Experimental Model of Coaxial Rotors Performance Degradation Induced by Wake Effect

Hyungjoo Ahn, Kwangwoo Jang, Dongwoo Lee, Junwoo Park, Kyungwoo Hong, and Hyochoong Bang

Abstract Coaxial rotors are widely used for large-sized multi-rotors to achieve the efficiency of spatial layout. However, as the wake effect of the upper rotor affects to the lower rotor, performance degradation of the lower rotor is common. In this paper, a model of performance degradation for the coaxial rotor configuration is proposed based on experiment results on a given combination of lower and upper rotor pulse width modulation (PWM) signals. For the performance reduction model, loss of actuator effectiveness with respect to the given PWM signal of the lower motor is estimated comparing with the single rotor configuration. For the coaxial rotor experimental data, the PWM percent of the upper rotor is fixed with a constant value in each scenario, while the lower rotor angular velocity is changed with a specific interval in the coaxial rotor configuration. Also, the PWM percent of the upper rotor is changed with another specific interval for each of the scenarios. In each scenario, thrust, torque and angular velocity of the rotor are measured. For comparison, these same measurements were taken for the single rotor configuration with the same PWM percent interval of the upper rotor in the coaxially configured rotor. By comparing the coaxial rotor and single rotor configuration, thrust and torque efficiency degradation with respect to the PWM signal combination of the upper and lower rotors is derived. To evaluate the performance reduction of thrust and torque, the loss of actuator effectiveness with the function of the upper and lower rotor PWM signal is derived with the ratio between the single rotor and coaxial rotor configuration in the same PWM percent of the upper rotor. This can be applied to precise multi-rotor modeling for simulation or controller design.

Keywords Coaxial propeller configuration · Large-sized multi-rotor · Experiment-based modeling · Loss of actuator effectiveness

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1 Introduction

In recent years, there has been an increasing need for carrying heavy payloads or passengers using unmanned aerial vehicles (UAVs) or urban air mobilities (UAMs) which necessitate corresponding platform size enlargement. Therefore, research on the development of large sized multi-rotors has been actively carried out [2, 6]. For large-sized multi-rotors, which are heavier in weight than conventional small multi-rotors, efficient propeller placement in limited space is essential to achieve sufficient thrust while reducing size. Among the many ways to efficiently place propellers in limited space, stacking several rotors in a coaxial configuration has been widely adopted, e.g., "CityAirbus" from Airbus, "Y6S" from Autonomous Flight, "S-A1" from Hyundai, and various heavy-lift multi-rotors [9].

However, for the coaxial propeller configuration, there is a significant loss of efficiency on the lower propeller caused by the wake effect from the upper propeller [6]. This implies that the performance of coaxially placed propellers is not equivalent to simply adding that of two individuals, and also raises an issue of accurate modelling of a multi-rotor thrust system. In other words, the absence of modelling for propeller performance degradation can be a cause of the model uncertainty. But with large-scaled aircrafts, it is common to develop a controller that is applicable for a specific target platform on the assumption of a well-known model. In this case, the model of aircraft is considered to have a suitable controller. If the assumed model includes any errors, an unexpected dynamic response can occur which is highly detrimental to the safety of the payload or passengers. From this point of view, accurate modelling of the performance difference for given coaxial propeller configurations is necessary to predict the motor thrust and torque on each of the multi-rotor arms to deliver improved control performance.

Most papers related to coaxial rotor performance analysis mainly focus on thrust reduction [1, 3, 8]. The common conclusion presented in several papers is that there is a thrust loss with the coaxial configured rotors. Also, some papers propose that the relationship between thrust and torque changes with respect to the configuration change of two motors with varying angular velocity [10]. But for multi-rotor modelling, the configuration of two rotors remains the same while the PWM and rotational velocity of the rotor changes every moment. Moreover, no existing studies show the direct connection from PWM to thrust and torque reduction which is important to construct a simulator or model-based controller of a multi-rotor with coaxial rotors.

