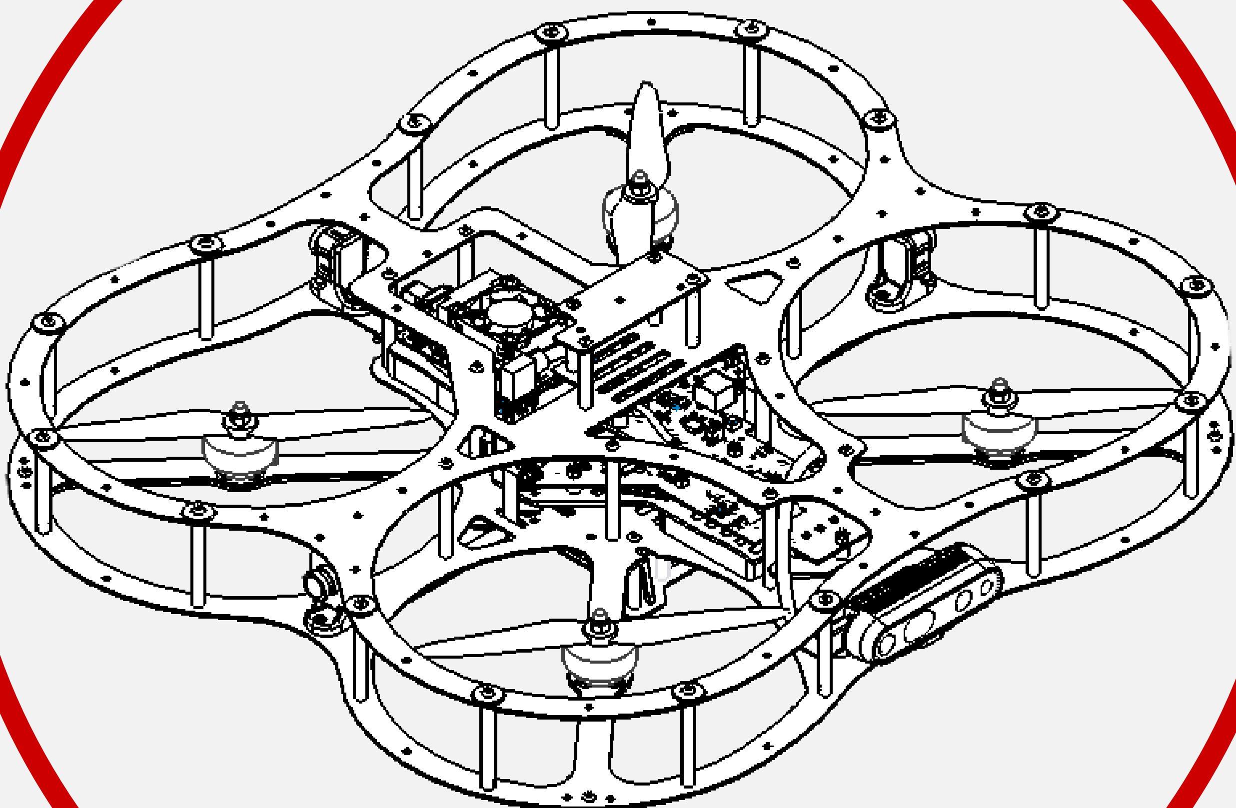

QDrone2

Thrust Parametrization

$v\,1.0\ -\ 17th\ July\ \ 2023$

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CE Compliance CE

This product meets the essential requirements of applicable European Directives as follows:

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Warning: This is a Class A product. In a domestic environment this product may cause radio interference, in which case the user may be required to take adequate measures.

Caution

This equipment is designed to be used for educational and research purposes and is not intended for use by the public. The user is responsible to ensure that the equipment will be used by technically qualified personnel only. While the end-effector board provides connections for external user devices, users are responsible for certifying any modifications or additions they make to the default configuration.

Table of Contents

A. System Parameters

The following table summarizes the mechanical parameters of the QDrone2.

Dimensions		
L_{roll}	Length of roll axis	0.254 m
L_{Pitch}	Length of pitch axis	0.2032 m
M_d	Mass of QDrone2	1.146 kg
M_b	Mass of 3700 mAh Battery	0.358 kg
M_t	Takeoff weight	1.504 kg
K_t	Motor torque constant	68.9055 N/N.m
K_v	Motor Speed Constant	1300 RPM/V

Table 1. Mechanical parameters for QDrone2

B. Thrust - Duty Cycle Motor Mapping

To create an accurate model of an aerial vehicle we need to identify the relationship between the voltage command from the ESC to the thrust generated by the rotating propeller. To calculate this relationship, we can use a device called a dynamometer to measure the thrust/current/battery voltage when a PWM command is sent to a motor/propeller combination.

