

# Autonomous Trajectory Planning to Copy Birdlike Aerial Maneuvers

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**Abstract**—Add the abstract last after all other sections have been completed. The abstract should be a summary of the entire proposal, including elements from each section -- not just the problem statement. It should be self-contained, which means it should not include undefined acronyms or cross references. Keep it under 250 words. You can check by highlighting it and selecting Review/Word Count.

## I. BACKGROUND AND MOTIVATION

Insert your motivation section here. It should be 1-2 pages in length, and include 1-2 figures and 5 references. In this section it may be appropriate to cite popular press articles (be sure to use IEEE format – see class notes). Your goals are to:

- educate the reader on your broad topic area;
- define any unfamiliar terms, concepts or acronyms;
- describe how your specific topic fits in a larger engineering context;
- discusses economic, societal, or policy impacts; and
- present current or future applications of your topic area.

## II. PROBLEM STATEMENT

The aim of my research is to replicate the display dives of Anna's hummingbirds with an autonomous quadrotor platform. My project assumes the following are provided: a quadrotor platform, a flight controller, and a method of obtaining 3 dimensional position data of the quadrotor in test flights. I also assume that all position vs. time data related to the Anna's hummingbird dive trajectories are given, and that each trajectory can be approximated as a 4<sup>th</sup> degree polynomial function in a fixed 3 dimensional right handed coordinate frame. Given a desired hummingbird flight trajectory, depicted in Figure 1 (left), my quadrotor will autonomously generate and execute the control inputs required to successfully complete the maneuver.

A successful maneuver is defined as a normalized root mean square error (NRMSE) calculation of less than 5% between the time-scaled hummingbird trajectory and the quadrotor trajectory, where each trajectory is defined as a matrix array of positions in the x, y, z right handed coordinate frame with a given sample period,  $\Delta t$ . The hummingbird trajectory will be scaled by a constant factor in time to allow for the physical limitations of the quadrotor—e.g. the quadrotor may only have to travel the desired trajectory at half the speed of the hummingbird to still achieve a successful maneuver. This is a necessary adaptation due to the impressive speed and acceleration capabilities of the Anna's hummingbirds relative to their size.[1] The ideal result is to fly the hummingbird trajectory at the same speed as the hummingbird, but this may prove to be impossible due to the physical constraints of the quadrotor.



Figure 1: The five stages of an Anna's hummingbird dive maneuver (left), and a quadrotor using path planning to fly through a thrown hoop (right).[1][2]

## III. LITERATURE REVIEW

The inspiration of this project proposal has its roots in the high maneuverability seen by hummingbirds. As such, it was essential to be able to gather data on hummingbird trajectories in order to study their feasibility of being replicated by a quadrotor. There have been many bio researchers that have delved into the study of hummingbirds, however I will mainly discuss the works [1] and [3]. The work in [3] determined the trajectory and body kinematics of four different hummingbird species in an evasive maneuver.

This was done by startling the birds while they were hovering, and observing their movements with 3 high definition cameras to provide a 3D position. Water-soluble white paint was used to make dot markings on the hummingbird's body to help model the wing and head positions for each trial. The data they acquired in their experiments includes many more details than I will need to use, however they provide data on the hummingbird's velocity and trajectories for several trials which I can use to help develop my quadrotor trajectories. I will even use a similar tracking method as [3], they and I will both be using optical data to obtain a position fix. With regard to the type of maneuver that these birds are required to perform, it aligns well with the type of experimentation that I aim to work with. Evasive maneuvers are certainly a type of extreme maneuver, and these patterns may prove to be something that I wish to try on my quadrotor. Evasive maneuvers can be useful for quadrotors if they are in threat of being netted, and if I am able to copy the hummingbird's trajectory, further analysis and testing may prove that this type of trajectory provides a maneuvering or sensing advantage to the quadrotor in evasive flight.

The work in [1] has also obtained very accurate data on hummingbird flight trajectories. This work specifically pertains to the study of the Anna's hummingbird's courtship dives in order to study extreme locomotor performance in animals. This was done using several cameras of varying resolution and frame rate to record the male hummingbird's dives. The video results were digitized using Peak Motus 8, and analyzed using mathematical relationships to determine the accelerations, velocities, flight paths, wing/tail movements of, and sounds produced by the hummingbirds in their dives. Again, this is more detailed data than I will need for trajectory replication on my quadrotor. This paper gives an insight into what exactly I will be trying to achieve through the extreme maneuverability of my quadrotor. Since this type of maneuver is estimated to cause a lot of strain on the hummingbird, it is likely to also cause a lot of strain on a quadrotor. Through simulation and proof of concept demonstration, I will be able to provide a more accurate picture of just how difficult these maneuvers can actually be.

