the human absolute hearing threshold curve, which reduces the perceivable noise of systems with lower propeller RPM.

We test our model with a series of propeller static thrust tests, measuring performance and the resulting sound pressure level. We compare our experimental results against our input dataset and model output. Our experimental data reveals the quietest propeller and system design from the propellers tested.

Because low noise multirotors are optimized for low acoustic footprint over other performance factors, they may not be suitable for applications that require heavy payloads or durable construction.

Sacrifices in thrust-to-weight ratio, frame strength, and propeller guarding are necessary to meet our design objective. Low noise multirotor systems show promise in enabling new applications where cooperation with people is required.

Noise Sources

The sound generated by a multirotor in flight comes from the motors, propellers, and interactions of props with the structure of the craft. Of these sources, propeller noise tends to dominate [7], although the motors and electronic speed controllers must be carefully chosen as to not contribute. A comprehensive overview of the mechanics of propeller noise can be found in *Fig. 2*.

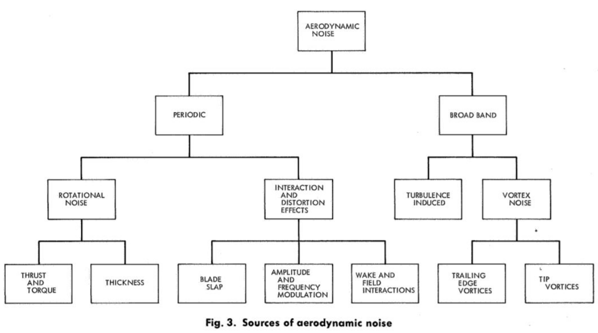


Fig. 2: Propeller Noise Sources

Propeller noise has two main components. Tonal noise is generated by the reciprocation of the blades and has a frequency proportional to the number of blades and the RPM of the propeller. Broadband noise is the result of the chaotic interactions in the wake of the prop. These components sum to create the audible sound signature of the propellers, and the multirotor craft, as shown in *Fig. 3*.

Propeller tip design is very important for noise performance, as tip vortices and turbulence are a large factor in efficiency and noise output. However, as we look solely at existing propeller designs in this paper, tip optimization is outside of our scope of research.

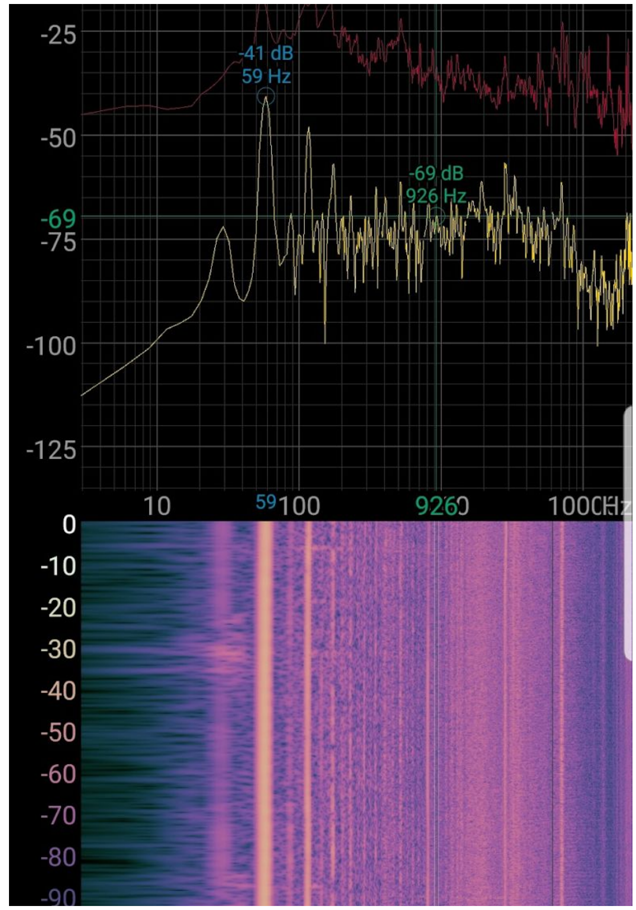


Fig. 3: Propeller Noise Spectrum

Due to the extreme complexity of propeller broadband noise generation, there are no general models for predicting broadband noise levels, as this requires computational fluid dynamics for accurate prediction. Broadband noise is chaotic in nature and immutable in character - it is the product of the turbulence inherent to propeller thrust production. There is no known way to change the character of generated broadband noise, but the magnitude of this factor is proportional to the magnitude of thrust produced. Thus our main method of reducing broadband noise is simply to reduce the amount of thrust required to fly.