Knowing the battery voltage and duty cycle is important because of the way the PWM command is generated by the ESC.

$$PWM_{Vout} = (V_{in})(Duty_{Cycle}) \tag{1}$$

This relationship is important for us since it gives an estimate of what the voltage command to the motor is. From our dynamometer we can see that the battery voltage is not constant as command percentage changes:

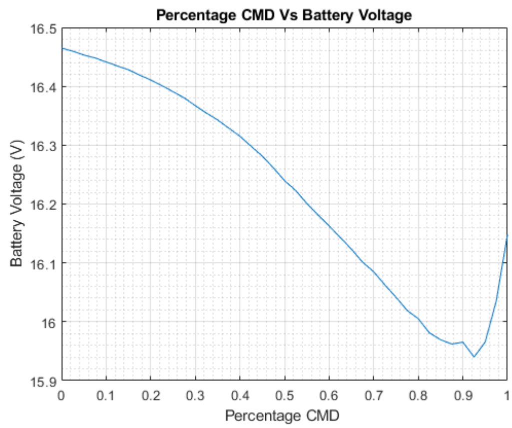

Figure 1: Battery voltage compared to percentage duty cycle command.

For this graph we specified the percentage command as the duty cycle from a 1000-2000Hz PWM pulse. This non-linear relationship means that we need to scale our motor command based on the battery voltage available when the command was generated. We will use this property to parametrize the thrust measured as a function of the desired motor voltage. The percentage command was calculated using the following equation:

$$\%_{CMD} = (ESC_{CMD} - 1000)/1000 \tag{2}$$

We need to predict what the voltage command from the ESC would be based on the $\%_{CMD}$ at that point. As an example using equation (2):

Measured battery voltage = 16.1016V, Duty Cycle = 0.675

$$V_{CMD} = V_{bat}Duty_{cycle} = (16.1016V)(0.675) = 10.8686V$$

At full battery voltage a duty cycle command of 0.675 would result in a voltage command of 11.34V. This implies the duty cycle will slowly increase as the available voltage decreases to generate the same thrust command. The QDrone2 DAQ will scale the duty cycle command depending on the available battery voltage.

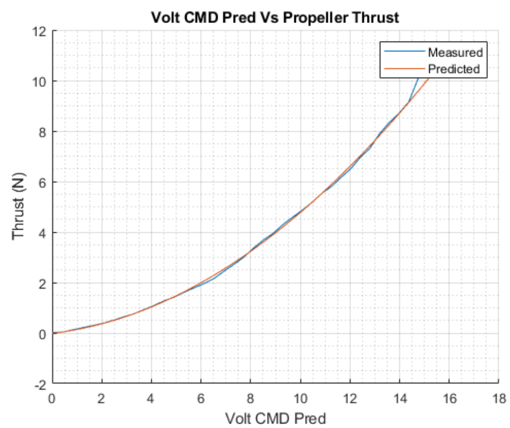

Figure 2: Measured predicted voltage command compared to the measured thrust.

Looking now at the voltage command to thrust relationship in Figure 2 we notice a non-linear relationship as the voltage command increases.

A polynomial fit was used to predict the non-linear relationship between voltage and thrust.

The second order polynomial has the form:

$$T_{pred} = Kt_0\, V_{CMD}^2 + Kt_1 V_{CMD} + Kt_2 \tag{3}$$

For the QDrone2 DAQ we require the reverse, based on a required thrust what should the voltage command be. This inverse relationship is calculated as:

$$V_{Pred} = \frac{-Kt_1 + \sqrt{\left(Kt_1^2 - 4Kt_0(Kt_2 - T_{des})\right)}}{2Kt_0} \tag{4}$$

Based on the polynomial fit the coefficients for K_t are:

$$K_t = [K_{t0}, K_{t1}, K_{t2}] = [0.0362\frac{N}{V^2} \quad 0.117\frac{\mathrm{N}}{\mathrm{V}} \quad -0.0121\ \mathrm{N}\,]$$

Figure 2 shows the comparison between the predicted thrust and the measured thrust based on the voltage command sent by the ESC. The last step is looking at the motor torque constant. Plotting the measured torque vs generated thrust gives us the following graph:

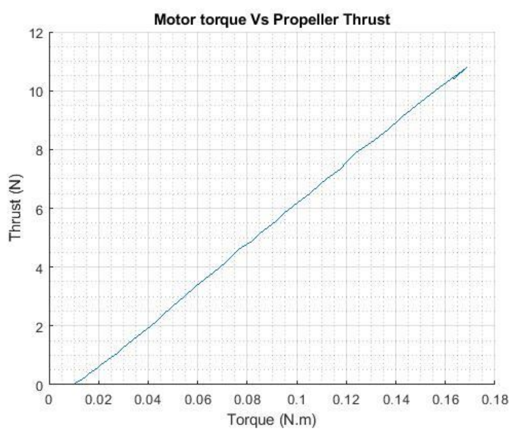

Figure 3: Generated thrust versus measured motor torque

Figure 3 shows a linear relationship which is useful for generating a dynamic model for the QDrone2. Using a polynomial fit the motor torque constants are:

$$K_\tau = [K_{\tau 0}\ K_{\tau 1}] = \left[\,68.9055\frac{N}{N.m} \quad -0.7568 N.m\,\right]$$

