

Experimental Identification and Characterization of Multirotor UAV Propulsion

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Abstract. In this paper, an experimental procedure for the identification and characterization of multirotor Unmanned Aerial Vehicle (UAV) propulsion is presented. Propulsion configuration needs to be defined precisely in order to achieve required flight performance. Based on the accurate dynamic model and empirical measurements of multirotor propulsion physical parameters, it is possible to design diverse configurations with different characteristics for various purposes. As a case study, we investigated design considerations for a micro indoor multirotor which is suitable for control algorithm implementation in structured environment. It consists of open source autopilot, sensors for indoor flight, “take off the shelf” propulsion components and frame. The series of experiments were conducted to show the process of parameters identification and the procedure for analysis and propulsion characterization. Additionally, we explore battery performance in terms of mass and specific energy. Experimental results show identified and estimated propulsion parameters through which blade element theory is verified.

1. Introduction

The ability to act in three-dimensional environment leads to new research challenges in the field of design, modelling and control of UAV [1]. Development of new technologies has enabled rapid progress and a large number of interesting applications. UAVs can be potentially used for accident site monitoring or search and rescue missions [2, 3]. There are several categories of UAVs which are in various stages of research, development and utilization (rotary-wing, fixed wing, flapping-wing, blimp, hybrid UAV). Because of their unique ability to perform vertical take-off and landing, stationary flight and flight at moderate speed, multirotor UAVs will be explored. They represent fixed pitch rotary-wing aircrafts. There are a variety of designs and sizes ranging from large aircraft to the micro air vehicles (MAV). From a mechanical point of view, multirotor has six degrees of freedom (6 DOF). The only moving parts are propellers with constant pitch connected to the rotor axis. It is assumed that the multirotor frame is symmetrical and rigid, thus rotors angular velocities are the only variables that have a direct impact on the multirotor dynamics. [4].

Design and development of multirotors is constrained by the size, weight and power consumption of the propulsion components [5]. Multirotor dynamics depends on the aircraft design and propulsion



aerodynamic forces. Batteries, electronic speed controllers (ESC), brushless DC (BLDC) motors and propellers have to be chosen as precisely in order to achieve optimal flight performance. In papers [6,7], the experimental setup for identification of propulsion physical parameters is described. Series of experiments was conducted in [8, 9] to evaluate the efficiency of coaxial propulsion configuration. The paper [10] investigate the effect of interactions between the rotor flow and thrust in order to achieve increase in thrust for a limited body size. Furthermore, authors in [11] examine the influence of propulsion configuration and arrangement on a system efficiency in hover mode. Since the batteries represent a significant constraint in the multirotor design, papers [12,13] investigated the problems of endurance and length of the flight.

In this paper, experimental test bench and procedure for propulsion characterization of the multirotor UAV are presented. Experimental measurements were conducted on components whose selection is based on the proposed case study. Experimental identification, analysis and propulsion characterization enable successful design of a different multirotor configurations. To develop faithful model, it is important to measure parameters which are associated with multirotor dynamics and parameters, important from the standpoint of energy consumption. Test bench design has the ability to test a large range of propulsions (from 2" to 20") with different configurations.

The paper is organized as follows. Section 2 describe design considerations for multirotor MAV. Section 3 presents experimental setup. In section 4, experimental results are shown. Conclusion is discussed in section 5.

2. Design Considerations for MAV

Multirotor design can be classified into two main categories: flat and non-flat configurations. From the control point of view, multirotor is highly nonlinear, multivariable and inherently unstable 6 DOF rigid body.

The conventional flat designs share properties of underactuated and strongly coupled systems. Flat designs are divided with respect to the propulsion configuration. The most common designs incorporate a single propulsion units (quadrotor, hexarotor and octarotor) or coaxial propulsion units (Y6 and X8 rotor) as shown in figure 1. There are also designs with overlapping propulsion arrangements [10].