Propeller Efficiency

Our most influential technique for reducing noise is increasing propeller efficiency. Noise is a form of wasted power, just like heat, and high noise levels indicate an inefficient prop. By using the inverse relationship, we can predict low noise output from highly efficient props. In our analysis, prop efficiency is defined as thrust output, measured in grams, per mechanical power input, measured in Watts. A rule of thumb of efficiency is that increasing propeller diameter as much as possible, whereby to deliver the same amount of thrust a larger amount of air is moved at a lower velocity. Similarly, every attempt is made to reduce disk loading, which is the average pressure change along the propeller. Other factors include propeller pitch, and number of blades; theoretical formulae for efficiency can be found here [17]. For the purposes of our research, we calculate efficiency based on simulated propeller performance data from the manufacturer.

Human Noise Perception

In designing to reduce the perceived noise of our system, we must take into account the sensitivity of the human ear. Sound is characterized by its frequency and its loudness, with loudness measured as a pressure level on a logarithmic decibel scale and where higher frequency sounds are perceived by the ear as higher-pitched. The human ear is sensitive to noises roughly between 20hz and 20khz, depending on the age of the person [9]; sounds outside of that range are not perceptible. However, the ear is not equally sensitive at every frequency. At each frequency there is a distinct threshold loudness below which the sound will not be heard. This curve is known as the absolute hearing threshold curve, and varies slightly depending on the age of the person measured. An ATH curve for the average person is found in *Fig. 4*.

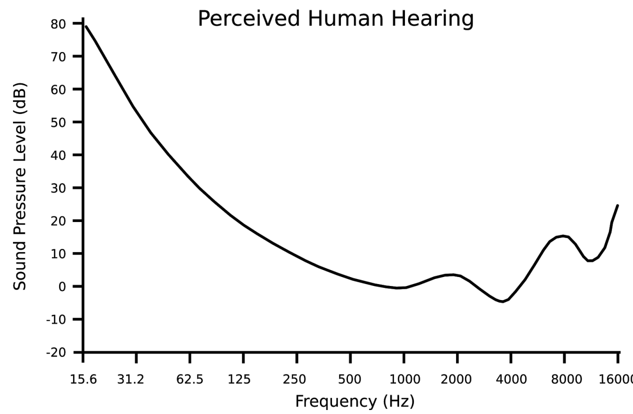


Fig. 4: Absolute Threshold of Hearing (ATH) curve

Analytical Method

By focusing on optimizing our performance with off the shelf components, we are able to greatly reduce the cost of our system and aid in reproducibility and future research. However there are difficulties that come with this approach, especially because we wanted to consider a vast variety of components, more than we would be able to independently test and characterize.

We noted that there are parts of the quadcopter design that are parametric - for example, the frame changes in size but keeps similar geometry when designed for propellers of various sizes - and parts that must be chosen from a discrete list, such as the motors and batteries. Our method synthesizes parametric and discrete design variables into a single system design model.

Data Sources

We started by creating a database of available components for our design, noting weight and performance specifications for each component. Propeller manufacturer APC [10] provides a set of performance data on their website. This simulated dataset is generated based on vortex theory and using actual propeller geometry. The NASA Transonic Airfoil Analysis Program is used to generate estimates for section lift and drag. For each propeller, APC provides diameter, pitch, number of blades, as well as thrust, power, and torque through the operating RPM range of the propeller, as shown in *Fig. 5*.