Therefore, this paper suggests a model for the performance reduction of given coaxially configurated propellers by estimating the reduction ratio of thrust and torque with respect to the PWM level on the Electronic-Speed-Controller (ESC) via experimental data. For the experiment, a pulse width modulation (PWM) signal of the upper motor is fixed with several levels and assumed to follow the thrust of a single propeller configuration. In each of the PWM levels on the upper propeller, the PWM signal of the lower motor is modulated to measure the corresponding thrust, torque, and angular velocity. Then, the relationship between efficiency reduction and the PWM signal levels of the upper and lower motor is derived from the experimental data. Also, a loss of actuator effectiveness with the function of upper propeller thrust is derived which can be applied to precise multi-rotor modelling before the building of a controller.

2 Experimental Setup

2.1 Experiment Procedure

The purpose of this experiment is to collect the thrust and torque data for validating the reduced effect of the lower propeller. Therefore, a coaxial rotor is needed with the test bench for measuring the necessary data. To verify the performance reduction regarding the input signal level of the upper rotor, the input signal of the upper rotor is fixed in each experiment with the same PWM level intervals. In each experiment, the input PWM level of the lower rotor is increased at fixed values while the upper rotor PWM level is maintained at a constant level.

2.2 Test Bench Setup

For the test bench, thrust and torque should be measured individually in each of the experiments with respect to the given PWM signal level and power. The test bench was constructed with four main parts: the mount frame, coaxial propulsion system, measuring equipment, and measurement processor. First, the mount frame is formed with aluminum extrusions fixed on the floor to mount two motors as a coaxial configuration. For the coaxial propulsion system, two motors with bi-blade propellers and ESCs were assembled on the mount frame. Measuring equipment consists of a load cell for thrust and torque measurement, and an optical rotation sensor for measuring motor angular velocity. Finally, for the measurement processor, a control board to process the analog signals from each sensor and software to arrange the measurement with synchronized time were used.

For the experiment, we assume the following conditions. First, two motors are mounted in a face-to-face configuration due to the thick aluminum extrusions and load cell mounted on the motor. As the conventional multi-rotor with coaxial rotor is configured with a back-to-back configuration, we assume that the performance of the coaxial propeller for the back-to-back and face-to-face configuration are similar with the same distance between the two propellers [7]. Also, as there is much less wake effect on the upper motor compared with the lower motor, we assumed that the performance of the upper motor is the same with the single rotor configuration.

For the propulsion system part, a "T-Motor U15II KV80" for the motor, a "T-Motor Flame 200A 14S" for the ESC, and a "T-Motor G40X13.1" for the propeller were used. Also, an "RC benchmark series 1780" with "Propulsion measurement software" from RC benchmark were used for the mount frame, measuring equipment, and measurement processor which contains the load cell to measure the thrust and torque of the motor, optical rotor speed sensor, aluminum frame, and control board.

3 Data Acquisition with Experiment

Based on the test bench in Sect. 2, motor angular velocity, torque, and thrust data was measured for the parameter approximation with the given PWM signal levels. In the experiment, the unit of PWM signal level percentage, motor angular velocity, torque and thrust data are percent, RPM, N, and Nm, respectively.

First for the single rotor configuration, the PWM signal of the lower rotor is assigned as 8 points from 0 to 100 percent at 12.5 percent intervals without the upper rotor flow. The PWM signal level percent to motor angular velocity, motor angular velocity to thrust, and motor angular velocity to torque data were obtained and are shown below.

Second, for the coaxial rotor configuration, the lower rotor PWM signal is also modulated as the same with the single rotor configuration experiment in each of the scenarios with a fixed upper rotor PWM while the PWM level percent of the upper rotor is divided into 10 points, from 0 to 100 percent, at 10 percent intervals. The PWM level percent interval of the lower rotor in the coaxial configuration and the interval in a single rotor configuration is the same for comparing the performance of each configuration under the same conditions. Thrust and torque value with respect to the PWM signal level percentage of the upper and lower rotors is acquired, as shown in the figure below.

4 Loss of Actuator Effectiveness

With the obtained thrust and torque values on the single and coaxial rotor configurations, it is possible to estimate the performance degradation. For the evaluation of performance reduction, a loss of actuator effectiveness is introduced with a ratio between the single and coaxial rotor performance. To obtain the loss of actuator effectiveness, two steps are introduced: the nominal thrust and torque estimation step and the loss of actuator effectiveness estimation step.

