Autonomous Trajectory Planning to Copy Birdlike Aerial Maneuvers

Student: Midn 2/C E. J. Marcello Adviser: Prof. D. Evangelista

***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^{th} 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 root mean square error 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, Δt. 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

To demonstrate the objective of replicating the Anna's hummingbird flight paths I will utilize a simulation created in MATLAB and Simulink. This will be followed up with a proof-of-concept demonstration, provided I am able to achieve successful trials in simulation first. Before I describe these processes, it is important to mention why these are the methods I chose to implement. A simulation is general in that I can run the simulation for many iterations to see how the controller will react to different input parameters. The input parameters themselves are very specific; however, the ability to change parameter values will allow me to assess the full capabilities of the quadrotor system to determine if I can eliminate the need to do a time-scaled comparison to the hummingbird trajectory. The simulation will be coded using MATLAB and Simulink, both are software with which I have the most experience in creating simulations. My simulation code will be made available after the completion to this project on Git for those wishing to replicate my simulated results. Unfortunately, the realism of this simulation is limited, and as a result I will have to do a proof-of-concept demonstration to truly prove the ability of the quadrotor. Being a much more specific process, it will likely vary slightly from the simulation results, and need to be tweaked based on the level of success seen in the first few trials. Ultimately, the proof-of-concept demonstration is an essential piece to this research since a simulation doesn't have any real world application except in principle. The experiment will enlist the use of a Crazyflie quadrotor platform, and an OptiTrack visual positioning system to gather position vs. time data. This will help ensure accuracy in the quadrotor's trajectory and as such, provide a higher level of confidence in the experiment's success.

A. Simulation

To create a feasible simulation for this research, I will model the Crazyflie quadrotor platform to be used in simulation. This involves determining the various thrust vectors of the motors, and the calculation of many performance metrics. Thankfully, much of this work has already been done, and I will be relying heavily on the work in [7] to create a useful model for the quadrotor in MATLAB and Simulink. Due to the extreme maneuvering of the quadrotor, I have chosen to use a quaternion coordinate system to describe its position, for flight control purposes only. The trajectory comparison will be conducted in the x, y, z Cartesian coordinate frame. A quaternion is defined as a vector of one real and three imaginary vector directions, *i*, *j*, and *k*. Once this has been accomplished, I will obtain and upload Anna's hummingbird flight trajectories into MATLAB. These will serve as truth, or the desired trajectories for my simulation to attempt to run through. Once this is complete, I will develop, or obtain from another source, a path-planning flight controller algorithm that is able to take in a desired flight path and create an appropriate response to fly this desired flight path with minimal error. The feedback diagram of this control concept is shown below in Figure 2. In principle, a desired trajectory will be developed from a path-planning algorithm that takes in the time scaled hummingbird trajectory and calculates the idealized pitch and motor torque and speed at each time step in order to fit this trajectory with as little error as possible. This signal will be combined with some sort of inertial measurement true position feedback to produce the error signal to the onboard flight controller. The flight controller will send a signal to the motors on the quadrotor based on this error signal to come as close as possible to zero error for the next time step, and the cycle will repeat until the quadrotor has completed its maneuver. My simulation will replicate this decision-making process using numerical integration to obtain the position data for every iteration.