10x10.dat

RPM	THRUST (LBF)	POWER (HP)	TORQUE (IN-LBF)
1000	0.04	0.00	0.04
2000	0.16	0.00	0.16
3000	0.35	0.02	0.35
4000	0.62	0.04	0.62
5000	0.97	0.07	0.94
6000	1.39	0.12	1.26
7000	1.88	0.18	1.60
8000	2.49	0.34	2.70
9000	3.27	0.76	5.33
10000	4.16	1.40	8.80
11000	5.18	2.31	13.21
12000	6.33	3.56	18.72
13000	7.62	5.26	25.49
13999	9.06	7.50	33.76
15000	10.67	10.43	43.82
16000	11.87	11.52	45.40
17000	13.09	12.52	46.40
18000	14.47	14.49	50.75

Fig. 5: APC Propeller data for 10x10 prop

APC sells propellers whose diameter range from 4-27 in., whose pitch varies from 2-22.5 in, and whose blade number from 2-4. In total, the manufacturer reports data on 508 unique propellers, which were all considered in our model.

For motors, the key specs are maximum power rating and Kv constant, which tells the RPM per volt applied to the motor. For batteries, we recorded voltage, capacity, and discharge rating through a large range of various options. For motors, we started with a broad list of brushless DC outrunner motors. Because we only know the Kv and maximum power of each motor, we generate a theoretical power output curve based on *Fig. 6*. In the future, this could be replaced by experimental dyno data.

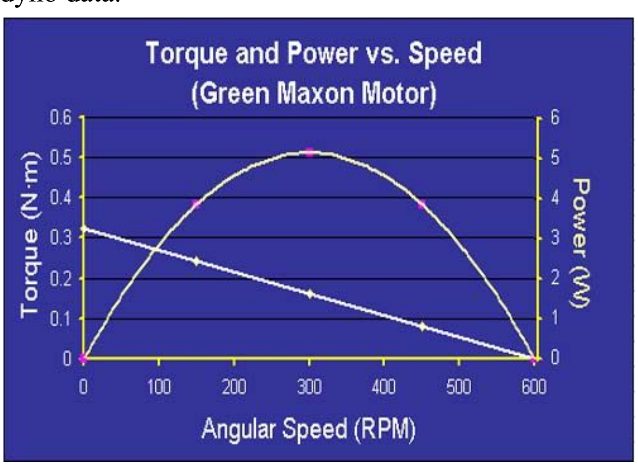


Fig. 6: DC Motor Power Model

Generative Model Design

With our initial data sourced, we tried many methods for comparing and selecting components, and eventually settled on a generative model that simulates all possible component permutations and selects the best system according to our design goals. The model outputs a complete quadcopter design and expected performance metrics for each propeller, greatly reducing the amount of analysis required for component selection. The only input is a requested thrust to weight ratio.

For a single propeller, the model parametrically generates a frame design out of pultruded carbon fiber tube, using the propeller diameter as input. Then, an initial estimate for the motors and battery is made based on frame size in order to calculate the full quadcopter weight. The full system weight determines the thrust per motor required to hover. By designing a system around hover operating points, we can optimize overall performance. Then the model interpolates the APC performance data to get the RPM and power needed to generate the hover thrust with each propeller. The motor selection algorithm finds the lightest motor that can deliver the power necessary for hover thrust at hover rpm. The battery selection algorithm finds the lightest battery that can provide the current needed for motor's power consumption at hover. Finally, the motor and battery selections are iterated to meet the system hover requirements. As a result, the model generates an optimized quadcopter design and reports the system weight, propeller RPM, thrust, and efficiency at hover for each propeller. These metrics can be compared to select the best design for the quietest quadcopter.

Model Outputs

Using our model, we can see how variables such as diameter, rpm, and pitch affect the propeller's mechanical efficiency. This is normalized to a system designed with the same constraints - a constant thrust to weight ratio and optimally chosen electronics and powertrain.

