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STUDY REGARDING FLIGHT AUTONOMY ESTIMATION FOR HEXACOPTER DRONES IN VARIOUS EQUIPMENT CONFIGURATIONS

Mihai-Alin STAMATE[1*], **Adrian-Florin NICOLESCU**[2], **Cristina PUPĂZĂ**[2]

1) Ph.D. Student, Eng., Robots and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania
2) Prof., Ph.D., Robots and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania

Abstract: *The use of multirotor drones in a wide range of applications in the civilian environment has seen an uprising trend over the past decade. It is estimated that by 2025, the market for drones used in the civilian environment will reach about 48 billion USD. Although there are currently different propulsion variants for the multirotor drones, such as LiPo batteries, fuel supply systems, and hybrid solutions none of reported articles comprise a synthetic comparative study from the designer point of view. This paper aims to address a hexacopter drone from the perspective of flight autonomy, which uses as a propulsion system 6 BLDC (Brushless Direct Current) motors, powered by LiPo batteries. This research was done by carrying out comparative studies, with different equipment configurations, by taking into account all of the hexacopter components: the frame, the propulsion system consisting of propellers, motors, ESCs – Electronic Speed Controller, LiPo batteries, communication/ telemetry/ FPV – First Person View systems, and different types of payloads respectively. The study was performed using online platforms: https://www.ecalc.ch/xcoptercalc.php, https://flyeval.com/, http://www.drivecalc.de/, and represents an alternative to choose the optimal combination of components, to ensure the best flight range. The novelty of the paper consists in the customization of available platform information gathering it in an extensive comparative study to allow the best decision in multirotor drone design. Because the work has also limitations, the continuation of the research is expected.*

Keywords: *drone, hexacopter, brushless motor, payload, autonomy*.

1. INTRODUCTION

Extensive use of multirotor drones in various applications, such as search-and-rescue, air reconnaissance missions, border surveillance, disaster response, public order, mining, agriculture, insurance and, more recently, transportation of goods and even passengers, involves numerous efforts by developers of various multirotor drone solutions, for providing an increased autonomy, thus making the drones able to carry out the desired tasks. When studying multirotor drones, one of the main concerns is the flight autonomy. Hexacopters are currently employed in a wide range of fields, from aerial reconnaissance and surveillance, disaster response, and recently in areas such as transport and package delivery, medical equipment, components for oil rigs, passenger transport, automatic management of warehouse products [1]. Therefore, a rigorous study of the increase in flight autonomy for multirotor drones is essential, so that they can successfully meet all the requirements for which they were created.

A method of optimizing the design of multirotor drones is presented in [2], in order to obtain a desired hover flight autonomy. Mathematical models with parameterizations for the components of the propulsion system have also been presented. Other papers [3, 4], respectively [5] deal with the problem of sizing the electric propulsion system in the case of multirotor drones, to predict performance and optimize their design. This study presents a different practical approach, by performing several comparative analyses, for different equipment variants, of a hexacopter drone (Fig. 1).

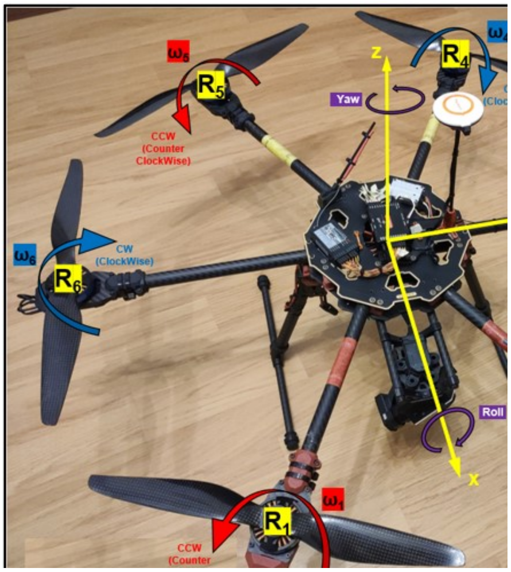

Fig. 1. The hexacopter used in this study.

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[*] Corresponding author: 313 Splaiul Independentei, Bucharest 6, 060042, Romania
Tel.: 004 021 4029 369
E-mail addresses: *stamyhay@yahoo.com* (M.A. Stamate), *afnicolescu@yahoo.com* (A.F. Nicolescu), *cristina.pupaza@upb.ro* (C. Pupăză)

Starting from the theoretical elements of preliminary calculation it employs specialized online platforms: www.omnicalculator.com [6] www.ecalc.ch [7], www.drivecalc.de [8], www.flyeval.com [9].

Based on the information we already have from the literature regarding the autonomy of multirotor drones, namely the fact that most drones have a fairly low flight range, between a minimum of 8–10 minutes and a maximum of 20–25 minutes, it is possible to increase the autonomy under certain conditions, by rigorous analysis and planning of the components list that are going to equip the drone, respectively by performing several tests, on the ground and in flight, in different atmospheric conditions.

Although both the hexacopter and octocopter have more propellers (compared to a quadcopter or tricopter), which increase the lifting capacity of a payload (DSLR camera, lifebuoy, etc.). This is done at the expense of efficiency. It is evident that the larger the drone is, the more power is needed, which means: more powerful motors, high-current ESCs, high-capacity batteries, wiring, etc.. In the end, everything adds-up to the final all-up-weight of the drone and thus turns into low traction to weight ratio. Therefore, it is reasonable to build a large drone only if it assures a large lift force capable of lifting larger masses, or the additional redundancy offered by a hexacopter - as in our case, namely the continuation in conditions of full flight safety for bringing the drone to land, if an engine fails during the flight. Moreover, the configuration of the frame and, implicitly, its dimensions directly influence the maximum size of the propellers that can be mounted on top of the engines, this being one of the main factors of the efficiency of the drone during flight.

The efficiency of the propeller is strictly related to its surface, so that, for the same input power, a propeller with a larger diameter will provide a higher lift compared to a propeller with a smaller diameter.

The paper is structured as follows: introduction section presents a short literature review regarding the flight time estimation and optimization of the propulsion system; section two illustrates the propulsion system of a hexacopter; section 3 aspect regarding the flight autonomy of a multirotor drone is treated in detail; in section 4 several multirotor configurations analysis and flight time estimation results are performed using online calculation platforms, as mentioned above and ends with conclusions in section 5.

2. HEXACOPTER PROPULSION SYSTEM

The propulsion system of a hexacopter has the following components (Fig. 2): batteries, ESCs (Electronic Speed Controllers), BLDC (Brushless Direct Current) motors, and propellers respectively. Each of these components has a specific role within the propulsion system accordingly.

The battery provides the necessary current to power the ESCs and other consumers (Rx, camera, gimbal, flight controller).

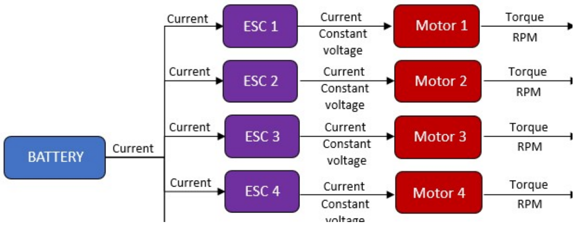


Fig. 2. Hexacopter propulsion system diagram.