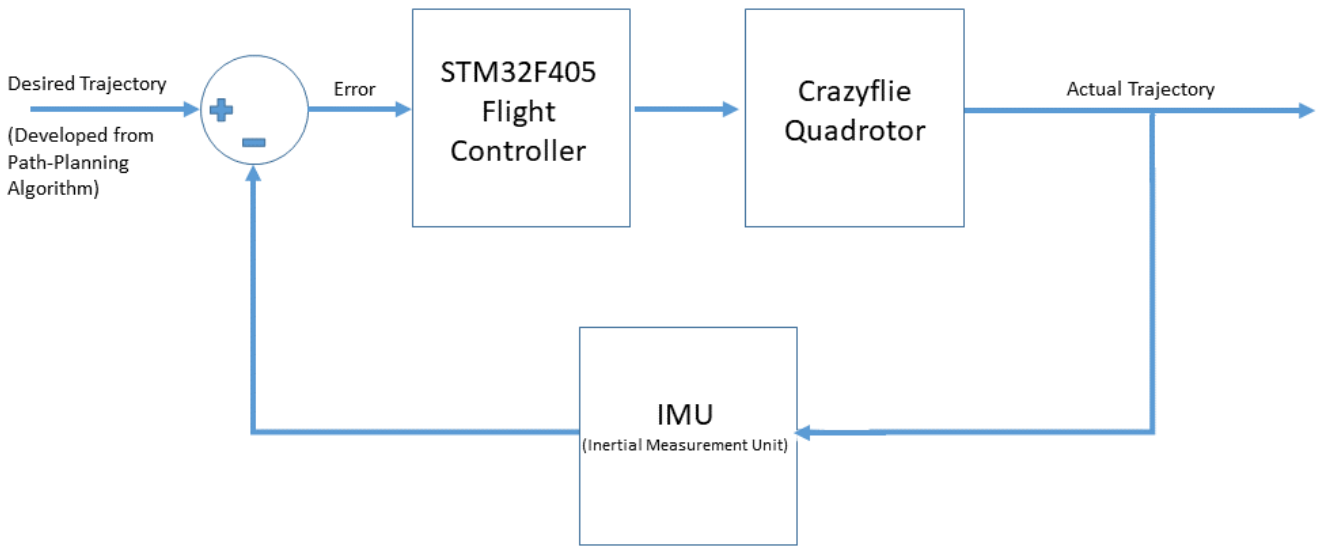


Figure 2: Functional Block Diagram of the controller feedback loop.

Finally, to determine accuracy of the trial I will compare the actual flight path of the quadrotor with the desired flight path, and determine a time-scaled root mean square error between the two position vs time datasets. This error will be calculated using equation 1 below:

$$e(t) = \sqrt{\begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}_a^2 - \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}_d^2} \tag{1}$$

where *e(t)* is the error at a specific time step in the trajectory, all operators are considered element-by-element matrix operations, and the subscripts *a* and *d* represent the actual traveled trajectory and the desired trajectory respectively. The error for every time step will be averaged together to determine the root mean square error of the data in the form of a 3x1 matrix. The magnitude of this matrix will be the official value for the root mean square error. Without any other indications, a successful trial will be considered a root mean square error of less than ten centimeters over the entire trajectory. Since the hummingbird trajectory is time-scaled—down to only a fraction of its true speed—the quadrotor will be responsible for marking every position at the time it is supposed to be located at that position, therefore removing motor operation constraints as a possible source of error.

If I am able to accomplish a working simulation with the Anna's hummingbird courtship dive maneuver, I will try to make the simulation slightly more general so it can apply to a wide variety of hummingbird dives and maneuvers. This can include evasive maneuvers, and potentially other types of stunts.

B. Experimental work

Provided that the simulation is able to achieve several successful runs, a proof of concept demonstration will be deemed necessary for further analysis into the possibility of actually autonomously flying a drone through hummingbird flight trajectories. The hardware components necessary for this experiment include a fully functional Crazyflie quadrotor, and an OptiTrack system. The quadrotor will be the object of the experiment, and the OptiTrack system is a highly accurate way to obtain position data for the Crazyflie in flight using visual information from nearly 20 cameras staged around the outside of the testing area. Experimentation will be conducted indoors for the initial trials to minimize any aerodynamic noise. There is a distant possibility to moving into an outdoor environment if early testing shows signs of having promising results. I will need several batteries for the Crazyflie to ensure sufficient trial and testing periods, and I will also need to attach approximately five OptiTrack visual markers on the Crazyflie drone to ensure that it is able to be detected by the OptiTrack system. These marker additions will be taken into account in simulation first in order to ensure readiness to counteract any effect they may have on the dynamics of the quadrotor in the feedback loop.

