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ME457 – Drone Control
Crazyflie Trajectory Final Report
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Control Approach for Crazyflie Quadcoptor

The bitcraze website and forums are rich with documentation for the Crazyflie's controllers. For our experiment, the quadcopter was in the gimble, restricting its north, east, and down motions (positions and velocities relative to earth frame). We focused on the attitude (expressed in Euler angles, ϕ, θ, φ) and the attitude rates (*p, q, r*).

There are three PID controllers on the Crazyflie, we used two. The attitude controller, which sets the desired angle rate, and the angle rate controller which sets desired thrusts to each of the four motors. This is an example of a cascaded PID controller. The outer loop runs the attitude controller, which takes inputs from the state estimator to calculate the error to the attitude setpoint, and outputs the desired attitude rate. The inner loop receives gyroscope readings directly to calculate the error between the desired angle rates. The output commands are send to the power distribution, which will send a pwm signal to each motor to achieve the required thrust calculated by the controller.

The stabilizer module, which is the path from sensor acquisition to motor control, uses the onboard sensors, such as the accelerometer and gyroscope, the state estimator (an extended Kalman filter), and the cascaded PID controller to realize and hold the desired state on the quadcopter.

Calculating Thrust for Each Motor

There are multiple motivations to know the thrust of each motor, one being to see how often each motor is saturated throughout the desired trajectory at different frequencies. Another idea that Mike had was to see if it was possible to estimate the state myself from the motor thrust data (more on that at the end).

The raw data from python scripts was a 16-bit integer (max value 65,535). On the bitcraze blog, an author named Tobias[1] created a thrust test stand to measure the thrust generated for each pwm signal sent to the motors. The polynomial fit takes in pwm as an 8-bit integer (max value 256) and is as follows:

$$Thrust(g) = 0.409e^{-3} * pwm^2 + 140.5e^{-3} * pwm - 0.099$$

This equation was used to calculate the thrust in grams for each of the motors during the trajectory experiments. The maximum thrust is found to be just over 60 g for each motor.

[1] https://www.bitcraze.io/documentation/repository/crazyflie-firmware/master/functional-areas/pwm-to-thrust/

Trajectory Results

In each of the following figures, the top plot shows the angle rates, the inner loop of the controller, containing the estimated values from the state estimator and the desired values set by the controller. The middle plot is the desired angle sent into the outer loop of the controller and the measured value from the stabilizer module. The lower plot shows the thrusts of each motor in grams (converted using the pwm to thrust mapping). The thrust values are quite noisy, perhaps a filter should be applied to them before any further calculations.

Figure 1 contains the first experiment, labelled “stable,” the state estimator is quite noisy but is able to follow the desired angle rates well. The outer loop has a slight phase delay between the desired angle values, but the amplitudes align. The thrusts for each motor are only saturated for a moment during the initial step of the system.

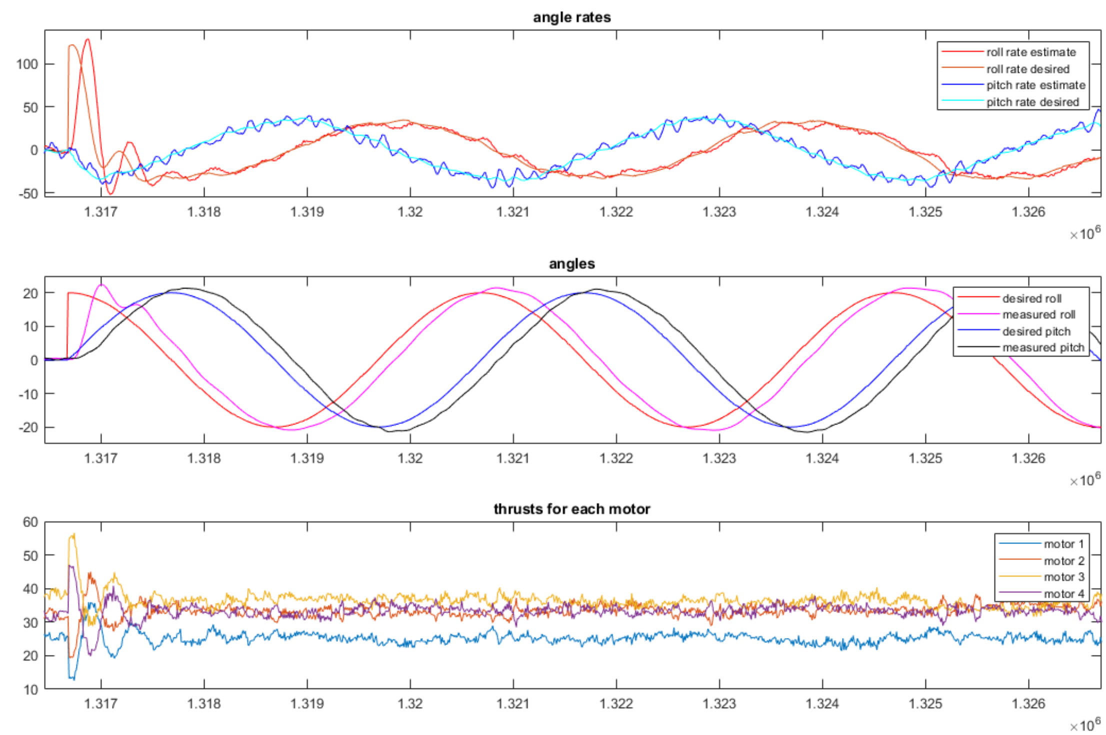


Figure 1: Stable Trajectory

Perhaps more interesting is the faster frequencies for the desired pitch and roll angles, in Figure 2, the 4 Hz trajectory is shown. The desired angles are changing too fast for even the inner loop of the controller to keep up, and even if it could, the motor thrust is often saturated, further increasing the error in the states. The estimated toll rate is nearly half the amplitude of the desired, and there is a significant phase lag. The pitch rate also has a large phase lag. The measured roll's phase is so behind, its cancelling itself out. The measured pitch is always below zero, unable to rotate fully to the other side. This inability to keep up with the setpoints is understandable when looking at how often each of the motors are saturated, especially motor 3 and motor 1 (I can guess that these two motors control pitch, because that has the most error in the angle across the experiment). Similar results are found for the 8Hz case, they are even more exaggerated, the roll and pitch are mostly zero, unable to track at that high frequency.

