Performance of Coaxial Propulsion in Design of Multi-rotor UAVs

Chapter *in* Advances in Intelligent Systems and Computing · March 2016

DOI: 10.1007/978-3-319-29357-8_46

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Performance of coaxial propulsion in design of multi-rotor UAVs

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Abstract. There are many different types of propulsion systems developed for multi rotor *UAV*s. One of the most interesting designs is so called X8 quadrocopter, which extends original quadrotor concept to 8 motors, arranged in 4 coaxial pairs. The advantage of this solution is increased lift of platform, with reasonable volume of platform kept. However, this design suffers from the loss of efficiency due to coaxial propellers' configuration, because the lower propeller loses thrust working in prop wash of upper propeller. This paper presents the experimental verification of performance of such propulsion system in practical terms of designing multi rotor platforms, comparing to design with 8 isolated propulsion units. In addition, its advantages versus classic quadrotor concept is shown. The series of experiments with different motors and sizes of propellers were conducted to estimate efficiency of coaxial propulsion regarding useful thrust generated by each configuration.

Keywords: coaxial propellers, x8 quadrotor, multirotor, octoquad

1 Introduction

The multirotor *UAV*s are widely used in many commercial and scientific applications. Depending from the purpose of given solution, different drone designs differ in size, lifting capabilities and maximum flight time [1][2][3]. One of the key issues in designing a micro multi-rotor vehicle is an adequate choice of propulsion system. The original quadrotor concept, introduced in 2000s [4], evolved into many various solutions. Nowadays, the tri-, quad-, hexa- and octocopters are available on the market, as well as many custom solutions with different propellers' configuration [5][6][7]. In our research concerning development of drones, we focus on few multirotor designs, with so called x8 quadrotor or octoquad among them. This configuration of multirotor extends original quadcopter concept by increasing the total thrust output of platform thanks to additional set of motors.

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On each side, there are two identical rotors installed, one above another. The propellers rotate in opposite directions, which equalizes the momentum of platform. The upper propeller works as a tractor, while the lower unit is a pusher. As a result, the total thrust of propulsion unit is increased with similar physical volume in comparison to single propeller [9].

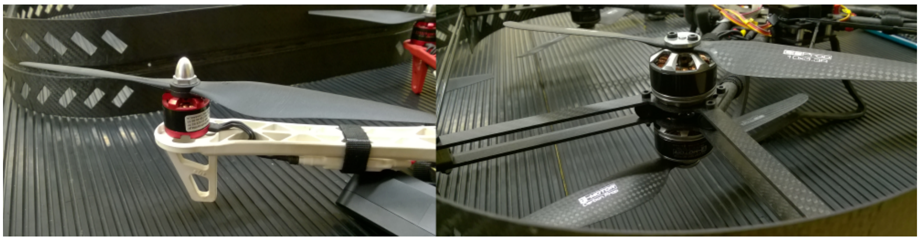

Fig. 1: Single propeller in *DJI Flamewheel 450* quadrotor and coaxial design in *Falcon V5* [12]

However, considering that a lower propeller operates in a prop wash of upper unit, the total thrust performance of coaxial propulsion is lower comparing to two separated propellers. In this paper we present experimental verification of this performance in practical terms of multirotor design with different propellers' sizes and motors intended for various classes and sizes of multi rotor aerial platforms. A large data set of experimental results was obtained during the tests on a motor test bench. A series of over 60 tests was conducted where the thrust, rotational speed and motor's power were measured in relation to control signal. Later, the data was processed to show the efficiency loss and provide practical information about the performance of coaxial propulsion. The article is arranged in following order: related work and multi rotor designs are described in second chapter. Third chapter is a description of experimental setup on which our data was obtained. The series of experiments is shown in details as well. Next chapter presents the results and analysis of experimental data, when last two chapters contain evaluation of our octoquad designs and present plans for future research.