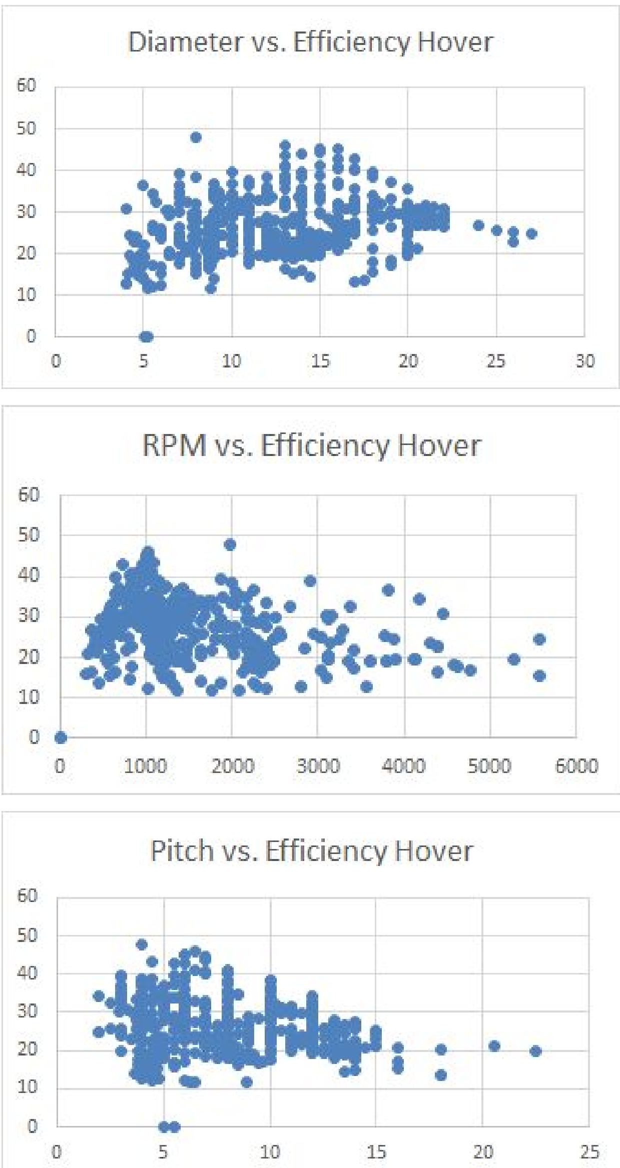


Fig. 7: Model Performance Trends

The graphs shown in *Fig. 7* seem to indicate that there is an optimal diameter for maximum efficiency with our dataset of props. The optimal diameter is between 13-17in. Additionally propellers that can achieve hover thrust around 1000RPM seem to have the highest efficiencies. Finally, high efficiencies can be achieved with low propeller pitches. We fed the system design outputs into our effective noise model to select the most promising propellers for experimental testing.

Effective Noise Model

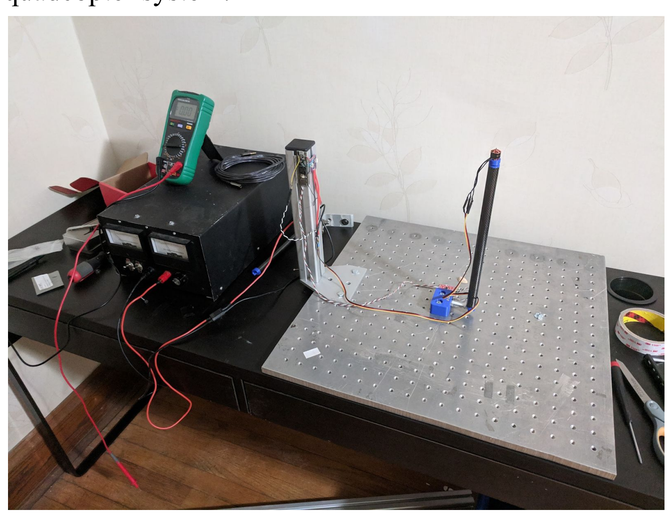
In order to compare the relative performance of each of the promising system designs, we postulate that the noise output is proportional to the following function:

N = ATH[RPM, F(Thrust, Efficiency)]

The output N is the effective noise prediction, which is dependent on the RPM, thrust, and efficiency of any given propeller. ATH[] is an equal loudness function for human perception that converts unweighted noise to A-weighted noise.