C. Motor Mapping Matrix

Before formulating the motor mapping matrix, the free body diagram for the QDrone2 is

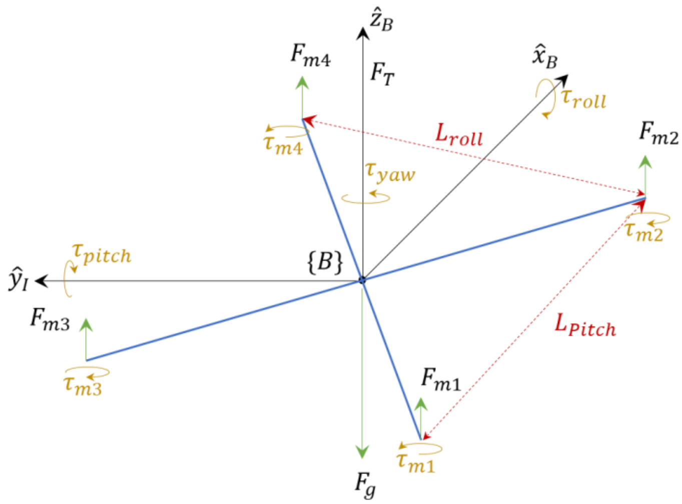

Figure 4: QDrone2 free body diagram

From the free body diagram, we can create the following equations:

$$F_{Net} = F_{m1} + F_{m4} + F_{m3} + F_{m4} - F_g \tag{5}$$

Note that $F_{m1} = F_{m2} = F_{m3} = F_{m4} = F_m$. The desired moments about the 3 principal axes are:

$$M_x = \tau_{roll} = \frac{L_{roll}}{2}(-F_{m1} - F_{m2} + F_{m3} + F_{m4}) \tag{6}$$

$$M_y = \tau_{pitch} = \frac{L_{pitch}}{2}(F_{m1} - F_{m2} + F_{m3} - F_{m4}) \tag{7}$$

$$M_z = \tau_{yaw} = \tau_{m1} - \tau_{m2} - \tau_{m3} + \tau_{m4} \tag{8}$$

To convert from torque to force we can use the equation $\tau = K_\tau F$. We use $k_{\tau 0}$ found in the previous section to scale the motor force to a torque value.

$$M_z = \tau_{yaw} = K_{\tau 0}(F_{m1} - F_{m2} - F_{m3} + F_{m4})$$

This gives us a general motor mapping matrix which allows us to calculate the forces and torques based on the motor commands.

$$\begin{bmatrix} F \\ \tau_{roll} \\ \tau_{pitch} \\ \tau_{yaw} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -\frac{L_{roll}}{2} & -\frac{L_{roll}}{2} & \frac{L_{roll}}{2} & \frac{L_{roll}}{2} \\ \frac{L_{pitch}}{2} & -\frac{L_{pitch}}{2} & \frac{L_{pitch}}{2} & -\frac{L_{pitch}}{2} \\ \frac{1}{K_{\tau 0}} & -\frac{1}{K_{\tau 0}} & -\frac{1}{K_{\tau 0}} & \frac{1}{K_{\tau 0}} \end{bmatrix} \begin{bmatrix} F_{m1} \\ F_{m2} \\ F_{m3} \\ F_{m4} \end{bmatrix} \tag{9}$$

We are interested in the inverse of the motor mapping matrix to calculate the desired motor thrust based on the higher-level controllers.

$$\begin{bmatrix} F_{m1} \\ F_{m2} \\ F_{m3} \\ F_{m4} \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & -\frac{1}{2L_{roll}} & \frac{1}{2L_{pitch}} & \frac{K_{\tau 0}}{4} \\ \frac{1}{4} & -\frac{1}{2L_{roll}} & -\frac{1}{2L_{pitch}} & -\frac{K_{\tau 0}}{4} \\ \frac{1}{4} & \frac{1}{2L_{roll}} & \frac{1}{2L_{pitch}} & -\frac{K_{\tau 0}}{4} \\ \frac{1}{4} & \frac{1}{2L_{roll}} & -\frac{1}{2L_{pitch}} & \frac{K_{\tau 0}}{4} \end{bmatrix} \begin{bmatrix} F \\ \tau_{roll} \\ \tau_{pitch} \\ \tau_{yaw} \end{bmatrix} \tag{10}$$

With each motor thrust value calculated we use equation 4. to convert the thrust to a voltage command. With the measured battery voltage, the thrust signal is converted to a duty cycle percentage sent to the ESC.

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