4.1 Nominal Thrust and Torque Estimation

Nominal thrust and torque relations are estimated based on the single rotor data which is shown in Table 1 and 2. Instead of estimating the thrust and torque value directly

Table 1 PWM level percent to motor angular velocity for the single rotor configuration

PWM signal level percent [%]	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0
Motor angular velocity [RPM]	892	1472	2005	2585	3167	3726	4262	4750

Table 2 Motor angular velocity to thrust and torque for the single rotor configuration

Motor angular velocity [RPM]	892	1472	2005	2585	3167	3726	4262	4750
Thrust [N]	5.913	18.217	35.1024	59.424	90.338	126.294	167.259	210.335
Torque [N.m]	0.3348	0.6551	1.2230	2.0316	3.0733	4.2898	5.6644	7.1179

from the PWM level, the PWM level to motor angular velocity is estimated by fitting the experimental data with the 1st order curve to derive the mapping function from the input(PWM signal) to the output(rotor angular velocity) of ESC. The equation of the fitted curve is shown below

$$\omega_{RPM}(s_{PWM}) = a_{RPM}s_{PWM} + b_{RPM}, s_{PWM} \in [0, 100] \tag{1}$$

whereω_{RPM}, s_{PWM}, a_{RPM}, and b_{RPM} are the motor angular velocity, PWM signal level in percentage, and parameters of the 1st order curve, respectively. The fitted nominal motor angular velocity is shown in Fig. 6 with the estimated value of $a_{RPM} = 5.5802$, and $b_{RPM} = -0.0055$.

Also, as it is widely known that the thrust and torque are proportional to the square of the motor angular velocity [4], the nominal thrust and torque relationship is estimated by fitting the experimental data with the 2nd order curve. The approximated equation of the nominal thrust and torque with curve fitting is shown below

$$T_N(\omega_{RPM}) \sim a_T\omega_{RPM}^2 + b_T\omega_{RPM} + c_T \tag{2}$$

$$\tau_N(\omega_{RPM}) \sim a_\tau\omega_{RPM}^2 + b_\tau\omega_{RPM} + c_\tau \tag{3}$$

where T_N and τ_N are the nominal thrust and torque, respectively, while a_T, b_T, c_T, a_τ, b_τ, and c_τ are the coefficient of the 2nd order curve on nominal thrust and torque. The fitted nominal thrust and torque is shown in Fig. 7 with the approximated coefficient values appearing in Table 3.

Table 3 Approximated coefficient of the function T_N and τ_N

Coefficient	a_T	b_T	c_T	a_τ	b_τ	c_τ
Value	1.0109e-5	–0.0041	2.1176	3.5271e-7	–2.278e-4	0.2502

Table 4 Approximated coefficient of the function r_T and r_τ

r_T	Coefficient	$p_{T,0}$	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	$p_{T,5}$	$p_{T,6}$	$p_{T,7}$	$p_{T,8}$	$p_{T,9}$
	Value	0.3837	–0.0260	0.0438	–0.0004	0.0009	–0.0007	2.13e-6	–4.2e-10	–5.0e-6	3.14e-6
r_τ	Coefficient	$p_{\tau,0}$	$p_{\tau,1}$	$p_{\tau,2}$	$p_{\tau,3}$	$p_{\tau,4}$	$p_{\tau,5}$	$p_{\tau,6}$	$p_{\tau,7}$	$p_{\tau,8}$	$p_{\tau,9}$
	Value	0.6044	–0.0112	0.0196	–0.0002	0.0005	–0.0002	9.11e-7	1.58e-7	–2.35e-6	–1.88e-7

Finally, from Eqs. (1)–(3), the nominal thrust and torque can be expressed as the function of the PWM signal levels, as shown in the equation below.

$$T_N(s_{PWM}) \sim a_T a_{RPM}^2 s_{PWM}^2 + a_{RPM}(2a_T b_{RPM} + b_T)s_{PWM} + (b_{RPM}^2 + b_T b_{RPM} + c_T) \tag{4}$$

$$\tau_N(s_{PWM}) \sim a_\tau a_{RPM}^2 s_{PWM}^2 + a_{RPM}(2a_\tau b_{RPM} + b_\tau)s_{PWM} + (b_{RPM}^2 + b_\tau b_{RPM} + c_\tau) \tag{5}$$

The function approximation step is divided from the PWM signal to the motor angular velocity, and from the motor angular velocity to the thrust with torque to have flexibility due to the ESC and motor change. The approximated equation in (1) is the unique function of the ESC while the equation in (2) and (3) are the unique functions of the motor. If the combination of the ESC and motor is changed, the corresponding Eqs. (4, 5) can be derived with the experimental data or the datasheet of the ESC and motor.