2 Related Work

There are various designs of x8 quadcopter available on the market. These designs are usually focused on very high lifting capability. From some point, the logical way to keep reasonable size of platform and increase the total thrust output is to apply the x8 configuration. One of the most popular middle-sized octoquads is DraganFlyer X8 platform, equipped with coaxial pairs of 16 and 15 inch propellers. The platform weighs about 1.7kg with payload capability of 0.8kg and maximum flight time of 20 min without payload [10]. In work of Sharft *et. al.*, the ground effect for this specific *UAV* model was analyzed. In addition, the average loss of total thrust outcome of coaxial propulsion unit in comparison to design with 8 isolated propellers was estimated at about 14 percent, with equal rotational speeds of both motors [8]. Another example of octoquad configuration in commercial platform is Hammer XB8 *UAV*, with excessive lifting capability of 15kg in reasonable size of about 2 meters in diameter. C. Simoes in his paper [9] focused on performance of coaxial propulsion in *UAV*s, describing efficiency of such propulsion design according to Glauert's theory with varying motors' speed or spacing and propellers' diameter and pitch. However, the analysis was made only for 12 to 14 inch propellers and one motor model, where current designs utilize wider range of sizes with different rotational speeds. In this paper, we present wider analysis of performance of coaxial propulsion in multi rotor *UAV*s, focusing on optimal choice of propulsion for practical applications.

3 Experimental setup

In order to collect data required for analysis of propulsion units, the custom test bench was constructed, based on load cell for thrust measurements. The instrument described in [11] was modified and adapted to new propulsion units presented in following sections. The size of test bench was extended to fit bigger propellers and the laser tachometer, allowing measurement of motor's rotational speed, was introduced.

3.1 Test bench

Constructed test bench is based on *L*-shaped steel frame with pivot in the connection point of both arms. The propulsion unit is mounted on top of the frame, while the load cell is located on opposite side of *L*-shape. With rotor producing thrust, the steel frame rotates and applies pressure on load cell. The Control Board module measures load cell's voltage using 12-bit ADC converter and handles the calibration process. Thrust measurement can be calibrated using remote PC software using set of precise weights. The measurement system is equipped with safety circuit based on high-power *MOSFET* transistors allowing to cut off power in case of emergency. Voltage and current of propulsion system are measured using multimeters. External laser tachometer with corresponding reflective stickers on motors is used to measure rotational speed. The concept and overview on test bench is shown in Fig. 2.

3.2 Analyzed propulsion units

Three different propulsion setups were tested, varying at size of propellers and motor models. Distance between propellers' disks in coaxial configuration was constant for each propulsion unit type. Each tested setup contains single or dual set of identical *BLDC* motors, propellers and *ESCs (Electronic Speed Controllers)*.

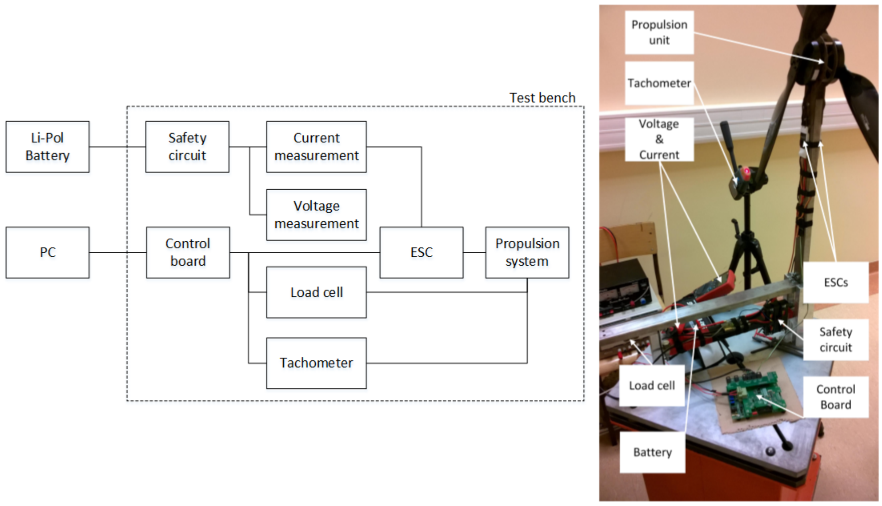

Fig. 2: Test bench block diagram and actual view

First propulsion setup
The first configuration of analyzed propulsion unit was based on *MN3110-15* brushless electric motor with a propeller with 10 inches of diameter and 3.3 inches of pitch. Single unit provides about 1.03kg of thrust with nominal rotational speed of 11544 rpm when powered with 14.8V lithium-polymer battery at maximum continuous power of 481W [1]. This setup, considering propeller's size and motor power, is quite common in most small, market-available quadrotors.

Second propulsion setup
Second configuration includes *MN4014* BLDC motor and 16x5.4 propeller. This setup is focused on maximizing thrust while maintaining small volume of platform. The solution is similar to the one applied in DraganFlyer X8 platform. This unit produces up to 3kg of thrust with maximum power consumption of 900W [2].