ESCs have an extremely important role within this chain due to their functions: they establish the rotational direction for the motors (CW-clockwise or CCW – counterclockwise), they act as a dynamic brake for motors, they provide the constant voltage to the motors from the battery and they also control the start/stop phases of the motors.

The BLDC motors have an important role within the propulsion system - they provide the speed and torque to propellers to produce lift necessary for flight. BLDC motors don't have brushes. This is why they need ESCs to achieve electronic commutation.

The propellers are the main components that create lift by rotating at a specific speed.

Very much attention has to be paid when choosing the right combination BLDC motor-ESC-propeller. This can greatly influence the overall performance of the drone thus resulting in a specific flight autonomy.

Section 3 presents, in detail, all the aspects regarding drone's flight autonomy and how can it be increased by choosing the optimal configuration.

3. ASPECTS REGARDING FLIGHT AUTONOMY

Before discussing the extension of the flight time, the general presentation of the hexacopter actual configuration is required.

The hexacopter is equipped with six Tarot 4006/620KV BLDC motors, six Hobbywing XRotor 40A-OPTO ESCs, six 13" carbon fiber Tarot 1355 type propellers, and as a power source, the hexacopter was initially equipped with a 4 cell LiPo 6600 mAh Multistar battery (Fig. 3).

First, the hovering flight has to be analyzed. At hover, the drone maintains a stable flight position, thus a stable altitude above ground level.

As a general rule, to obtain the best performance during hover, which is necessary when this maneuver is desired to inspect a location, an industrial installation, aerial photography, etc., the drone should have a mass as low as possible and propellers with the largest possible lifting surface – thus, in this case , the best flight

Fig. 3. Components of the hexacopter propulsion system currently mounted on drone frame.

autonomy is obtained. The following convention will be used across this paper: Hexacopter Under Test – HDT.

The first scenario is HDT when the hexacopter is inspecting an oil pipeline. Its flight autonomy must be as high as possible, so that between refueling points, when changing the battery is mandatory to continue its flight along the path, and thus to be able to cover a longer distance. Obviously here, much more attention must be paid to the maximum speed of HDT along the trajectory.

In a theoretical approach several calculation formulas can be employed to calculate the flight time. However, it is necessary to consider the atmospheric conditions (temperature, atmospheric pressure, wind, precipitation) because they have a significant role in influencing the flight behavior of the drone.

One of the formulas that can be used to calculate flight autonomy is [6]:

$$Time = Battery\,Capacity \cdot Battery\ Disc\ Rate - AAD\ , \qquad (1)$$

where:

Time is the flight time of the drone, expressed in hours,

Battery Capacity is expressed in milliamp-hours (mAh) or amp-hours (Ah),

Battery Discharge Rate – the battery discharge that is allowed for the flight. As LiPo batteries can be damaged if they are fully discharged, it is a common practice never to discharge them by more than 80%. If it is desired to change this default value, on must type the required discharge into the respective field of the above drone flight time calculator.

AAD is the average amp draw of the drone, calculated in amperes and can be obtained by the following formula [6]:

$$AAD = AUW \cdot P / V\ , \qquad (2)$$

where:

AUW is the all-up weight of the drone – the total weight of the equipment that goes up in the air, including the battery, usually measured in kilograms (kg).

P – the power required to lift one kilogram of equipment, expressed in watts per kilogram (W/kg).

V – the battery voltage, expressed in volts (V).

Otherwise, by using Ohm's law, an alternative version of the formula above can be employed [6]:

$$AAD = AUW \cdot I\ , \qquad (3)$$

where *I* stands for the current (in A) required to lift one kilogram of payload.

Using the above formulas for the studied hexacopter with the current configuration, the following initial data results:

- Battery discharge rate: 80%.
- HDT AUW: 2770 g = 2.77 kg.
- to determine how many watts are needed to lift one kg of equipment in the air, in this case, when Tarot 4006/620 KV BLDC motors are employed and with the current configuration of the drone, the value obtained is about 131 W/kg;

Accordingly, the following results are obtained: *AAD* = 24.52 A and *Time* = 13.32 min. Therefore the hexacopter will be able to stay in the air for about 12–13 minutes. As mentioned above, this is only a theoretical result, without considering external factors, especially atmospheric influence factors.

In the case of replacing the existing battery with another one with a capacity of 16000 mAh, in the configuration shown in Fig. 9, after applying the above formulas, the following data results: *AAD* = 37.66 A and *Time* = 20.38 min.

Depending on the performed tasks, the flight time calculated in both the above situations may vary as follows:

- for flights that do not involve paths, but rather stationary at a fixed point (aerial photography), the flight time is approximately 75% of the calculated one;
- if the drone flys in areas with strong wind or performs frequent movements, the flight time is approximately 50% of the calculated time;
- for drones used in First Person View (FPV) flights or the case of flights with high RPM (revolutions per minute), the flight time decreases dramatically, to approximately 25–30% of the calculated one.

To find the optimal configuration that offers the desired flight autonomy, not only theoretical calculation elements are sufficient, but also a comprehensive analysis of the compatibility and integration of the various electronic and mechanical components that are going to equip the drone need to be considered. Some aspects related to this field will be presented further.

From the point of view of the components that equip the drone, there is a close connection between the propulsion part, which includes: motors, ESC – electronic speed controllers, propellers and the battery. BLDC motors play a very important role. In other words, more power is required to rotate a 17" propeller than a 12" one. The power depends on torque and RPM. RPM is an essential equivalent to the KV parameter of the motor – the RPM that the motor can provide when a voltage of 1 V is applied to its terminals with no-load current, for example at idle, without propellers fitted. Not to confuse KV with kilo-volt (kV).

As the components that create drag become larger, that means a larger drone frame, DSLR cameras, more components mounted on the drone, they encounter greater forward resistance (drag force) than in the case of smaller elements – small propellers, mini cameras. Therefore, they require more torque to be produced.

For instance, a 12 V with an 880 KV motor will be able to reach a theoretical maximum of 10,560 RPM. While motors always try to rotate at a speed of $KV \cdot U$, they never do so because of losses.

Motors with a low KV index have lower speeds compared to those with a high KV index but produce much higher torque (traction) and are more economical. On the other hand, engines with a high KV index tend to rotate much longer and can reach higher speeds, but with the disadvantage of decreasing efficiency.

Therefore, engines with a small KV index are better suited to rotate large propellers at low speeds, and engines with a large KV index to rotate small propellers at high speeds.

For example, to be able to rotate huge 26" effective propellers, a quadrotor uses motors with the very low index of only 150 KV. Instead, there are many multi-rotor vehicles used in aerobatics, with much shorter flight times, employing engines with a very high KV index (> 1000), and relatively small propellers. If in the above example, the 26" propellers were mounted on engines with a KV index of 1000, the load on them would be too high and the engines would overheat, which would inevitably lead to their final destruction.