Non-flat designs with tilted rotors have the ability to overcome the inherent underactuated property of flat designs. In this case it is necessary that multirotor consists of six or more propulsion units. Fully actuated multirotors can decouple position from orientation which has significant influence on the multirotor control design.

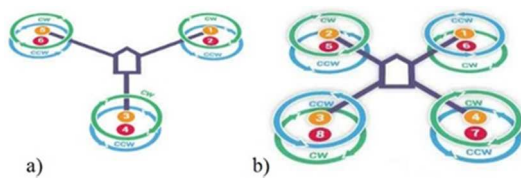


Figure 1. Coaxial flat configurations: a) Y6 rotor, b) X8 rotor (PixhawkTM motor layout).

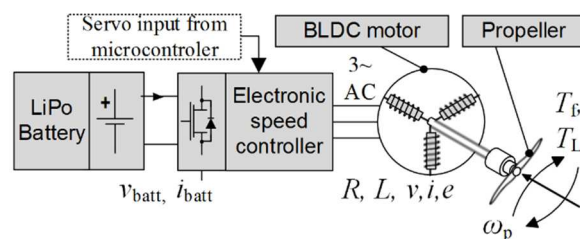


Figure 2. Model of the multirotor propulsion unit.

2.1. Propulsion components selection

For successful multirotor design, it is necessary to identify the propulsion physical parameters. Take off the shelf components mostly have insufficient or inaccurate data therefore it is necessary to conduct experimental measurements.

Before the measurement procedure, it is necessary to select propulsion components for which the identification and characterization will be conducted (see figure 2). In this research components are selected based on the case study.

2.1.1. Propeller. During rotation, the propeller produces aerodynamic forces that directly affect the multicopter dynamics. They depend on the angular velocity and the propeller geometrical shape. Thrust force of i -th propulsion is equal to:

$$f_i = k_f \omega_i^2 \quad (1)$$

where ω_i is angular speed of the i -th rotor, and k_f is the thrust force factor which can be calculated as:

$$k_f = C_T \rho A r^2 \quad (2)$$

where C_T is thrust coefficient, ρ is air density, A is the area of propeller disk and r is the propeller radius. Drag moment of i -th propulsion is equal to:

$$\tau_i = k_\tau \omega_i^2 \quad (3)$$

where k_τ is the drag torque factor:

$$k_\tau = C_P \rho A r^3 \quad (4)$$

where C_P is the power coefficient.

This paper proposes the procedure for propeller testing, with various geometric characteristics (given in Table 1), on the whole range of possible rotor angular velocities. Changing the propeller geometric characteristics result in a change of treated air quantity per rotation. The higher quantity of air has a higher motion resistance and thus increases a drag moment, which requires an increase in motor torque. As a result, motor current and power consumption increases. Therefore, selection of the propeller necessarily affects the choice of motors and batteries. The experiment will yield dependence of physical parameters on propeller geometrical features.

Table 1. Considered geometric characteristics of propellers.

Diameter	Pitch	Blade Number	Bull Nose	Label
3''	3''	2	Yes	3030_2_BN
	3''	3	No	3030_3
	3''	4	Yes	3040_4_BN
	4''	3	No	3040_3
4''	4''	2	No	4040_2
	4.5''	2	No	4045_2
	4.5''	3	No	4045_3
	4.5''	2	Yes	4045_2_BN
	4.5''	3	Yes	4045_3_BN
	4''	4	Yes	4040_4_BN
5''	3''	2	No	5030_2
	3''	3	No	5030_3
	4''	2	No	5040_2
	4''	3	No	5040_3
	4''	4	No	5040_4
	4''	6	No	5040_6
	4.6''	2	Yes	5046_2_BN
	5''	3	Yes	5050_3_BN
6''	4''	2	No	6040_2
	4''	3	No	6040_3
	4.5''	2	Yes	6045_2_BN
	5''	2	Yes	6050_2_BN

2.1.2. Brushless DC (BLDC) motor. BLDC motor is a synchronous electric motor with electronic commutation system instead of mechanical commutation (brushes in DC motor). Additionally, the electromagnets (armature) remains static while permanent magnets rotate. This type of design allows greater efficiency and less maintenance with respect to brushed (DC) motors. The research evaluates three different types of motors with three different manufacturers for each type.