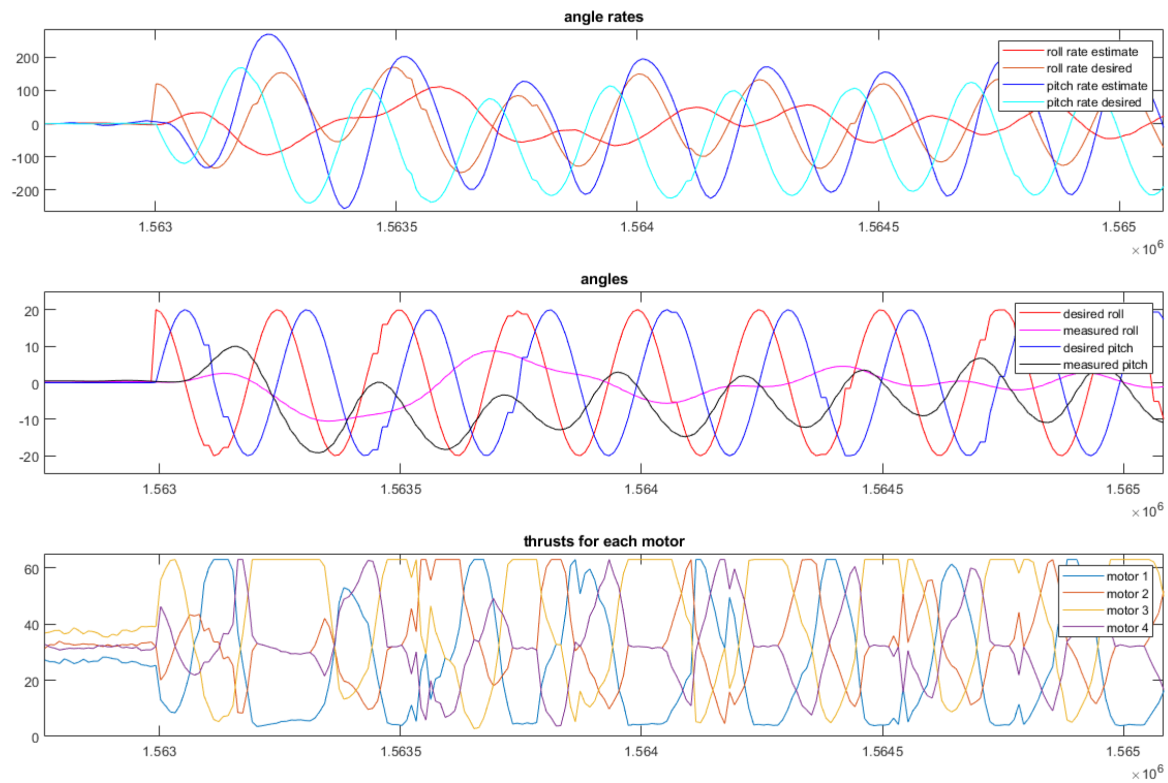
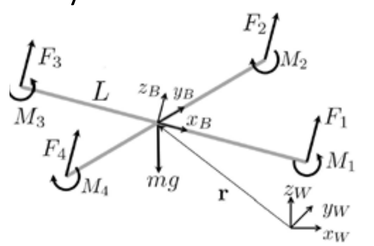


Figure 2: 4 Hz Trajectory

An Attempt at State Estimation from the Thrust Measurements

The execution of this method was not fully successful, but an attempt was made to estimate the rotational states from the motor thrust measurements. In the Crazyflie quadcopter, each of the motors supplies a force, in the form of thrust, onto each arm of the drone. The propellers act in opposite directions to avoid adding any moments on the ends of each arm. On the Bitcraze Blog, an author Percy Jaiswal[2] supplies this image as the free body diagram, showing the forces in the body frame of the drone:



Each of the propellor thrusts create a moment on the center of mass of drone, expressed in the body frame as *L, M.* The lever arm for the Crazyflie is 46 mm. These moments are along the north and east directions of the drone (but in the body frame).

$$L = arm * (F_1 - F_2 - F_3 + F_4)$$
$$M = arm * (-F_1 + F_2 - F_3 + F_4)$$

The moment of inertia of the Crazyflie has been studied[3] and found to be:

$$I = \begin{bmatrix} 16.571710 & 0.830806 & 0.718277 \\ 0.830806 & 16.655602 & 1.800197 \\ 0.718277 & 1.800197 & 29.261652 \end{bmatrix} * 10^{-6}\ kgm^2$$

Using Coriolis Theorem, the angular acceleration of the drone can be found using the moments from the thrusters and the angular velocity states. Where *I* is the 3x3 matrix above. This can be rearranged for the attitude acceleration.

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} I \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

The attitude rates (*p,q,r*) and the euler rates (ϕ, θ, φ) are related using a series of rotation matrices:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)\sec(\theta) & \cos(\phi)\sec(\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

[2] https://www.bitcraze.io/2018/11/demystifying-drone-dynamics/
[3] Förster, Hamer, D'Andrea - System Identification of the Crazyflie 2.0 Nano Quadrocopter