As mentioned, the larger the diameter of the propeller, the more efficient the drone's hover, but the less efficient will be its response to commands given by the operator.

A propeller with a pitch-to-diameter ratio greater than 0.667 tends to lose its lift as the load on it increases, leading to a loss of control over the drone. As a rule, it is good to choose a propeller with a pitch-diameter ratio of less than 2 / 3.

Another aspect to consider is the ESCs and the battery mounted on the drone. The test hex rotor is equipped with Hobbywing XRotor 40A-OPTO ESCs and a Multistar High Capacity 4S 6600mAh Lipo Pack battery. This is what it is called a high voltage system. In general, these are the most effective settings.

Corresponding to the HDT case, for example, in the case of 620 KV motors, on top of which the 1355 CW / CCW 13 × 5.5 Tarot propellers are mounted, connected to a 14.8 V (4S1P LiPo) battery, they consume, according to the technical data provided by the manufacturer, approximately 26 A, which equates to a power of 426 W.

The relationship between P, I, and U means that a high voltage system with a low amperage consumption can generate the same power in W as a low voltage system with a high amperage consumption. This aspect is very useful for carefully choosing the LiPo battery because its capacity, which translates into flight time is expressed in mAh.

From the analyzed data we conclude that *the use of the largest propellers, the motors with the lowest KV index, and the batteries with the highest capacity, offers the possibility to achieve the most efficient configurations*, but, unfortunately, things are not so simple.

In classic aviation of conventional propeller aircraft, in the case of HDT, the propeller is the one that ensures the lift capacity of the drone. From the perspective of the higher Reynolds (Re) number, greater means more efficient. Due to the limitations of the specific modulus (property of a material that expresses the ratio between the modulus of elasticity and mass density of a material - materials with a high specific modulus are used in large aerospace applications where minimum structural weight is required) of composite materials that are found today and applying the principles of square-cube law (or law Cube-square – which is a mathematical principle, applied in a variety of scientific fields, that describes the relationship between the volume and surface area of a body), it ultimately results in reaching an optimal size of propellers above which, if surpassed, an unbalance occurs that can no longer be kept under control.

In other words, *a larger rotor (propeller) is more efficient, but a more generous frame will be needed to allow it to be mounted, thus more powerful and larger engines, higher capacity batteries, resulting in too much mass and poor drone performance will be needed.*

While the general principles are true, on must take into account a very important aspect, namely, fine-tuning (in generic terms constructive & functional optimization). All electronics and electromechanical components are designed to operate within a specific operating range / an optimal range. To obtain an efficient system, the components must be carefully selected to suit the types of missions the drone is designed to perform, but at the same time, special attention must be paid to their interconnection so that they work efficiently and to get the drone best results while in flight.

To avoid selecting the wrong components, the first question to be answered is that of the traction force that will be required to carry the payload needed to perform different types of missions and also to allow the execution of in-flight maneuvers (pitch, roll, rotation) in conditions of maximum safety, without the deviation of the drone from the route.

The masses of all selected components will be added to the mass of the drone. If the choice of a specific frame is considered and the payload that the drone has to carry onboard is known, in the first theoretical stage it is possible to make an average estimation for motors, battery, propeller, controller, other consumers, etc.

The basic rule in the case of multirotor drones is that *the motors can produce a traction force equal to twice the total flight mass of the drone*. This safety margin assures the ground operator that the motors will be able to react quickly to the received commands or to stop a rapid vertical descent even when the battery voltage is reduced over time. After calculating the required total traction force, it is then divided by the number of motors.

4. MULTIROTOR CONFIGURATIONS ANALYSIS AND FLIGHT TIME ESTIMATION RESULTS

For calculating the flight time, computer modeling tools, such as *eCalc.ch*, *flyeval.com*, *DriveCalc.de*, *PropCalc.de* utilities, can be useful to simulate different configurations, but the only way to be sure is to test different engine-propeller-battery combinations and, of course, most importantly, before physically mounting the components on the drone, they must be measured to obtain the actual values.

Next, using the *eCalc* online platform - one of the most used and efficient tools in the field of configuration simulations for multirotor drones – assuming that the accuracy of the data provided by the utility is not 100% so that the margin of deviation at actual values is around ±15%, several equipment configurations were tested, both for the above-mentioned hexacopter drone and other types of multirotor drones, to find an optimal configuration that allows the transport of a large payload on board and increase the autonomy of the drone.

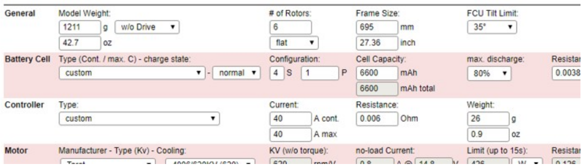
The autonomy that can be theoretically obtained will be analyzed, considering the corresponding margin of error, in the case of HDT, equipped according to several configurations.

First, version 1 (v.1) of HDT will be analyzed, as follows:

- The HDT frame comprises: motor support arms, upper and lower plates between which the arms are mounted, battery support plate, landing gear, and support plates on which the motors are mounted is made of carbon fiber, having a total mass of only 833 g, ensuring at the same time an increased resistance to shocks and vibrations. The size of the frame, that means the distance between the centers of two motors is 695 mm.
- 13" propellers that equip the HDT are also made of carbon fiber, having a mass of only 16 g each. They have a pitch of 5.5";
- the flight controller (autopilot) limits the HDT inclination to a maximum of 35 °. This together with Power Module Unit (PMU) and LED module consumes about 0.3 A.
- HDT flight testing is done at an altitude of approximately 85 m above sea level corresponding to Bucharest altitude, at a temperature of 22 °C and an atmospheric pressure of 1010 hPa corresponding to 757.5 mmHg;
- The battery mounted on HDT is a LiPo type with 4 cells, each having 3.7 V and its mass of 134.25 g. The total mass of the battery is 537 g in 4S1P configuration, that means 4 cells in series/1 cell in parallel, with an internal resistance of about 0.0038 Ohm, voltage – 14.8 V. C rating is a parameter that measures how quickly a battery can be discharged, safely, and without damaging it, when a load is applied to it – in our case: motors, ESC, controller, PMU, LED, etc. The battery used has 10 C – 66A in continuous operation – with a maximum of 20 C, namely 132A – for short periods of 10–15 seconds. As mentioned above, it is recommended that the battery must not be discharged to more than 80% of its capacity.
- Electronic speed controllers (ESC) can withstand a maximum load of 40 A, have an internal resistance of approximately 0.0006 Ω, and a mass of 26 g each.
- a gimbal with three-axis of rotation is mounted, which is also powered by the battery, being also a consumer, so it will be included in the Accessories category; it has a mass of 178 g and consumes about 0.05 A;
- Tarot 4006/620 KV motors produce 620 RPM/V, have an internal resistance of 0.126 Ω, and a mass of 82 g each.
- Tarot ZYX-M flight control system: flight controller, Power Module Unit, LED unit, GPS antenna, and mounting post, cables, accessories, with a total mass of 140 g.
- Rx - Receiver, with a mass of approximately 25 g.