Third propulsion setup
Last propulsion unit's configuration utilizes energy-efficient *U8-16 Pro* BLDC motor with 26 inch propeller. This solution, with much lower nominal rotational speed of about 2500 rpm and much bigger propeller's span, provides up to 2kg of thrust with maximum power of 300W.

3.3 Experiment assumptions

In overall, 6 series of experiments were performed, for three different propulsion unit setups. For every setup, the single and coaxial configuration were analyzed. To maintain high data reliability, ten identical sequences were performed in

[1] `http://www.rctigermotor.com/html/2013/Navigator_0910/35.html`
[2] `http://www.rctigermotor.com/html/2013/Navigator_0910/40.html`

Fig. 3: Comparison of tested propulsion units:
(1) - *MN3110* + 10" prop., (2) - *MN4014* + 16" prop., (3) - *U8 Pro* + 26" prop.

each phase and the results were averaged. Each sequence was conducted with constant supply voltage provided for both motor and measuring equipment. The calibration process was performed before each sequence and the data was stored in PC connected via USB with Control Board. Afterwards, all gathered data was post-processed and analyzed in *MATLAB R2014a* software. Obtained results are shown in the next section.

4 Experimental results

One of the basic experimental assumptions was to maintain equal rotational speed of both motors in coaxial configuration, the same as in single propeller configuration. The Fig. 4 shows the record of rotational speeds for three different classes of motors and propellers analyzed during the experiment, with different range of effective operational speeds. The speeds of propellers does not differ more than 3%, which rules out the factor of difference in rotational speed affecting performance of coaxial propulsion.

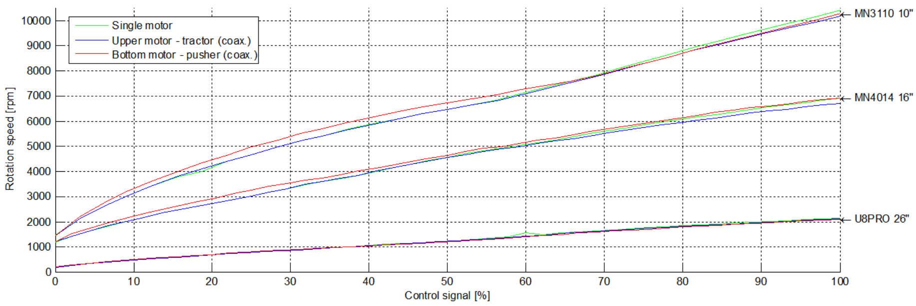

Fig. 4: Rotational speeds of propulsion units analyzed during experiment

In order to show the performance of coaxial propulsion, the useful thrust in coaxial and single configuration was compared. By useful thrust, we understand the measured thrust generated by propellers minus the weight of complete propulsion unit. The comparison of useful thrust to power of propulsion unit is shown on Fig. 5. We conclude that pair of motors in coaxial arrangement produce less thrust comparing to single motor when operating at the same total power of propulsion unit. However, the loss in efficiency varies depending on propeller's size, but does not change significantly with increasing rotational speeds of propellers.

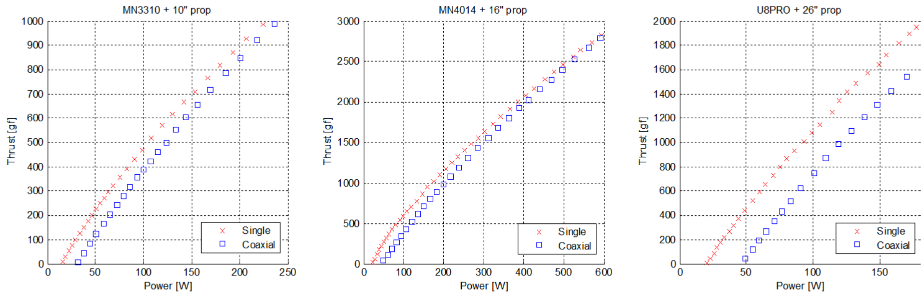

Fig. 5: Thrust produced by different propulsion units in single and coaxial configurations

In order to estimate performance of coaxial design in practical application of multirotor propulsion system we calculated the efficiency of tested configurations. The efficiency factor, given in grams of force per watts, shows how much thrust can be achieved with 1 watt of electric power. The results are given on Fig. 6.

