Extreme Aerial Maneuverability in Nature and Robotics
Advisor: Professor Dennis Evangelista

1.

Paper Identifier: Tomic, Maier, Haddadin "Learning Quadrotor Maneuvers From Optimal Control and Generalizing in Real-Time"

Abstract— In this paper, we present a method for learning and online generalization of maneuvers for quadrotor-type vehicles. The maneuvers are formulated as optimal control problems, which are solved using a general purpose optimal control solver. The solutions are then encoded and generalized with Dynamic Movement Primitives (DMPs). This allows for real-time generalization to new goals and in-flight modifications. An effective method for joining the generalized trajectories is implemented. We present the necessary theoretical background and error analysis of the generalization. The effectiveness of the proposed method is showcased using planar point-to-point and perching maneuvers in simulation and experiment.

URL: https://core.ac.uk/download/pdf/31011877.pdf

Process: 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.

Properties: The main objective is to obtain a generalization of 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.

Demonstration: They were able to create and validate their optimal trajectories using both simulink simulations, and lab demonstrations.

Relevance : 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.

Strengths: The paper 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 working in a 2D plane, and I can also try to utilize their proxy-based joining method to create a desired path curvature.

Weaknesses: The paper doesn't do a very good job of defining terms. Other than that it seems to be written pretty well. I may want to include a third dimension in my problem statement depending on how much of the hummingbird flight display patterns I would like to emulate.

2.

Paper Identifier: Sabatino (2015)

Abstract-In this work, a mathematical model of a quadrotor's dynamics is derived, using Newton's and Euler's laws. A linearized version of the model is obtained, and therefore a linear controller, the Linear Quadratic Regulator, is derived. After that, two feedback linearization control schemes are designed. The first one is the dynamic inversion with zero dynamics stabilization, based on Static Feedback Linearization obtaining a partial

linearization of the mathematical model. The second one is the exact linearization and non-interacting control via dynamic feedback, based on Dynamic Feedback Linearization obtaining a total linearization of the mathematical model. Moreover, these nonlinear control strategies are compared with the Linear Quadratic Regulator in terms of performances. Finally, the behavior of the quadrotor under the proposed control strategies is observed in virtual reality by using the Simulink 3D Animation toolbox.

URL:
https://www.kth.se/polopoly_fs/1.588039.1441112632!/Thesis%20KTH%20-%20Francesco%20Sabatino.pdf

Process: This paper is concerned with obtaining a linear model of a quadrotor in planar motion using Newton's and Euler's laws. This is done for 3 different linearization methods and each method 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.

Properties: He is demonstrating the step responses for position and yaw in comparison to each other. Specifically, he compares rise time, percent overshoot, and settling time.

Demonstration: A Simulink simulation is used to compare the models using a 3D animation.

Relevance : 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 for my project.

Strengths: This paper was highly detailed, and discussed a lot of properties that I am used to dealing with. In this respect, the experiment that was conducted should be highly repeatable, and as a result will be a good aid to my research.

Weaknesses: Although the idea of nonlinear control was expressed as being a better solution several times, there was no such implementation in this design. One way I could add to this work would be by implementing a nonlinear controller for my quadrotor.

3.

Paper Identifier: Clark (2009)
Abstract-Behavioural displays are a common feature of animal courtship. Just as female preferences can generate exaggerated male ornaments, female preferences for dynamic behaviours may cause males to perform courtship displays near intrinsic performance limits. I provide an example of an extreme display, the courtship dive of Anna's hummingbird (Calypte anna). Diving male Anna's hummingbirds were filmed with a combination of high-speed and conventional video cameras. After powering the initial stage of the dive by flapping, males folded their wings by their sides, at which point they reached an average maximum velocity of 385 body lengths s21 (27.3 m s21). This is the highest known length-specific velocity attained by any vertebrate. This velocity suggests their body drag coefficient is less than 0.3. They then spread their wings to pull up, and experienced centripetal accelerations nearly nine times greater than gravitational acceleration. This acceleration is the highest reported for any vertebrate undergoing a voluntary aerial manoeuvre, except jet fighter pilots. Stereotyped courtship behaviours offer several advantages for the study of extreme locomotor performance, and can be assessed in a natural context

Process: This paper aims to study the Anna's hummingbird and their 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.

Properties: Clark aimed to extract from these videos information about the accelerations, velocities, flight paths, wing/tail movements of, and sounds produced by the hummingbirds in their dives.