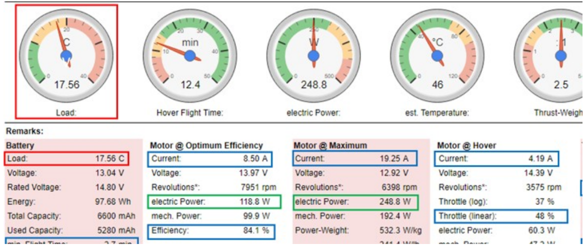
After running the calculations, the following data and observations are obtained (Fig. 5):

- first of all, the load on the battery is 17.56 C, which means a continuous load of ≈ 116 A.



General	Model Weight: 1211 g w/o Drive ▾ 42.7 oz	# of Rotors: 6 flat ▾	Frame Size: 695 mm 27.36 inch	FCU Tilt Limit: 35° ▾	
Battery Cell	Type (Cont. / max. C) - charge state: custom ▾ - normal ▾	Configuration: 4 S 1 P	Cell Capacity: 6600 mAh 6600 mAh total	max. discharge: 80% ▾	Resista 0.0038
Controller	Type: custom ▾	Current: 40 A cont. 40 A max	Resistance: 0.006 Ohm	Weight: 26 g 0.9 oz	
Motor	Manufacturer - Type (Kv) - Cooling:	KV (w/o torque):	no-load Current:	Limit (up to 15s):	Resista

Fig. 4. Current configuration of the HDT (v.1) using [7].



17.56 Load:

12.4 Hover Flight Time:

248.8 electric Power:

46 est. Temperature:

2.5 Thrust-Weigh

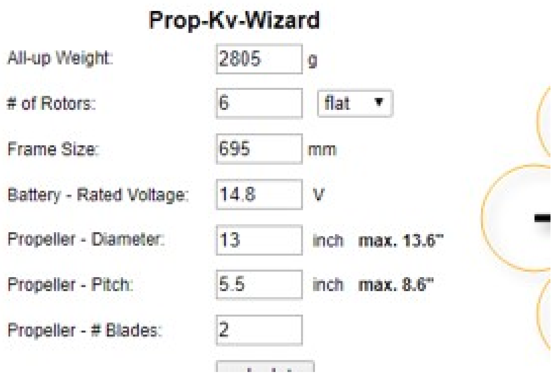
Remarks:

Battery		Motor @ Optimum Efficiency		Motor @ Maximum		Motor @ Hover	
Load:	17.56 C	Current:	8.50 A	Current:	19.25 A	Current:	4.19 A
Voltage:	13.04 V	Voltage:	13.97 V	Voltage:	12.92 V	Voltage:	14.39 V
Rated Voltage:	14.80 V	Revolutions*:	7951 rpm	Revolutions*:	6398 rpm	Revolutions*:	3575 rpm
Energy:	97.68 Wh	electric Power:	118.8 W	electric Power:	248.8 W	Throttle (log):	37 %
Total Capacity:	6600 mAh	mech. Power:	99.9 W	mech. Power:	192.4 W	Throttle (linear):	48 %
Used Capacity:	5280 mAh	Efficiency:	84.1 %	Power-Weight:	532.3 W/kg	electric Power:	60.3 W

Fig. 5. Results obtained after running the calculations (v.1) using [7].

On the indicator, the value obtained is positioned in the orange area. Given the characteristics of the battery: continuous load of 10 C and maximum 20 C for short periods, it turns out that the battery will be most of the time over-loaded, with tendencies to work more towards the maximum area, which can lead to its deterioration. Although there are no warning messages on the results page, it is recommended to use a battery with a higher C-Rating.

- a flight autonomy of 9.1 minutes is obtained for the combined flight – forward flight, backward flight, ascensional flight, descent, respectively 12.4 minutes for hovering flight;
- in the case of optimal engine performance, a speed of 7951 RPM is obtained and an efficiency of 84.1%. For hover flight a speed of 3575 RPM is obtained; at this point, the engine speed is at 48% of its capacity, which means a very good result. The efficiency is preferable to be around 50% to allow the drone other in-flight maneuvers that will require the additional thrust, and, implicitly, will increase the temperature at the level of motor housing. A power-to-mass ratio of 132.6 W/kg is a good result – the most efficient systems end up lowering this ratio to the value of 80 W/kg, an efficiency of 78.3% and a temperature of the only 28 °C;
- another very important aspect is the traction-mass ratio, which in our case is 2.5:1, versus an usual standard ratio of 2:1, but the higher this ratio is, the better the drone responds to operator inputs. For values equal to or greater than 1.8 the engine speed will be less than or equal to 60% of their capacity. For values between 1.2 –1.8 the engine speed will be between 60–80% of the capacity and the maneuverability of the drone will be limited. Below the value of 1.2 the stability of the drone at a fixed point cannot be ensured;
- the specific traction of the propellers is a good indicator of the drone's performance of hovering. Form this perspective the levels are: ≥ 6 g/W – high efficiency, between 4–6 g/W – low efficiency and < 4 g/W is inefficient. In the case of HDT, a ratio of 7.76 g/W is obtained, which means high efficiency;


Prop-Kv-Wizard

All-up Weight: 2805 g

# of Rotors: 6 flat

Frame Size: 695 mm

Battery - Rated Voltage: 14.8 V

Propeller - Diameter: 13 inch max. 13.6"

Propeller - Pitch: 5.5 inch max. 8.6"

Propeller - # Blades: 2

Fig. 6. Prop-motor combination selection based on the current configuration (v.1) using [7].

- it is noted that additional equipment can be attached that cannot exceed the mass of 3.3 kg, which is more than generous;
- the maximum speed obtained is 37 km/h, and the ascending speed is approximately 7.1 m/s;
- a hexacopter has an important and critical ability to ensure a stable flight until landed safely, in case of a motor failure. The white checkmark inside the green circle presented in Fig. 5 states that the HDT meets all the requirements to be landed safely in case of a motor failure.

Figure 6 presents the propeller-motor combination selection based on the current configuration of the HDT. As it can be observed, for the frame of 695 mm, a propeller with a maximum diameter of 13" and a maximum pitch of 5.5" can be mounted on the frame. Also, the platform recommends a motor with a KV between 470–680 RPM/V, a minimum motor power between 240 and 415 W – the current motors have 426 W of power, and an ESC with a minimum of 20–35 A. Tarot motors that equip HDT in v.1 have a KV value of 620 RPM/V and ESCs that equip HDT in v.1 have a maximum current of 40A.

After running the program, two graphs are obtained that show data regarding the flight distance, speed, respectively the characteristics of the motors at maximum speed, as follows (Fig. 7):

- the maximum flight time without drag is about 12 minutes; the maximum flight time with the drag decreases below 10 minutes; the maximum flight distance without drag is about 4000 m; the maximum flight distance with the drag is about 2300 m. The best performances of the HDT are obtained within the speed range 15–27.5 km/h.
- it is noted that the motors are capable of operating at all speeds at an acceptable temperature of about 60 °C. *Care must be taken for the motors to not exceed* 80 °C *because this might lead to permanent failure*.