Static Bench Testing

In order to validate and tune our analytical model, we built a test bench to experimentally measure propeller performance. The goal of our testing was to confirm the accuracy of our propeller performance dataset, test our effective noise model and find coefficients, and validate our model's system design output. We also tested individual prop and motor combinations to confirm each motor's ability to generate enough thrust to lift the entire quadcopter system.



Test setup

Our test setup shown in *Fig. 8* consisted of a motor stand mounted on a load cell to measure thrust output, an electrical power sensor, and a calibrated microphone.

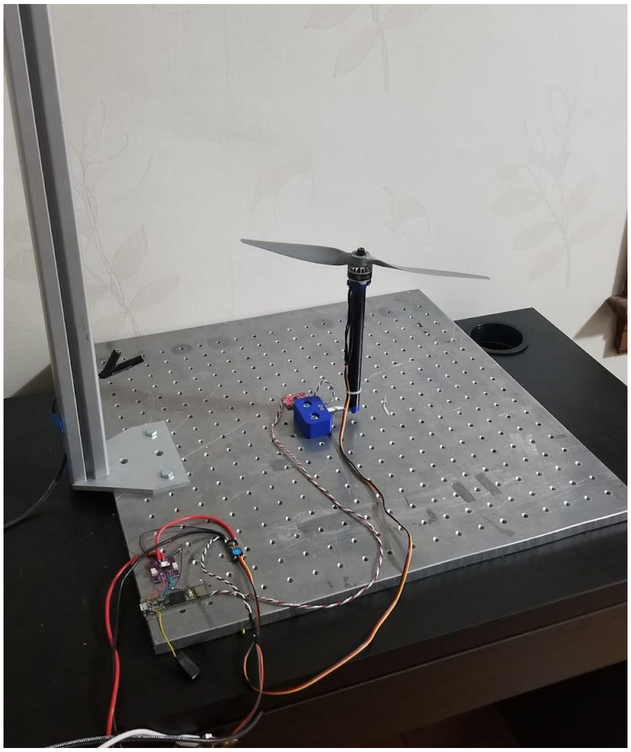


Fig. 8: Propeller Testing Stand

All propellers tested were oriented upwards in order to have an unobstructed airflow in the high velocity region. We positioned our microphone beneath the propeller in order to capture the noise emitted by the propeller just outside of its turbulent stream. We deemed this positioning appropriate considering humans are rarely hearing a quadcopter from directly beneath its rotors but rather from a distance. We designed various motor mount adapters and propeller adapters to be able to test a range of propeller and motor sizes.

Bench Test Results

We tested 16 propellers varying in diameter from 7-16”. For all of these tests, we used one of our larger motors, a Brother Hobby 2206 2300Kv, in order to ensure we could deliver enough power to each propeller. For each propeller, the RPM was increased until the thrust being produced was equal to the thrust required to hover the system design output generated for that propeller. The noise decibel level and frequency were recorded at this RPM. Although we did not have a dedicated RPM sensor, we were able to calculate the RPM from the peak tonal frequency, which is directly proportional to RPM. The conversion is: $RPM = \frac{freq}{N} * 60$, where N is the number of blades of the propeller. By converting recorded frequencies to RPMs, we were able to compare the actual RPM required to generate the desired thrust with the predicted RPM according to our model. *Fig. 9* shows the actual thrusts generated at hover RPM versus the predicted thrust output at that RPM.

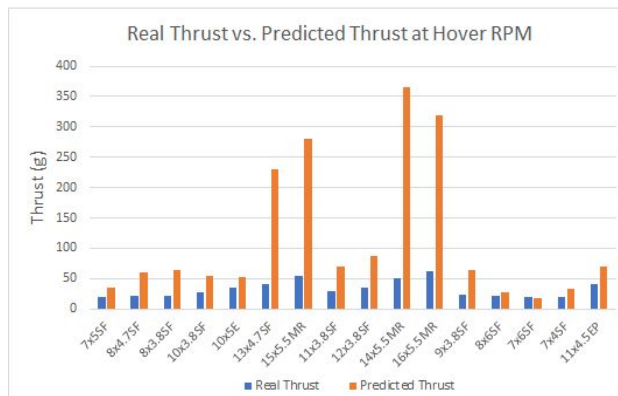


Fig. 9: Real vs Predicted Thrust at System Hover

In almost every case, the experimental data showed that higher RPM values than predicted by the dataset were required to reach the thrust needed for hover. This draws into question the accuracy of the APC performance data at our operating points. This error in RPM and thrust mapping leads to error in propeller efficiency calculation, which depends on the thrust produced and the mechanical power required.