Table 2. Considered BLDC motors.

Motor	K_v	Propeller diameter	Mass
1306	4000	3-4''	13 g
1806	2700	4-5''	23 g
2205	2300	5-6''	30 g

Motor number specifies the physical dimensions of the rotor. K_v is voltage constant depends on motor's design, and relates voltage, induced emf voltage and rotor angular velocity.

2.1.3. Electronic speed controller (ESC). ESC is integrated inverter/switching power supply which provide three phase bi-directional square voltage to drive the motor. Commutation depends on the rotor position which can be determined by sensed or sensorless methods. Motor speed is affected duty-cycle variation (chopping of supply voltage). With higher PWM frequency, phase voltage increases and as consequence angular velocity of motor increases.

2.1.4. Lithium-polymer (LiPo) battery. Multirotor is high energy consumption UAV. When choosing a battery, it is necessary to consider to several parameters, including relationship between mass and capacity. The main characteristics of the lithium-polymer (LiPo) battery is a very high energy density i.e. the ratio of stored energy per mass. The nominal voltage of individual LiPo battery cell is 3.7V. Fully charged cell has a voltage of 4.2V. Emptying the cells below 3V is not recommended due to the risk of damage and inflammation. Therefore, the possibility of monitoring the battery voltage during the multirotor autonomous flight is extremely important [14]. Research will consider 2S, 3S and 4S battery with high discharge rate as presented in figure 3.

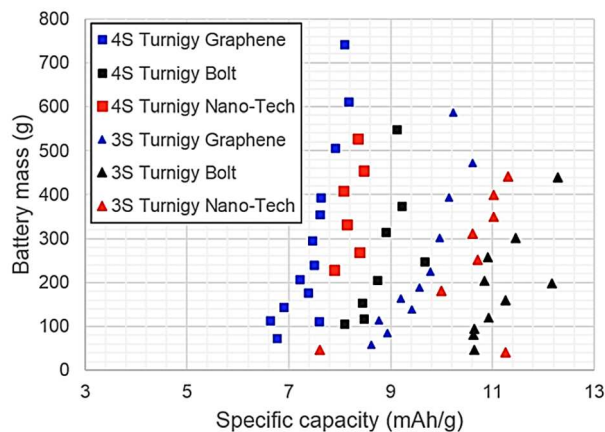


Figure 3. Plot for rechargeable LiPo batteries with high discharge rates [15].

2.2. Multirotor propulsion configuration

The experimental setup allows testing of three various propulsion configurations that could be used for multirotor design. Configurations are defined with rotors arrangement. Single, coaxial and overlapping rotor arrangement can be evaluated.

For single configuration, influence of propeller geometric characteristics on aerodynamic forces will be investigated. For the propeller with the same diameter, influence of various pitch, blade number and so called bull nose design will be examined. Experiment will also compare three BLDC motors of the

same geometry and K_r . Measurements will be conducted for 2, 3 and 4 cell batteries. As shown in figure 4, single configuration can be puller or pusher version.

Therefore, analysis of single propulsion yields valuable information regarding influence of specific components combination on overall performance. More efficient combinations of motor and propeller where tested in coaxial configuration (see in figure 5) where rotor flow interaction occurs and have a significant influence to coaxial propulsion efficiency. Therefore, combination of pusher and puller propeller with the same diameter, and various geometric features will be tested.

After testing the coaxial propulsion and propulsion efficiency analysis, so-called overlapping configuration (see in figure 6) will be examined and influence of the overlap area on aerodynamic forces and efficiency where investigated.