For the same configuration of HDT, namely v.1, Fig. 8 illustrates the results obtained by running the calculations offered within flyeval.com online platform.

From Fig. 8 we can observe the followings: a flight autonomy of 12.9 minutes is obtained for the combined flight, respectively 13.57 minutes for stationary flight (hover). A total flight time of 5.6 minutes is achieved at maximum throttle.

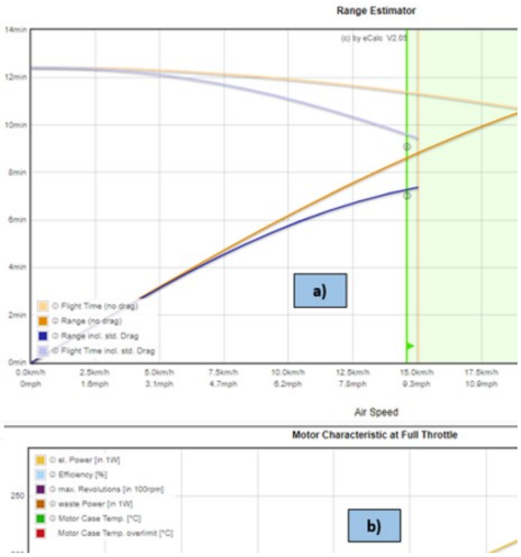
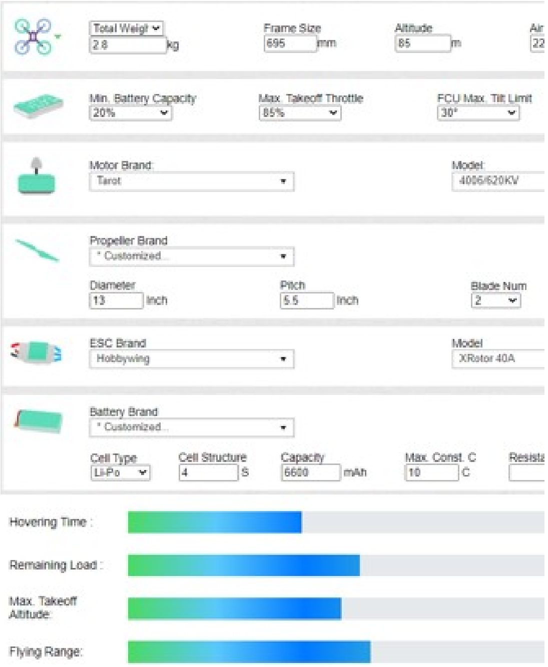


Fig. 7. a) HDT v.1 range estimator using [7];
b) Motor characteristics at full throttle using [7].


Total Weig 2.8 kg

Frame Size 695 mm

Altitude 85 m

Air 22

Min. Battery Capacity 20%

Max. Takeoff Throttle 85%

FCU Max. Tilt Limit 30°

Motor Brand: Tarot

Model: 4006/620KV

Propeller Brand * Customized...

Diameter 13 inch

Pitch 5.5 inch

Blade Num 2

ESC Brand Hobbywing

Model XRotor 40A

Battery Brand * Customized...

Cell Type Li-Po

Cell Structure 4 S

Capacity 6600 mAh

Max. Const. C 10 C

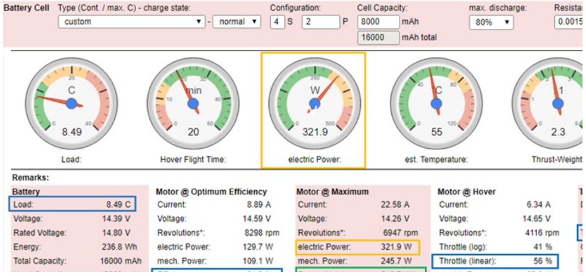
Resista

Fig. 8. HDT v.1 performance using *flyeval* platform [8].

In the second scenario, when the 6600 mAh LiPo battery is replaced with a 16000 mAh 4S2P/12-24C LiPo battery and this will be referred to as HDT v.2.

The obtained results are as follows:

- a considerable increase of flight autonomy is obtained: 15.1 minutes for the combined flight, respectively 20 minutes for the hovering flight; in the case of optimal motor performance, a slight increase in efficiency is obtained from 84.1% to 84.2%; For hover flight, a speed of 4116 RPM is obtained, the motor speed increases from 48% to 56% of its capacity, which means a good result, a power-to-mass ratio of 151.4 W/kg, efficiency of 77.5% and a temperature of only 31 °C. However, an increase in power at the input to the motor to 321.9 W, but only in the maximum operating mode of the motor is observed. In this case, the traction-mass ratio



Battery Cell Type (Cont. / max. C) - charge state: custom - normal
Configuration: 4 S 2 P
Cell Capacity: 8000 mAh
16000 mAh total
max. discharge: 80%
Resista 0.0015

Remarks:

Battery		Motor @ Optimum Efficiency		Motor @ Maximum		Motor @ Hover	
Load:	8.49 C	Current:	8.89 A	Current:	22.58 A	Current:	6.34 A
Voltage:	14.39 V	Voltage:	14.59 V	Voltage:	14.26 V	Voltage:	14.65 V
Rated Voltage:	14.80 V	Revolutions*:	8298 rpm	Revolutions*:	6947 rpm	Revolutions*:	4116 rpm
Energy:	236.8 Wh	electric Power:	129.7 W	electric Power:	321.9 W	Throttle (log):	41 %
Total Capacity:	16000 mAh	mech. Power:	109.1 W	mech. Power:	245.7 W	Throttle (linear):	56 %

Fig. 9. Results obtained after running the calculations (v.2). using [7].

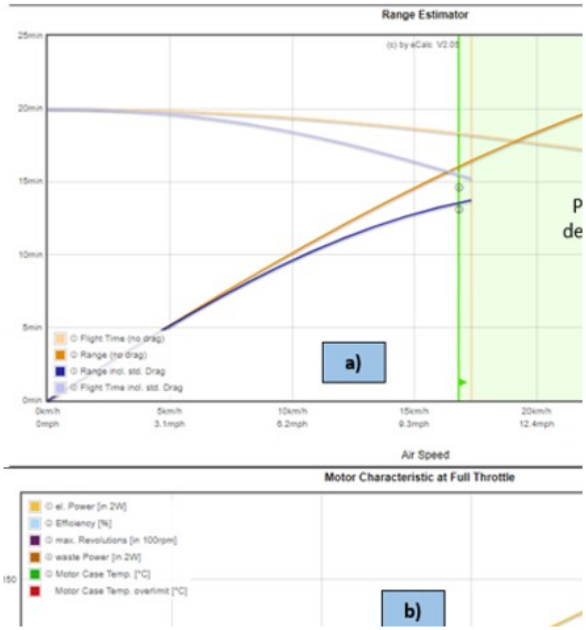


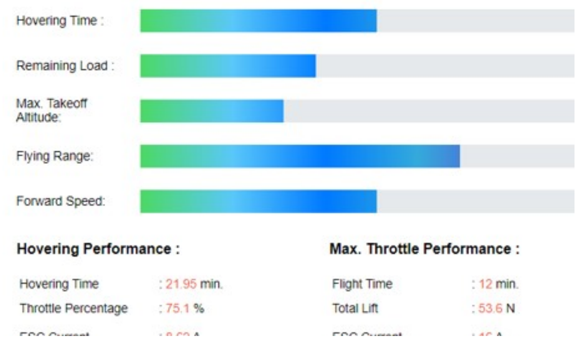
Fig. 10 a) HDT v.2 range estimator [7];
b) Motor characteristics at full throttle [7].