The first step to demonstration will involve the conversion of coding language—from MATLAB used for the simulation to Python—and upload of the path-planning control algorithm onto the Crazyflie. To fly the trajectory, the quadrotor system will follow the feedback loop portrayed in Figure 2 above. When the quadrotor is ready to fly the trajectory, the OptiTrack system will obtain the position vs. time information of the Crazyflie using visual sensor data, accurate to one millimeter. This data will be compared to the desired hummingbird trajectory in post-processing to determine the flight accuracy, just as in the simulation.

C. 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?

D. 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?

E. 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.

F. Budget

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

TABLE 1
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.

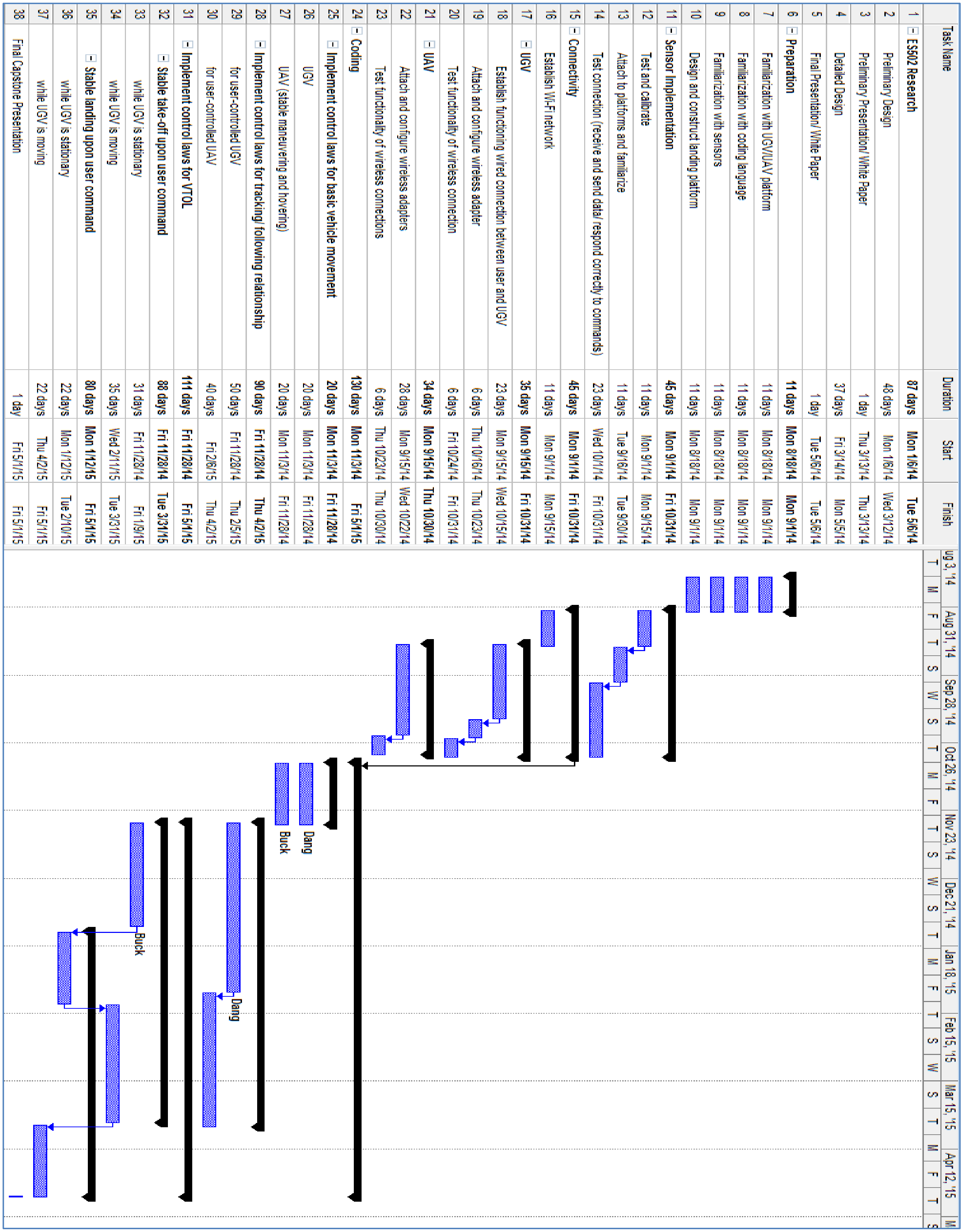
[5] F. Sabatino, "Quadrotor control: modeling, nonlinear control design, and simulation," KTH Royal Institute of Technology in Stockholm, 2015.