Figure 4. Single rotor arrangement: a) puller, b) pusher.

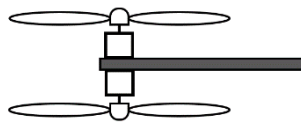


Figure 5. Coaxial rotor arrangement.

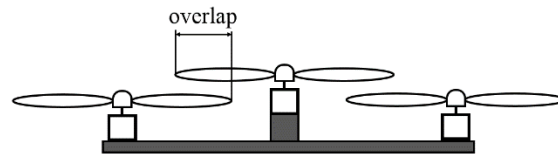


Figure 6. Overlapping rotor arrangement.

3. Experimental setup

The experimental setup for the identification of propulsion physical parameters (see in figure 7) consist from the stand, DC power supply control unit and measurement equipment (as shown in figure 8) which enables data acquisition important for subsequent processing and analysis. Control unit enables simple programming and provides required control signals for identification and further analysis.

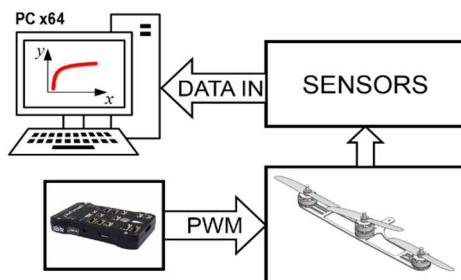


Figure 7. Experimental setup scheme.

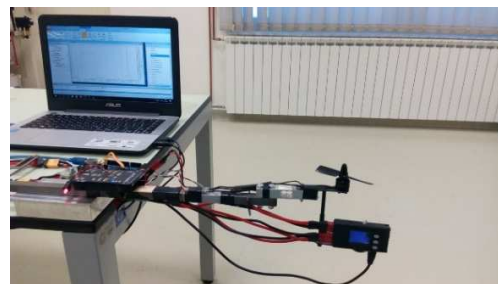


Figure 8. Experimental test bench.

For each propulsion combination, four measurements will be conducted.

3.1. Sensors

To identify the propulsion physical parameters, two sensors where used. Aerodynamic forces where measured with load cell type sensor, while multifunctional logging meter is used to measure angular velocity and power consumption (see in figure 9).

3.1.1. Logging meter. One of the requirements to the design of the experimental setup is simple acquisition and processing of sensor data. Among other things, compact multifunctional and logging meter "PowerLog 6S" is selected because of its simple integration with PC, support for various logging software, 32 bit ARM processor and 12 bit A/D convertor. Also, it provides non-contact optical sensing

for propeller revolutions per minute (RPM) measurement with settable blade number and measurement of motor voltage constant [16].

Table 3. PowerLog 6S specifications [16].

Parameter	Value
Input voltage range	4.5 – 60 VDC
Current measurement range	-40 A – +40 A
Cell voltage range	0.05 – 28 VDC
Pulse measurement range	10 μ s – 999999 μ s
Pulse width output range	0–20 ms (0.5 μ s step)
RPM measurement range	0–99999 RPM
Voltage resolution / accuracy	0.001V / 0.5%
Current resolution / accuracy	0.01A / 5%
Current loading of test	12 mA
Sample logging time interval	0.25 – 3600 s

3.1.2. Force sensor. Load cell sensor is composed of a strain gauge and an amplifier HX 711 as shown in figure 10. HX711 is a precision 24-bit analog-to-digital converter (ADC), designed for weigh scales and industrial control applications to interface directly with a bridge sensor.

The force sensor where calibrated using precision digital scale (Kern PCB 1000-2) in a range for scheduled measurements. Appropriate control software for measuring and calibration where developed and implemented in Atmel microcontroller.

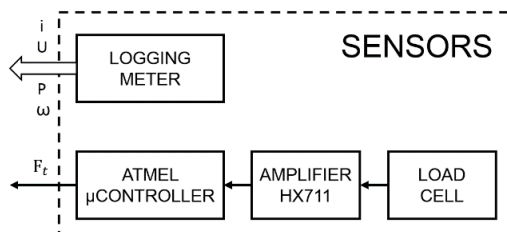


Figure 9. Sensors scheme.