4.2 Loss of Actuator Effectiveness Estimation

For the loss of actuator effectiveness estimation, the performance degradation ratio of the coaxial rotor based on the experiment is calculated with the nominal thrust and torque values. The performance degradation ratio is calculated with the ratio between the nominal and experimental value of torque and thrust in each of the scenarios, $r_{exp,T}$, and $r_{exp,\tau}$ as follows:

$$r_{exp,T}\left(s_{PWM,L}, s_{PWM,U}\right) = T_{exp}(s_{PWM,L}, s_{PWM,U})/T_N(s_{PWM,L}) \tag{6}$$

$$r_{exp,\tau}\left(s_{PWM,L}, s_{PWM,U}\right) = \tau_{exp}(s_{PWM,L}, s_{PWM,U})/\tau_N(s_{PWM,L}) \tag{7}$$

where T_{exp}, τ_{exp}, $s_{PWM,U}$ and $s_{PWM,L}$ are the experiment-based thrust and torque values of the coaxial rotor shown in Fig. 5, and the PWM signal level percentage of the upper and lower rotors with the range of $s_{PWM,L}, s_{PWM,U} \in [0, 100]$, respectively.

As $r_{exp,T}$ and $r_{exp,\tau}$ are the sparsely distributed points based on the experimental data, the loss of actuator effectiveness is approximated as the 3rd order curved surface, which is the function of $s_{PWM,U}$ and $s_{PWM,L}$ in the range of $s_{PWM,L}, s_{PWM,U} \in [0, 100]$. The equation of the approximated loss of actuator effectiveness function is shown in Eq. (8) as follows:

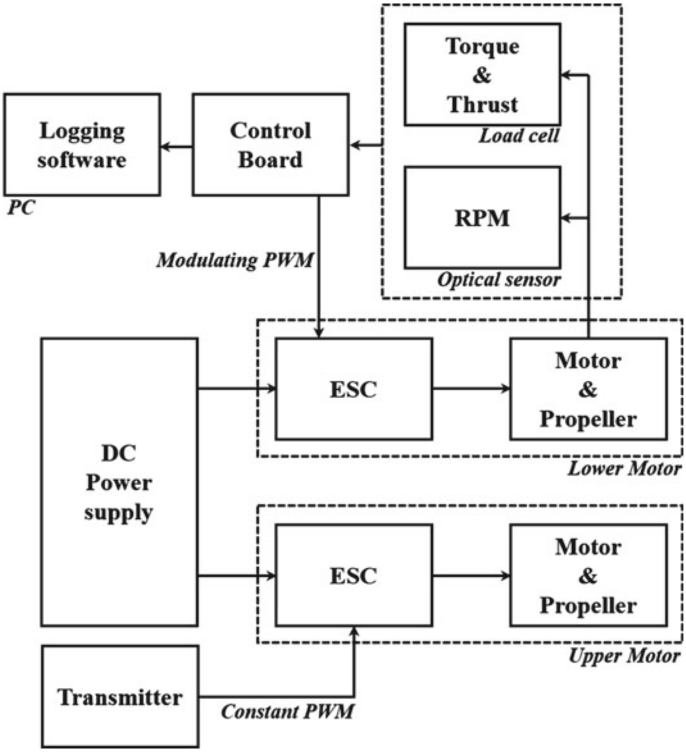

Fig. 1 Block diagram for the test bench

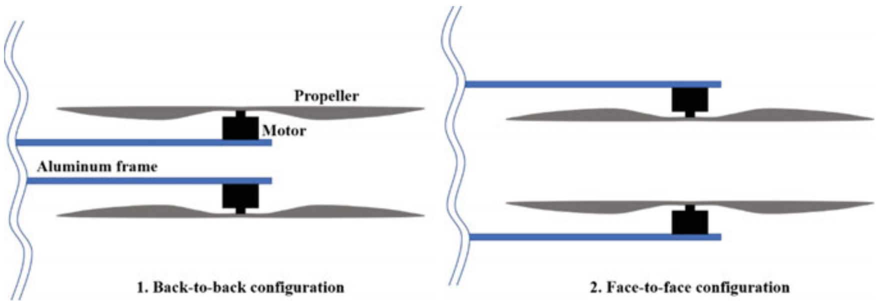

Fig. 2 Difference between back-to-back and face-to-face configuration for the coaxial rotor