is 2.3:1, a value grater then 1.8 being usually considered a very good one. The specific traction of the propellers is located at the value of 6.67 g/W, which is ≥ 6 g/W – correspong to high efficiency. It is noted that additional equipment with a mass of approximately 3.6 kg can be attached. An increase of the maximum speed is observed, at the value of 40 km/h, and the ascending speed remains at the value of 7.1 m/s.

From the graphs on Fig. 10 the maximum flight time without drag is about 20 minutes, maximum flight time with the drag decreases to 15.1 minutes, maximum flight distance without drag is about 7600 m, maximum flight distance with the drag is about 4400 m. The best performances of HDT v.2 are obtained within the speed range of 17–31 km/h. It can be observed in Fig. 10,*b* that the motors manage to operate at all speeds at an acceptable temperature of up to 55 °C.

Also, as expressed in Eq. (1), the overall flight time of the HDT v.2 obtained after the calculation of the expressions was 20.38 minutes.

Figure 11 illustrates the results obtained in using *flyeval* platform, after running the calculations: a flight autonomy of 20.8 minutes is obtained for the combined flight, respectively 21.95 minutes for stationary flight (hover). A total flight time of 12 minutes is achieved at maximum throttle.



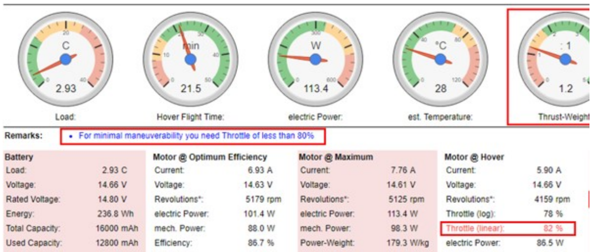
Hovering Performance :

Hovering Time	: 21.95 min.
Throttle Percentage	: 75.1 %

Max. Throttle Performance :

Flight Time	: 12 min.
Total Lift	: 53.6 N

Fig. 11. HDT v.1 performance using *flyeval* platform [8].



Remarks:
- For minimal maneuverability you need Throttle of less than 80%

Battery		Motor @ Optimum Efficiency		Motor @ Maximum		Motor @ Hover	
Load:	2.93 C	Current:	6.93 A	Current:	7.76 A	Current:	5.90 A
Voltage:	14.66 V	Voltage:	14.63 V	Voltage:	14.61 V	Voltage:	14.66 V
Rated Voltage:	14.80 V	Revolutions*:	5179 rpm	Revolutions*:	5125 rpm	Revolutions*:	4159 rpm
Energy:	236.8 Wh	electric Power:	101.4 W	electric Power:	113.4 W	Throttle (log):	78 %
Total Capacity:	16000 mAh	mech. Power:	88.0 W	mech. Power:	98.3 W	Throttle (linear):	82 %
Used Capacity:	12800 mAh	Efficiency:	86.7 %	Power-Weight:	179.3 W/kg	electric Power:	86.5 W

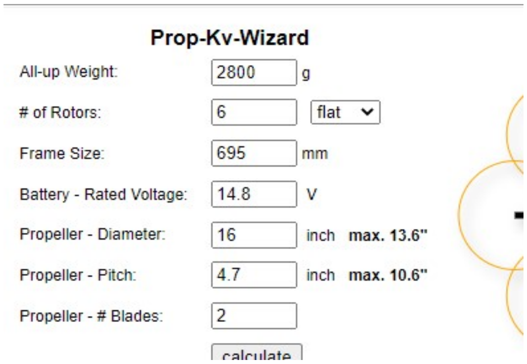
Fig. 12. HDT v.2. Low KV motor results in an undesirable configuration, unfit for flight [7].

In the case of a motor with a low KV, on only 380 RPM/V, for HDT v.2, the results indicate undesirable values, namely: the program warns that for minimum maneuverability of the drone, the throttle must be below 80%. The value obtained is 82% – too high; the traction-mass ratio decreases considerably to the value of only 1.2:1 and at this value, the drone is practically impossible to operate, it cannot take off. HDT flight cannot be ensured even if one of the engines fails, because, for this, the drone it would need the motors to be running at more than 80% of their capacity, which will lead to overheating and permanent failure (see Fig. 12).

As stated before, attention has to be paid when choosing the optimal motor-ESC-propeller-battery combination, but an important aspect to be taken into account is the frame size and the configuration: tricopter, quadcopter, hexacopter, octocopter, or other special configurations that the user can choose to build.

HDT used in this paper has a maximum frame size of 695 mm, which accommodates propellers with a maximum size of 13.6", according to Fig. 6. Larger propellers will lead to failure because the tips of two contiguous blades will interact with one another (Fig. 13). For instance, if the frame size is increased, larger propellers can be used, but, at this point, a trade-off must be done, since an increase in frame size results in the need for more powerful motors and high current ESCs, which can increase the production costs accordingly.

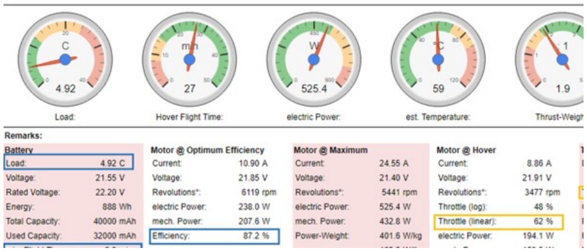
The next case shows the configuration of an octocopter referred to as HDT v.3 with eight BLDC motors in flat configuration, equipped with 2 6S2P/12-24 C 20000 mAh batteries, 18" 5.5" pitch propellers, and 300 RPM/V motors. In this case, the dimensions of the frame are almost double that of the HDT v.1 and v.2 (1250 mm), which will lead to a considerable increase in the maximum take-off mass of the drone.



Prop-Kv-Wizard

All-up Weight: 2800 g
# of Rotors: 6 flat
Frame Size: 695 mm
Battery - Rated Voltage: 14.8 V
Propeller - Diameter: 16 inch **max. 13.6"**
Propeller - Pitch: 4.7 inch **max. 10.6"**
Propeller - # Blades: 2

Fig. 13. HDT v.1 using propellers with a larger diameter than the maximum allowed [7].