After obtaining these hummingbird trajectories, an effective method of modeling a quadrotor and conducting trajectory planning is required. In [4], the aim of the paper is to develop a general standard to measure against in terms of quadrotor maneuvering performance and constraints. This is achieved through the solving of an optimal control problem offline, and then using a machine learning technique to learn these trajectory solutions with the given constraints. This will then translate into an online general solution for near-optimal trajectories for a quadrotor. This was done in the x-z plane for point to point and perching maneuvers, as well as joint trajectories. To validate their solution, they flew these optimal trajectories using both simulink simulations, and proof of concept demonstrations. Since I will be using a quadrotor platform, this paper directly applies to my problem statement as a good reference base that I can use to springboard my exploration into more complex extreme maneuvering. The basis of this work will give me a much more quantitative measure of success in terms of how close my developed trajectories are to an optimal path. [4] is very thorough and provides a clear distinction and improvement on previous work in quadcopter trajectories, especially with regard to the joint trajectory problem. I can build on this by expanding into 3D trajectories instead of just working in a 2D plane, and I can also try to utilize their proxy-based joining method to create a desired path curvature.

In [5], they are primarily concerned with obtaining a linear model of a quadrotor in planar motion using Newton's and Euler's laws. The careful process by which the quadrotor dynamics are identified and modeled will be helpful in my own research as I develop my own model for the quadrotor that I will be using. In [5], their modeling method is done for 3 different linearization methods and each of these is compared to each other by running a Simulink simulation with each controller. Quantities compared include several attributes of the step response, and the actual trajectory of the quadrotor compared to the desired trajectory. This comparison method between the different trajectories is similar to the validation work that I will need to do on my own simulation. As such, this work will help me to better understand ways of determining the accuracy of my trajectory testing in simulation, and in proof of concept demonstration. This paper, while a good starting point for my work, does not attempt to go into more complex maneuvers. These are discussed in greater detail in the following works.

In [6], the development of trajectories and path planning for UAVs was accomplished. They did this by determining the maximum overload, minimum turn radius, and maximum flight endurance of the experimental quadrotors in order to come up with feasible aggressive trajectories. Trajectories had the constraint that they had to follow a sixth order (or lower) polynomial trajectory. Much like my proposed concept, this work develops an attitude and trajectory controller with appropriate initial and final conditions, as well as a boundary "tube" which the quadrotor must stay within for every trajectory. The work in this project is heavily relevant to my proposed work, as they achieve a working simulation of aggressive trajectories with their path-planning algorithm and onboard controllers. I would like to expand on this work by flying a shorter trial with hummingbird-like flight patterns.

Finally, [2] offers some of the closest work to exactly what I am proposing for my own work. The main focus of this paper is to create trajectories for quadrotors in real time in an indoor or constrained environment. They also pay particular attention to the velocity and acceleration vectors of the quadrotor throughout its maneuver. I will also need to be able to achieve these types of measurements from my system, and be able to change my controller to affect them in an appropriate manner in order to fully achieve a trajectory flight path that replicates a hummingbird maneuver. [2] also uses temporal scaling to fly their trajectories at different speeds, which is exactly what I will need to do when and if I find that flying the hummingbird trajectory at full speed is either not possible or extremely dangerous.

#### IV. DEMONSTRATION PLAN

This section is the most substantial and part of your proposal. Typically it is 3 pages or longer (including figure) and includes many details.

Begin with an overview paragraph briefly stating what types of demonstrations will be used: proofs, simulations, or experiments. You must justify this choice in terms of Generality, Replicability, Realism and Control. See class notes for more details.

Only include the relevant subsections below from A,B and/or C. All proposals include subsections D-H.

#### A. *Mathematical analysis*

If your project involves modeling or proving theorems you should outline your argument, review similar proofs or describe analysis techniques. If you plan to use a new control design technique, explain the method with equations and examples.

When discussing math, be sure to define the variables. Equations should be part of a sentence and punctuated as such. They should be numbered for cross referencing as in,

$$y = mx + b. \quad (1)$$

#### B. *Simulation or computational studies*

If your project involves simulations or computational studies describe them here. List the inputs, outputs and parameters of the model or functions. Decompose complex simulations into sub-systems or sub-routines. Include either a simulation diagram, flowchart or pseudo code. For simulation diagrams each signal and block should be labeled. For each block dedicate about a paragraph for explanation. Use the `pseudo-code` style inside a text box for algorithms.

Describe the software package, or programming language used as well as any non-standard computing hardware. If you will use any databases or publically available data-sets describe them here.

If you are planning multiple simulations, for example using different data-sets, parameter values, initial conditions, etc. list them here. Tabular format or an itemized list might be appropriate.

#### C. *Experimental work*

If your project involves either proof-of-concept experiments or statistically repeatable trials describe your plan here. Include at a minimum a functional block diagram with each signal and block labeled. Conceptual, mechanical or circuit drawings should be included. Include photos of key components and justify component selection with basic engineering calculations. Are the sensors you have selected accurate enough to demonstrate the property in question? Address electrical power needs. What voltage do the various components require?