$$
\begin{aligned}
r_T\left(s_{PWM,L}, s_{PWM,U}\right) = {} & p_{T,0} + p_{T,1}s_{PWM,L} + p_{T,2}s_{PWM,U} + p_{T,3}s_{PWM,L}^2 \\
& + p_{T,4}s_{PWM,L}s_{PWM,U} + p_{T,5}s_{PWM,U}^2 + p_{T,6}s_{PWM,L}^3 \\
& + p_{T,7}s_{PWM,L}^2 s_{PWM,U} + p_{T,8}s_{PWM,L}s_{PWM,U}^2 + p_{T,9}s_{PWM,U}^3
\end{aligned} \tag{8}
$$

Fig. 3 Assembled test bench

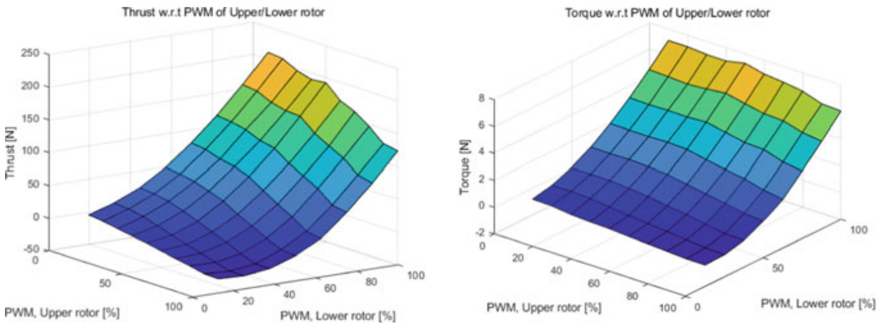

Fig. 4 Thrust and torque of the coaxial rotor with respect to the given PWM signal level percentage

$$\begin{aligned} r_\tau\left(s_{PWM,L}, s_{PWM,U}\right) = {} & p_{\tau,0} + p_{\tau,1} s_{PWM,L} + p_{\tau,2} s_{PWM,U} + p_{\tau,3} s_{PWM,L}^2 \\ & + p_{\tau,4} s_{PWM,L} s_{PWM,U} + p_{\tau,5} s_{PWM,U}^2 + p_{\tau,6} s_{PWM,L}^3 \\ & + p_{\tau,7} s_{PWM,L}^2 s_{PWM,U} + p_{\tau,8} s_{PWM,L} s_{PWM,U}^2 + p_{\tau,9} s_{PWM,U}^3 \end{aligned} \tag{9}$$

with the coefficient of the 3rd order surface $p_{T,k}$ and $p_{\tau,k}$ in $k = 0, 1, \ldots, 9$. The actual value of $p_{T,k}$ and $p_{\tau,k}$ are shown in the table below.

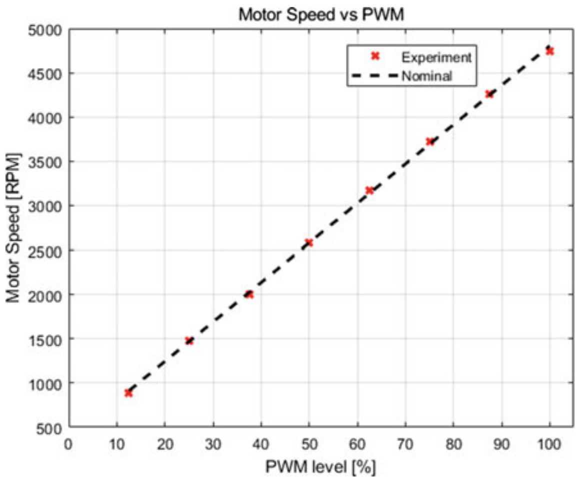

Fig. 5 Thrust and torque of the coaxial rotor with respect to the given PWM signal level percentage