[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.

[7] M. Greiff, "Modelling and Control of the Crazyflie Quadrotor for Aggressive and Autonomous Flight by Optical Flow Driven State Estimation," Lund University Department of Automatic Control, 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.



	Task Name	Duration	Start	Finish
1	ES502 Research	87 days	Mon 1/6/14	Tue 5/6/14
2	Preliminary Design	48 days	Mon 1/6/14	Wed 3/12/14
3	Preliminary Presentation/ White Paper	1 day	Thu 3/13/14	Thu 3/13/14
4	Detailed Design	37 days	Fri 3/14/14	Mon 5/5/14
5	Final Presentation/ White Paper	1 day	Tue 5/6/14	Tue 5/6/14
6	Preparation	11 days	Mon 8/18/14	Mon 9/1/14
7	Familiarization with UGV/UAV platform	11 days	Mon 8/18/14	Mon 9/1/14
8	Familiarization with coding language	11 days	Mon 8/18/14	Mon 9/1/14
9	Familiarization with sensors	11 days	Mon 8/18/14	Mon 9/1/14
10	Design and construct landing platform	11 days	Mon 8/18/14	Mon 9/1/14
11	Sensor Implementation	45 days	Mon 9/1/14	Fri 10/31/14
12	Test and calibrate	11 days	Mon 9/1/14	Mon 9/15/14
13	Attach to platforms and familiarize	11 days	Tue 9/16/14	Tue 9/30/14
14	Test connection (receive and send data/ respond correctly to commands)	23 days	Wed 10/1/14	Fri 10/31/14
15	Connectivity	45 days	Mon 9/1/14	Fri 10/31/14
16	Establish Wi-Fi network	11 days	Mon 9/1/14	Mon 9/15/14
17	UGV	35 days	Mon 9/15/14	Fri 10/31/14
18	Establish functioning wired connection between user and UGV	23 days	Mon 9/15/14	Wed 10/15/14
19	Attach and configure wireless adapter	6 days	Thu 10/16/14	Thu 10/23/14
20	Test functionality of wireless connection	6 days	Fri 10/24/14	Fri 10/31/14
21	UAV	34 days	Mon 9/15/14	Thu 10/30/14
22	Attach and configure wireless adapters	28 days	Mon 9/15/14	Wed 10/22/14
23	Test functionality of wireless connections	6 days	Thu 10/23/14	Thu 10/30/14
24	Coding	130 days	Mon 11/3/14	Fri 5/1/15
25	Implement control laws for basic vehicle movement	20 days	Mon 11/3/14	Fri 11/28/14
26	UGV	20 days	Mon 11/3/14	Fri 11/28/14
27	UAV (stable maneuvering and hovering)	20 days	Mon 11/3/14	Fri 11/28/14
28	Implement control laws for tracking/ following relationship	90 days	Fri 11/28/14	Thu 4/2/15
29	for user-controlled UGV	50 days	Fri 11/28/14	Thu 2/5/15
30	for user-controlled UAV	40 days	Fri 2/6/15	Thu 4/2/15
31	Implement control laws for VTOL	111 days	Fri 11/28/14	Fri 5/1/15
32	Stable take-off upon user command	88 days	Fri 11/28/14	Tue 3/31/15
33	while UGV is stationary	31 days	Fri 11/28/14	Fri 1/9/15
34	while UGV is moving	35 days	Wed 2/11/15	Tue 3/31/15
35	Stable landing upon user command	80 days	Mon 1/12/15	Fri 5/1/15
36	while UGV is stationary	22 days	Mon 1/12/15	Tue 2/10/15
37	while UGV is moving	22 days	Thu 4/2/15	Fri 5/1/15
38	Final Capstone Presentation	1 day	Fri 5/1/15	Fri 5/1/15