If your plan to do statistically repeatable testing, include the number of trials, subjects, and conditions here as well. You should explain what the controlled variables are and how you plan to statistically analyze the results. If your work involved human subjects you should include a justification for this as well as any documents required by the HRPP office.  $y = mx + b. \quad (1)$

#### D. *Property Measurement*

Regardless of the approach used, a research project demonstrates the properties of a process -- how will these properties be measured and quantified? This includes physical measurements (sensors, calibration, "ground truth") as well as subjective properties like "easy to use" or "robust". If you plan to turn a quantitative measurement into a yes/no answer, provide a threshold value or rating scale along with justification. This justification should be based on some external standard or related work whenever possible.

#### E. *Technical risks and mitigation*

Is there any part of your project that may just not work at all? For experimental studies, is there any possibility of losing or destroying some critical piece of equipment? Are there safety concerns?

#### F. *Time risks and mitigation*

Every project has time risks. Cross reference and discuss your Gantt chart here (it will be included in the Appendix). The best practices for mitigating time risk is to start with as many off the shelf components as possible; use existing code and data-sets; schedule as many tasks in parallel; order parts and shop work as soon as possible. Is your project weather dependent or does it require access to any special facilities?

#### G. *Justification of special high risk activities*

These are: (1) buying parts > \$3500; (2) testing on human or animal subjects; (3) learning a new programming language; (4) working in a subject area new to the student *and adviser*; (5) designing and building a system from scratch; or (6) interfacing with new or undocumented hardware or software.

#### H. *Budget*

Insert your budget as in TABLE 1. Be sure to discuss any new equipment expenditures.

TABLE I  
BUDGET

LABOR	Category	Hours	hourly rate	Cost
	Midshipman	336	\$25	\$8,400
	Faculty	64	\$60	\$3,840
	Staff	45	\$40	\$1,800
Sub-total				\$14,040
OVERHEAD	Category	Base Amount	Rate	Cost
	Fringe Benefits	\$14,040	35%	\$4,914
	Facilities	\$14,040	50%	\$7,020
	General Service	\$14,040	15%	\$2,106
Sub-total				\$14,040
MATERIALS	Category	Items	Cost Estimate	
	In-stock Items	Item 1		\$150
		Item 2		\$500
	To be purchased			
		Item 1		\$200.00
		Item 2		\$100.00
Sub-total				\$950.00
TOTAL COST				\$29,030
OUT-OF-POCKET COST				\$950

## V. CONCLUSION

A brief conclusion will summarize the process, properties and proposed demonstration, explaining why the project is novel and important. You should also re-state the biggest risk and the steps you will be taking to mitigate it.

Do not introduce any new ideas in this section. Do not include exaggerated claims of the importance of your work.

## REFERENCES

- [1] C. Clark, "Courtship dives of Anna's hummingbird offer insights into flight performance limits", *Proceedings of the Royal Society B: Biological Sciences*, vol. 276, no. 1670, pp. 3047-3052, 2009 [Online]. Available: <https://royalsocietypublishing.org/doi/pdf/10.1098/rspb.2009.0508>. [Accessed: 19- Feb- 2019]
- [2] D. Mellinger and V. Kumar, "Minimum snap trajectory generation and control for quadrotors," 2011 IEEE International Conference on Robotics and Automation, Shanghai, 2011, pp. 2520-2525 [Online]. Available: <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5980409&isnumber=5979525>. [Accessed: 19- Feb- 2019]
- [3] B. Cheng, B. Tobalske, D. Powers, T. Hedrick, S. Wethington, G. Chiu and X. Deng, "Flight mechanics and control of escape manoeuvres in hummingbirds. I. Flight kinematics", *The Journal of Experimental Biology*, vol. 219, no. 22, pp. 3518-3531, 2016 [Online]. Available: <http://jeb.biologists.org/content/219/22/3518>. [Accessed: 08- Feb- 2019]
- [4] T. Tomić, M. Maier, and S. Haddadin, "Learning quadrotor maneuvers from optimal control and generalizing in real-time," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, no. Section III, pp. 1747–1754.
- [5] F. Sabatino, "Quadrotor control: modeling, nonlinear control design, and simulation," KTH Royal Institute of Technology in Stockholm, 2015.
- [6] S. Liu, M. Watterson, K. Mohta, K. Sun, S. Bhattacharya, C. J. Taylor, and V. Kumar, "Planning Dynamically Feasible Trajectories for Quadrotors Using Safe Flight Corridors in 3-D Complex Environments," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1688–1695, 2017.

## APPENDIX: GANTT CHART

Insert the Gantt chart here. Be sure the font is legible. Crop it tight, use landscape orientation and make it as large as possible.