Demonstration: The video results were digitized using Peak Motus 8, and analyzed using mathematical relationships to determine the above properties.

Relevance : This paper gives an insight into what exactly I will be trying to achieve through the extreme maneuverability of my quadrotor. It places some definite milestones that I will have to reach in order to attempt to replicate this behavior on a quadrotor.

Strengths: This is a strong and thorough paper, with most details laid out in a very intuitive fashion. Since obtaining vertebrates for study at the Naval Academy is nearly impossible, there is little that I can do with regards to obtaining more data on the subject. The basis of my research will be to dake these findings and try to replicate the behavior on an autonomous quadrotor.

Weaknesses: One area that could be improved is exactly how the video data was processed. It didn't seem to be discussed very much throughout the paper. In reading this, it has given me a particular high-g maneuver that I should be trying to replicate on my quadrotor, including attributes such as maximum acceleration, and dive trajectory.

4.

Paper Identifier: Kress (2015)

Abstract-Diurnal flying animals such as birds depend primarily on vision to coordinate their flight path during goal-directed flight tasks. To extract the spatial structure of the surrounding environment, birds are thought to use retinal image motion (optical flow) that is primarily induced by motion of their head. It is unclear what gaze behaviors birds perform to support visuomotor control during rapid maneuvering flight in which they continuously switch between flight modes. To analyze this, we measured the gaze behavior of rapidly turning lovebirds in a goal-directed task: take-off and fly away from a perch, turn on a dime, and fly back and land on the same perch. High-speed flight recordings revealed that rapidly turning lovebirds perform a remarkable stereotypical gaze behavior with peak saccadic head turns up to 2700 degrees per second, as fast as insects, enabled by fast neck muscles. In between saccades, gaze orientation is held constant. By comparing saccade and wingbeat phase, we find that these super-fast saccades are coordinated with the downstroke when the lateral visual field is occluded by the wings. Lovebirds thus maximize visual perception by overlying behaviors that impair vision, which helps coordinate maneuvers. Before the turn, lovebirds keep a high contrast edge in their visual midline. Similarly, before landing, the lovebirds stabilize the center of the perch in their visual midline. The perch on which the birds land swings, like a branch in the wind, and we find that retinal size of the perch is the most parsimonious visual cue to initiate landing. Our observations show that rapidly maneuvering birds use precisely timed stereotypic gaze behaviors consisting of rapid head turns and frontal feature stabilization, which facilitates optical flow based flight control. Similar gaze behaviors have been reported for visually navigating humans. This finding can inspire more effective vision-based autopilots for drones.

Process: The objective of this paper was to observe the "turn on a dime" maneuver of lovebirds. To do this, birds were placed in a small arena where they only had one perch to take off from and land on. This required them to make this maneuver when taking off from the perch. Paint markings were made on the lovebirds heads to help identify the rapid head movements made by these birds. The maneuver

was recorded using several high and low speed cameras, and the data from this was analyzed to determine the final results.

Properties: The integral contribution of this paper is the discovery of the ultra-fast head saccades and gaze shifting of the lovebirds, which indicates some sort of optical flow sensing is likely used during flight, and especially for extreme maneuvering.

Demonstration: They were able to observe and record live lovebirds to help demonstrate their findings.

Relevance : The "turn on a dime" or U-turn maneuver studied in this paper is yet another type of maneuver that I may wish to try to automate on my quadrotor. This paper also gives me an idea that I may want to also implement some sort of optical flow sensing on my quadrotor to provide another input to assist it in completing these extreme maneuvers.

Strengths: Being an online paper, it includes video footage of the birds in flight which is a neat advantage to just a simple .pdf file. It also goes into great detail about every aspect of the birds flight, which includes takeoff and landing on the perch. It also notes the applicability of their findings to potentially improving drone autopilots in other work, which is an interesting discussion I can have in my paper.

Weaknesses: The paper did not cover more complex maneuvering, since is was more focused on the gaze aspect of the birds flight. There may be additional techniques that the birds use in an open environment to navigate and maneuver.

1. Problem Statement Brainstorm:
   a. Autonomously replicate the display dives of Anna's hummingbirds using a nonlinear control algorithm on a quadrotor.
   b. Explore enhanced autonomous quadrotor maneuverability through optic flow sensing techniques portrayed by lovebirds.
   c. Develop a quadrotor capable of replicating several extreme maneuvers of different bird species.