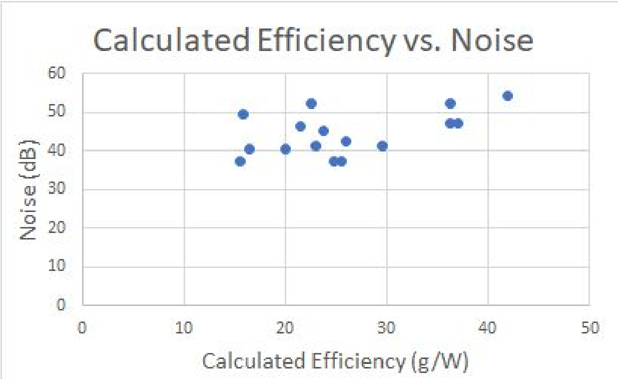


Fig. 10: Model Efficiency vs Measured Noise

Fig. 10 shows propellers with lower calculated efficiencies produced lower noise, which is contradictory to our assumption that higher efficiency leads to lower noise. This discrepancy is likely caused by the inaccuracies in the dataset we used to feed our model. One supporting correlation we did find, however, is between the hover thrust and noise produced.

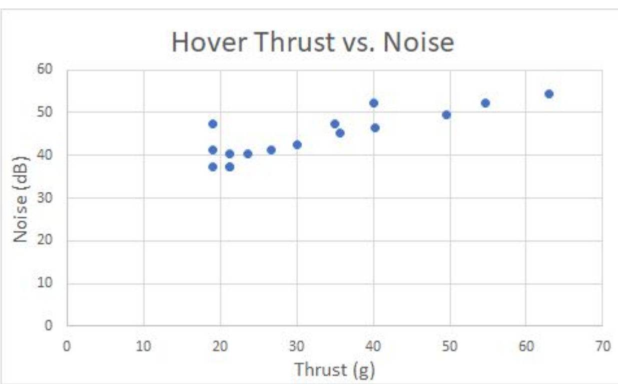


Fig. 11: Hover Thrust vs Measured Noise

As shown in *Fig. 11*, the lower the thrust required to hover, the quieter the propeller.

Conclusion

Unfortunately, we are left to conclude that our model did not accurately predict propeller noise. This negative result finds its roots in the fact that our experimental data for propeller thrust versus RPM does not match the manufacturer performance data that we used as an input to our model. This discrepancy shows that the input data is likely inaccurate in the extremes of low RPM and thrust output - the exact range where a quiet quadcopter needs to operate.

However, the authors believe the techniques described in this paper still show promise for the kind of system design and modeling that was attempted, if reevaluated with more trustworthy data. We believe that continued research using improved CFD simulations or real experimental data can return a positive result and groundbreaking noise performance.

There were many lessons learned that will need to be incorporated into future research.

Future Work

The first step in continued research will be to create a new experimental propeller performance dataset, to remove our reliance on inaccurate manufacturer simulation data. We will record the thrust, noise spectrum, RPM, and mechanical input power of each propeller as a new source of truth to feed into our model.

Ideally these tests would be performed in an anechoic chamber, eliminating any background noise and allowing us to examine the broad spectrum noise created by each propeller. We can then integrate along the A-weighted spectrum for a more accurate reading of perceived noise performance.

We would like to build a motor dynamometer to more accurately characterize the torque and power of each motor, allowing us to more accurately select an optimized powertrain for each simulated system design. More work needs to be done on electrical motor noise and drive methods, for example comparing trapezoidal and sinusoidal BLDC motor controllers.

Further static testing is required to find coefficients for our effective noise model, which is the final link that synthesises operating RPM, thrust, and mechanical efficiency into noise performance.

Finally, we would like to test our optimized system design in flight, and compare noise performance to that of currently available quadcopter systems.

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