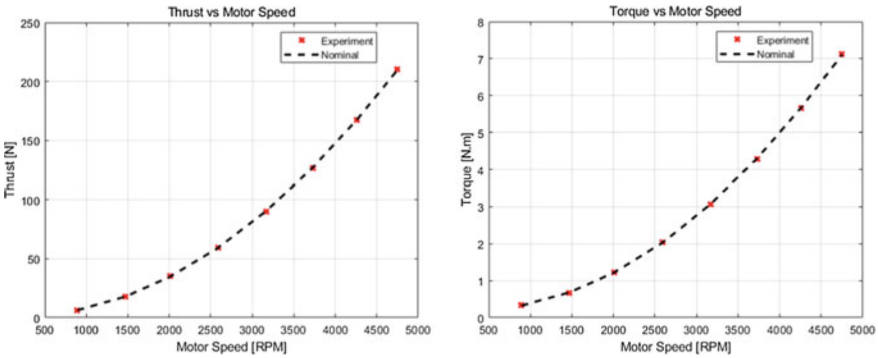

Fig. 6 Nominal thrust and torque estimation with single rotor experimental data

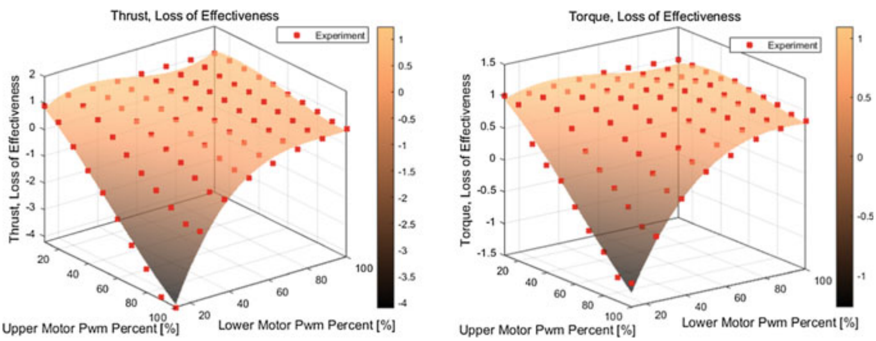

Fig. 7 Estimated loss of actuator effectiveness of thrust and torque with respect to the given PWM signal level percentage

Also, the function of r_T and r_τ are visualized below, where the approximated function is denoted as the surface and the ratio of the nominal value and experimental data of the thrust and torque are marked with red points.

Most fundamentally, we could see a performance diminution on both trust and torque for the coaxial rotor compared to the single rotor. Also, with the derived loss of actuator effectiveness function in thrust and torque, a decreasing tendency exists on both thrust and torque as the upper motor PWM is increased with the same lower motor PWL level. This indicates the wake flow of the upper rotor affects the performance degradation. Moreover, it is verified that performance decreases dramatically as the thrust and torque of the lower motor decrease below the maximum.

5 Conclusion

In this study, an experiment was conducted to evaluate the approximated performance reduction of the thrust and torque in a coaxial rotor with a loss of effectiveness function for the given upper and lower PWM level percentage combination. The experiment was designed with two parts: generating the thrust and torque with an ESC, motor, and propeller, and measuring the thrust, torque, and motor angular velocity. A coaxial rotor configured motor was implemented by mounting rotors on the aluminum extrusions frame with a face-to-face configuration. Experimental data of the thrust and torque was acquired for both the single rotor and lower rotor in the coaxial rotor. The nominal performance function for thrust and torque is approximated with the single rotor configuration and is used for the loss of actuator effectiveness function estimation with the 3rd order curve. With the approximated loss of actuator effectiveness, our method estimate the performance reduction on both the thrust and torque on the coaxial configured rotor with a specific decreasing tendency with respect to the PWM level of the upper and lower motors.

By analyzing the loss of actuator effectiveness results, it is shown that the thrust is reduced with some specific relationship instead of simply doubling the thrust of a single rotor. In addition, it is also possible to conclude that there can be a torque imbalance, even if the same PWM level on the upper and lower rotor is used. This may cause a coupling effect on a multi-rotor with coaxial motors while changing its attitude if there is no consideration of the performance difference.

For the practical applications of the proposed methodology, it is possible to have the estimated loss of actuator effectiveness functions with the different ESC and motor set as mentioned in Sect. 4.1. Moreover, it is possible to model more accurate coaxial multi-rotor dynamics considering the thrust and torque performance reduction. This can be implemented to simulate a more accurate model or to design a model-based controller of coaxial multi-rotors.

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