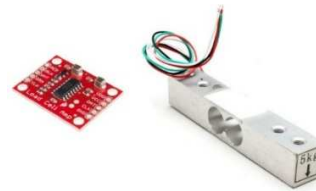


Figure 10. Load cell with amplifier HX711.

3.2. Data Acquisition

Acquisition and fusion of signals (signal from load cell and signals from logging meter) where captured by LogView Studio software, and exported in appropriate format for analysis in MATLAB.

Signal from HX711 analog-to-digital converter where processed in Atmel ATxmega microcontroller. Data is transmitted by USB connection to virtual serial port, in open zero sensor format, to capture data in LogView. Example of a raw vector obtained from the force sensor is shown in figure 11.

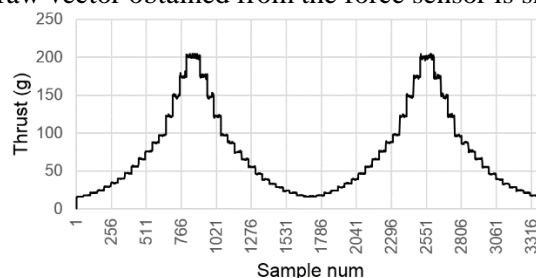


Figure 11. Measured thrust raw vector.

3.3. Data Analysis

The data obtained by the sensors were analysed in MATLAB software. Input data represent vectors which are then processed and from which the average values are obtained. The end result are dependences of aerodynamic forces, the angular velocity of the rotor and power consumption in relation to a control signal given from the control unit. From these data, aerodynamic coefficients and propulsion efficiency were obtained which can be used for further design optimization and proper components selection. The results of experimental measurements are presented in section 4.

4. Analysis and Characterization

In order to validate experimental procedure, measurement results for the single configuration propulsion are presented. For this purpose, propeller with 3" diameter and various geometric characteristics in combination with 1306 BLDC motor and 3S battery were used.

4.1. Identified physical parameters

The identified parameters are presented as a function of the signal from the control unit. Parameter values are obtained as the average values of four measurements (see in figures 12-14).

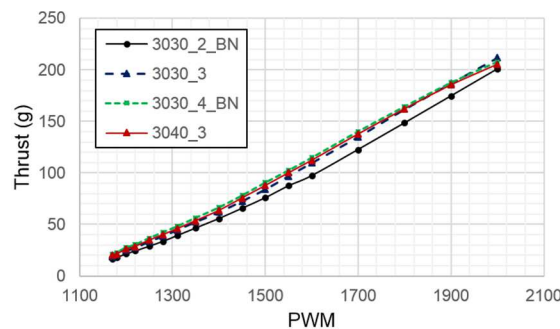


Figure 12. Thrust as a function of the control signal.

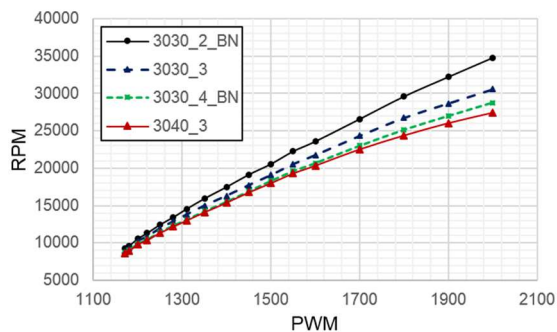


Figure 13. RPM as a function of the control signal.