Remarks:

Battery		**Motor @ Optimum Efficiency**		**Motor @ Maximum**		**Motor @ Hover**	
Load:	4.92 C	Current:	10.90 A	Current:	24.55 A	Current:	8.86 A
Voltage:	21.55 V	Voltage:	21.85 V	Voltage:	21.40 V	Voltage:	21.91 V
Rated Voltage:	22.20 V	Revolutions*:	6119 rpm	Revolutions*:	5441 rpm	Revolutions*:	3477 rpm
Energy:	888 Wh	electric Power:	238.0 W	electric Power:	525.4 W	Throttle (log):	48 %
Total Capacity:	40000 mAh	mech. Power:	207.6 W	mech. Power:	432.8 W	Throttle (linear):	62 %
Used Capacity:	32000 mAh	Efficiency:	87.2 %	Power-Weight:	401.6 W/kg	electric Power:	194.1 W

Fig. 14. Results obtained after running the calculations (HDT v.3) using [7].

Hovering Performance :

Hovering Time : 32.18 min.
Throttle Percentage : 58.8 %
ESC Current : 7.33 A

Max. Throttle Performance :

Flight Time : 9.9 min.
Total Lift : 222.3 N
ESC Current : 24.3 A

Fig. 15. HDT v.3 performance using *flyeval* platform [8].

After running the program [7], the following values are obtained (Fig. 14): the battery load is very low – 4.92 C. Compared to HDT v.1 and v.2, a significant increase of the flight autonomy is obtained, 23.3 minutes for the combined flight, respectively, 27 minutes, at hover. The maximum speed obtained is 35 km/h, and the ascending speed is 4.6 m/s. Figure 15 illustrates the results obtained after running the calculations using *flyeval* platform [8]: a flight autonomy of 31 minutes is obtained for the combined flight, respectively 32.18 minutes for stationary flight (hover). A total flight time of 9.9 minutes is achieved at maximum throttle.

Supplementary, from the graphs (see Fig. 16) the maximum flight time without drag is 23.3 minutes; the maximum flight time with drag is 27 minutes; the maximum flight distance without drag increases to approximately 9.7 km; the maximum flight distance with drag increases to about 5000 m; the best performances of the octocopter are obtained in the speed range 14–28 km/h;

Using formulas (1), (2) and (3) for HDT v.3 case, the following results were obtained [6]: *AAD* = 106.01 A and *Time* = 36.22 min.

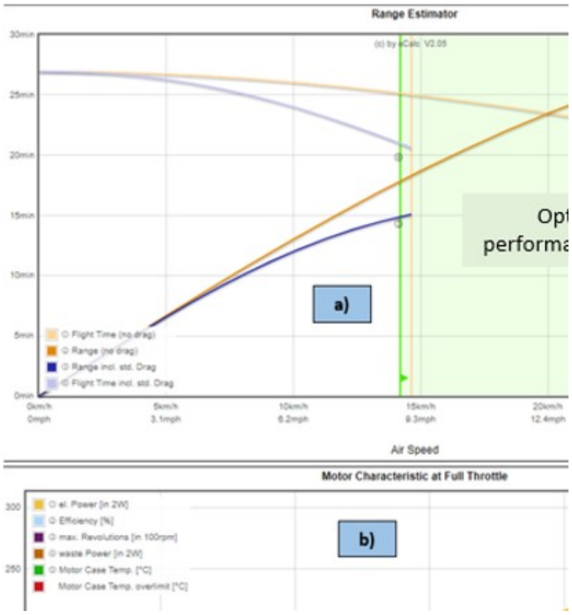
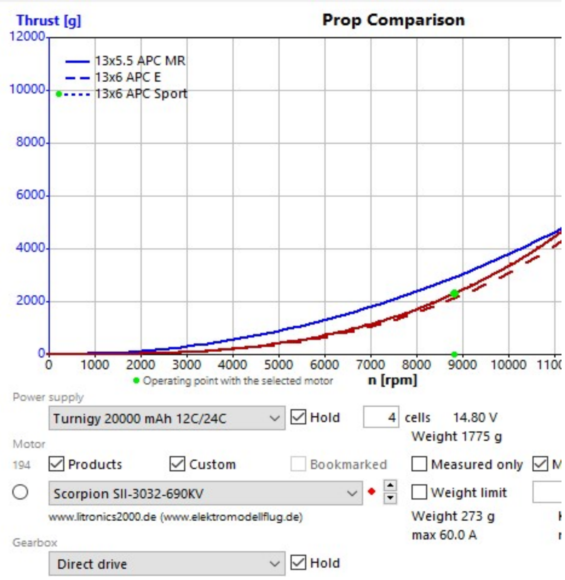


Fig. 16 a) HDT v.3 range estimator [7]; b) Motor characteristics at full throttle [7].

Choosing the right combination of motors, ESCs, propellers, and battery is not an easy task, as previously mentioned. A helpful platform is *DriveCalc.de* [9] online calculator which can help the user to select several configurations for the propulsion system, based on different types of components preloaded within the database supplied on the platform or based on the user's choice of defining new components with their parameters accordingly. Although this platform is mostly dedicated to model aircraft, it can also be used to study different components data and their interaction in the case of a multirotor.

APC propeller manufacturer online site [10] offers a database that contains a wide range of propellers with their parameters respectively. These data can be used for comparisons when testing different variants of multirotor drones.



Power supply
Turnigy 20000 mAh 12C/24C ☑ Hold 4 cells 14.80 V
Weight 1775 g

Motor
194 ☑ Products ☑ Custom ☐ Bookmarked ☐ Measured only ☑ M
○ Scorpion SII-3032-690KV ☐ Weight limit
www.litronics2000.de (www.elektromodellflug.de)
Weight 273 g
max 60.0 A

Gearbox
Direct drive ☑ Hold

Fig. 17. Propeller comparison using driveCalc.de [9].

Figure 17 shows a comparison regarding three types of APC props that can be fitted to equip a drone, taking into account the motor type, the battery type and configuration, and the ESC used. All these data are expressed as results of previously performed measurements and are offered by the platform [9].

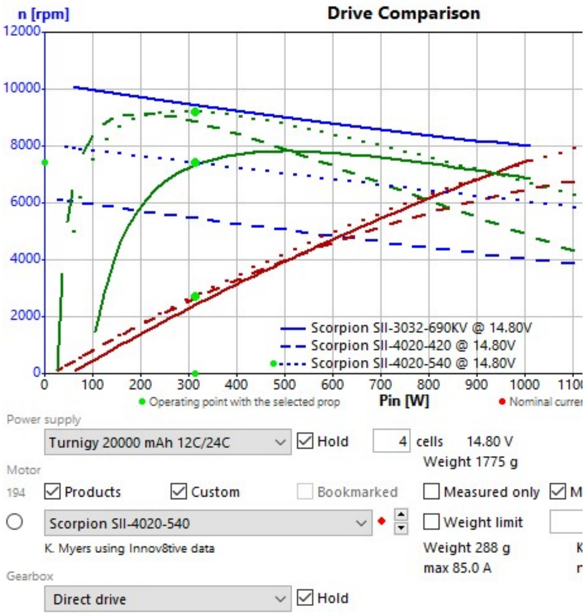
Figure 18 shows a comparison of three drive systems, based on a chosen type of propeller, where user can observe several parameters and performances: RPM, power, efficiency, propeller data reliability, thrust, velocity.