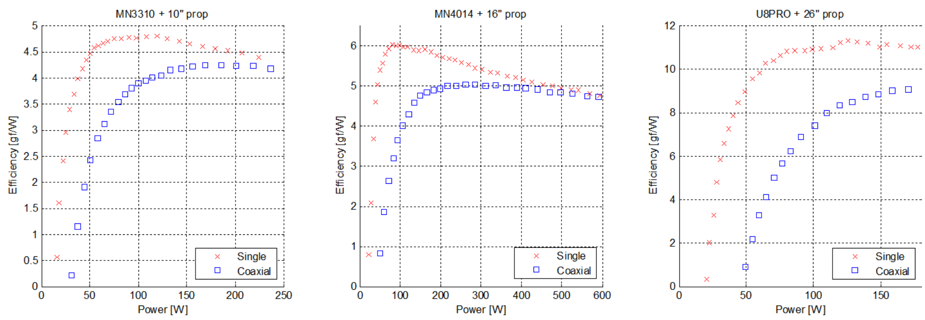

Fig. 6: Efficiency in single and coaxial setup

First of all, we conclude that bigger propellers provide significant gain in efficiency. However, the performance of coaxial propulsion decreases. We estimated average loss in efficiency for coaxial motor pair comparing to single unit. For the biggest tested propulsion setup, the coaxial propulsion has a efficiency at about 77% of single unit. For 16 inch propeller and MN4014 motor and 10 inch propeller with MN3110 motor, these values estimate at about 85%. Having in mind that 10 and 16 inch configuration are quite similar, with smaller difference in propellers' size and rotational speed, we assume that efficiency of coaxial propulsion decreases for bigger, low-speed propulsion. In most common sizes of *UAV* multirotor's propulsion (varying from 8 to 16 inches of propeller's diameter [1][10]), the coaxial configuration of propellers requires about 17% more power to generate the same thrust, considering useful lift including motors' weight.

However, one of the biggest advantages of octoquad configuration is ability to provide significantly higher thrust for the platform in smaller volume. The comparison of maximum thrust for both versions of propulsion system - classic quadrotor concept and octoquad configuration - is shown in table 1. The maximum thrust capability of coaxial design is reduced by mass of additional motor and propeller.

Table 1: Maximum thrust in quadrotor and octoquad configuration

Configuration	**Quadrotor (4x1)**		**Octoquad (4x2)**		
	Thrust[gf]	Power [kW]	Thrust[gf]	Power[kW]	Thrust Gain [%]
MN3110 + 10" prop.	3940	0.89	5539	1.35	136%
MN4014 + 16" prop.	12904	2.57	18542	4.23	144%
U8PRO + 26" prop.	9399	0.71	13389	1.28	142%

4.1 Conclusions

- Introducing octoquad configuration allows to increase lift capabilities by about 40%, considering weight of additional motor unit and slight rise in vehicle's volume, comparing to classic quadrotor design.

- Coaxial propulsion does not operate on maximum motor's power, probably because of the lower propeller operating in prop wash of upper unit.

- The loss in efficiency for coaxial propulsion is not that significant, because lower than double thrust gain comes with less power consumption. Considering grams per watt ratio, coaxial propulsion units needs about 17 to 29% of more power to produce the same thrust. However, this values vary for different rotational speeds. In addition, different sizes of propellers have different loss in efficiency, with best results for smaller, high-speed propellers.

5 Evaluation

Based on experimental results, we conclude that octoquad configuration of *UAV*'s propulsion is worth considering, when maintaining small volume with significant thrust is essential for the design. Presented analysis of coaxial propulsion for quadrotor platforms found a practical application in our projects. The *MN3310* paired with 10 inch propeller setup was already applied in our *Falcon V5* quadrotor [12], providing 6.5kg of total thrust in octoquad configuration. Another example of our application of coaxial propulsion is the *Dropter* platform [13], with maximum total thrust of 21 kg, developed for European Space Agency's *StarTiger* project.

6 Future work

Experiments performed with third propulsion setup (*U8-16 Pro* BLDC motor with 26 inch propeller) introduce possibility to develop energy efficient multi rotor platform, focused on maximizing flight time. Comparing experimental data with first drafts of mechanical design gives over one hour of estimated maximum operational time.

Performed experiments are planned to be enhanced towards testing different propellers' pitches and diameters in symmetrical and unsymmetrical configuration of coaxial propulsion.

In addition, dual propulsion systems creates opportunity to explore the subject of redundancy and fail-safe control algorithms for multi rotors. When one of the motors in coaxial pair fails, it is still possible to continue flight and maintain stability, with completely changed control laws and different state estimation, which appears as promising field of research.

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