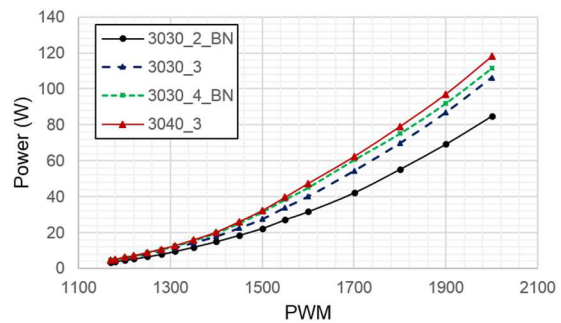


Figure 14. Power consumption as a function of the control signal.

4.2. Aerodynamic force coefficients

For dynamics simulation and control design it is necessary to know thrust and drag coefficients. Using equation (1) and identified thrust and RPM, it is possible to estimate thrust coefficient (see in figure 15 and figure 16). The same procedure applies to the drag coefficient estimation with certain adjustments of experimental setup hardware.

4.3. Propulsion efficiency

The comparison of thrust to consumed power of propulsion unit for different propellers is shown in figure 17. Performance of various propulsion configurations were evaluated based on the efficiency factor which shows how much thrust can be achieved with 1W of electric power (see in figure 18).

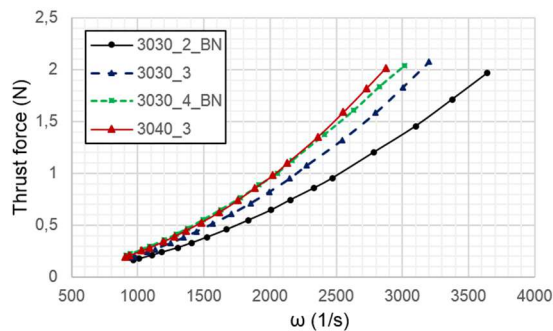


Figure 15. Thrust force as a function of the angular velocity.

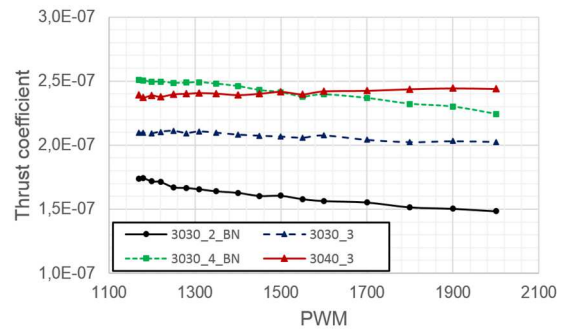


Figure 16. Thrust coefficient.

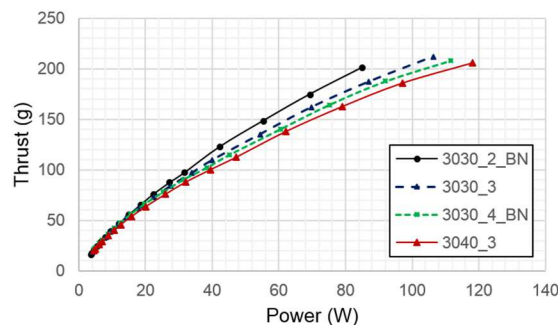


Figure 17. Thrust as a function of the consumed power.

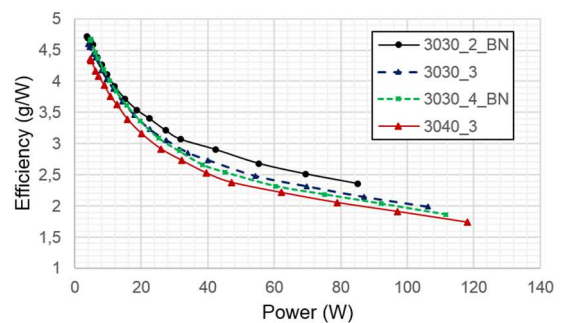


Figure 18. Propulsion efficiency.