In Fig. 19 one can also observe the motor types, represented in grey dots within the graph, that can be matched with the selected propeller.

Figure 20 illustrates the performance sheet of a specific propeller type. Users can introduce new data for propeller types that do not exist in the database provided or they can use already existing data for comparison and analysis.

To conclude, the results regarding flight time estimation of a multirotor drone, obtained from the above observations and calculations and from several more calculations that were performed but not shown within this paper, may be summarized in the following graphs (see Figs. 21–23).

Although there are differences between the above-illustrated results, we can conclude that they follow the same leading path to obtain the best flight time.



Power supply

Turnigy 20000 mAh 12C/24C ☑ Hold 4 cells 14.80 V

Weight 1775 g

Motor

194 ☑ Products ☑ Custom ☐ Bookmarked ☐ Measured only ☑ M

○ Scorpion SII-4020-540 ☐ Weight limit

K. Myers using Innov8tive data

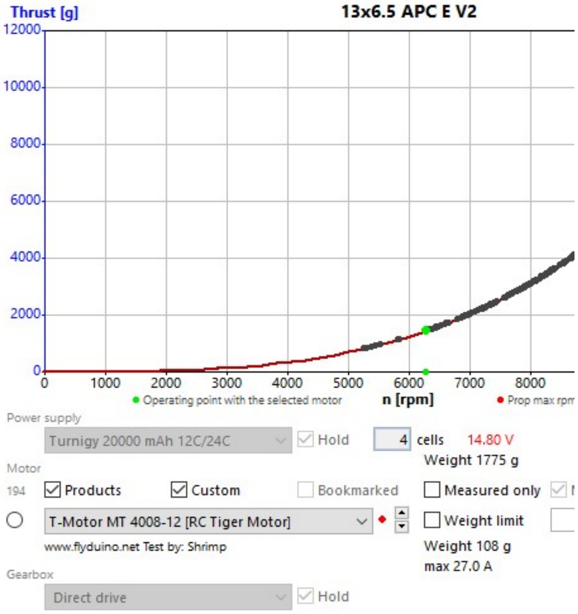
Weight 288 g

max 85.0 A

Gearbox

Direct drive ☑ Hold

Fig. 18. Drive comparison using driveCalc.de [9].



Power supply

Turnigy 20000 mAh 12C/24C ☑ Hold 4 cells 14.80 V

Weight 1775 g

Motor

194 ☑ Products ☑ Custom ☐ Bookmarked ☐ Measured only ☑

○ T-Motor MT 4008-12 [RC Tiger Motor] ☐ Weight limit

www.flyduino.net Test by: Shrimp

Weight 108 g

max 27.0 A

Gearbox

Direct drive ☑ Hold

Fig. 19. Motor matching based on a chosen propeller type using driveCalc.de [9].

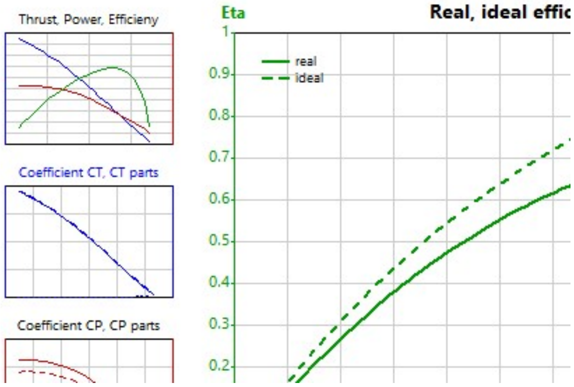


Fig. 20. Propeller performance [9].

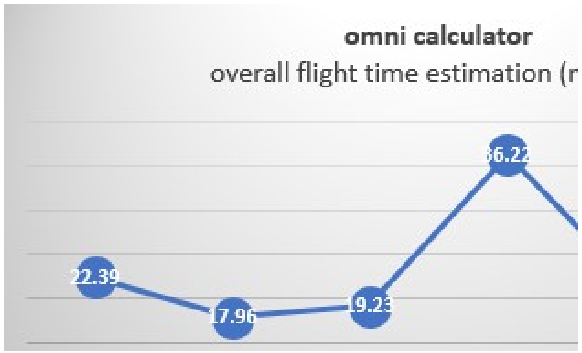


Fig. 21. Overall flight time estimation results using *omnicalculator.com* formulas.

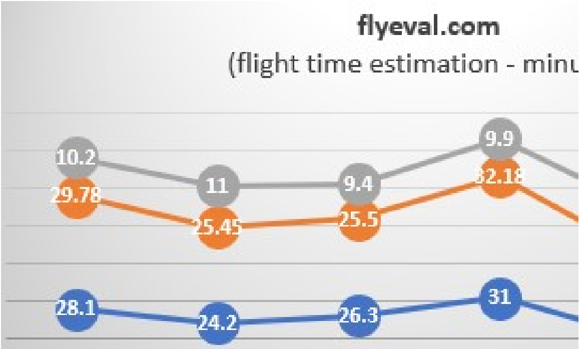


Fig. 22. Flight time estimation results using *flyeval.com* platform.

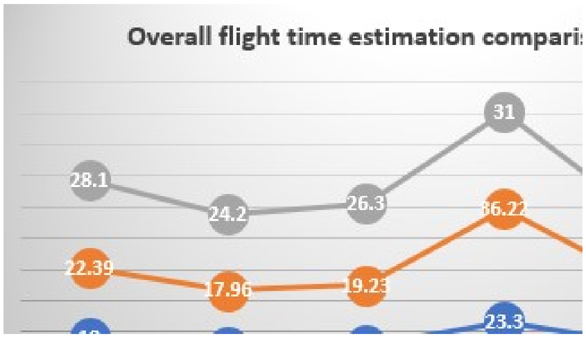


Fig. 23. Overall flight time estimation comparison.

All the presented data are not fully reliable, although they follow mathematical models with different approaches to determine the best configurations, with the best as possible flight range and flight time, as well as, nonetheless a stable drone, to ensure a safe and secure flight along the path and a safe landing in case of motor failure.

Thus, to determine the real performances of a drone, one must first read the components specs, then test them before mounting on a frame, and perform ground testing with no loads, and flight tests outside respectively.

5. CONCLUSIONS AND FUTURE WORK

This paper presents a sistematic approach when choosing the proper component combination for a multirotor drone, using online platforms that provide methods based on mathematical models, to theoretically test different variants of propulsion systems, frame sizes, and configurations, which might give to the user an idea about how to build a powerful and safe operating multirotor drone, with a flight range and flight time as long as possible.

Future approaches regarding flight time estimation of a multirotor drone will imply a mathematical modeling with parametrizations for all the propulsion system components. Afterwards the mathematical model will be implemented in a simulation environment, (MATLAB/SIMULINK) to test it and make the fine-tunning, and then implemented on the flight controller of the drone, which will be tested on flight accordingly.

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