5. Conclusion

In this paper, the experimental setup and procedures for identification and analysis of physical parameters for multirotor UAV propulsion is presented. In addition to multirotor design, the greatest impact on the system dynamics and performance have the configuration of propulsion. Therefore, for a successful control design and optimized aircraft design it is necessary to know all the influential physical characteristics. Experimental setup and procedure have been validated in the case of single propulsion unit for combination of 3S battery, 20A ESC, 1306 BLDC motor and propellers with different geometrical characteristics.

Further work will include an analysis of the various propulsion configurations for the proposed components in order to optimize multirotor design and estimation of aerodynamic coefficients and factors.

References

- [1] Kumar V and Michael N 2012 Opportunities and challenges with autonomus micro aerial vehicles *Int. J. Rob. Res.* **31**(11) 1279–91
- [2] Mizutani S, Okada Y, Salaan C J, Ishii T, Ohno K and Tadokoro S 2015 Proposal and experimental validation of a design strategy for a UAV with a passive rotating spherical shell, *Int. Conf. on Intelligent Robots and Systems (Hamburg)* p 1271–8
- [3] Briod A, Kornatowski P, Zufferey J C and Floreano D 2014 A collision-resilient flying robot *J. Field Rob.* **31**(4) 496–509
- [4] Bouabdallah S, Murrieri P and Siegwart R 2004 Design and control of an indoor micro quadrotor, *Proc. of the Int. Conf. on Robotics and Automation (New Orleans)*, vol 5 p 4393–8

- [5] Mulgaonkar Y, Whitzer M, Morgan B, Kroninger C M, Harrington A M, Kumar V 2014 *Micro- and Nanotechnology Sensors, Systems, and Applications VI*, ed George T, Saif Islam M, Dutta A K, *Proc. of SPIE*, vol 9083
- [6] Cheron C, Dennis A, Semerjyan V and Chen Y 2010 A multifunctional HIL testbed for multirotor VTOL UAV actuator, *Int. Conf. on Mechatronics and Embedded Systems and Applications*, p 44-48
- [7] Prior S D and Bell J C 2011 Empirical measurements of small unmanned aerial vehicle co-axial rotor systems *J. Sci. Innov.* **1**(1) 1–18
- [8] Simoes S M 2015 Optimizing a coaxial propulsion system to a quadcopter, <https://fenix.tecnico.ulisboa.pt/downloadFile/563345090412782/Resumo.pdf>
- [9] Bondrya A, Gardecki S, Gasior P and Giernacki W 2016 Performance of coaxial propulsion in design of multi-rotor UAVs, *Challenges in automation, robotics and measurement techniques (Advances in Intelligent Systems and Computing)*, ed Szewczyk R et al. (Springer International Publishing Switzerland) vol 440 p 523–31
- [10] Otsuka H and Nagatani K 2016 Thrust loss saving design of overlapping rotor arrangement on small multirotor unmanned aerial vehicles, *Int. Conf. on Robotics and Automation*, p 3242–8
- [11] Theys B, Dimitriadis G, Hendrick P and De Schutter J 2016 Influence of propeller configuration on propulsion system efficiency of multi-rotor unmanned aerial vehicles, *Int. Conf. on Unmanned Aircraft Systems (Arlington)*, p 195–201
- [12] Gatti M, Giulietti F and Turci M 2015 Maximum endurance for battery-powdered rotary-wing aircraft *Aero. Sci. Tech.* **45** 174–9
- [13] Abdilla A, Richards A and Burrow S 2015 Power and endurance modelling of battery-powdered rotorcraft, *Int. Conf. on Intelligent Robots and Systems (Hamburg)*, p 675–80
- [14] Brezak H 2016 Robust control of unmanned aerial vehicle with four rotors, Department of Robotics and Production System Automation, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb
- [15] Hobbyking Li-Poly (All brands) 2016 https://hobbyking.com/en_us/batteries/lipoly-all-brands.html
- [16] PowerLog 6s Multifunctional Monitor&Logger User's Manual 2016 <https://www.progressiverc.com/media/PowerLog%206S%20Manual.pdf>