ASPECTS REGARDING THE ELECTRIC PROPULSION OF THE UAV MULTICOPTER

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Abstract: *The UAVs is, by definition, the technical system which includes a lightweight frame and a number of on-board equipment. Equipment features make a major contribution to determining global air vector capabilities (C2, performance) and mission accomplishment.*

The article aims to simulate the characteristics and performance of multi-copters in terms of electrical equipment by using freeware tools that can lead to optimization in the pre-design phase of a multicopter used in transport missions.

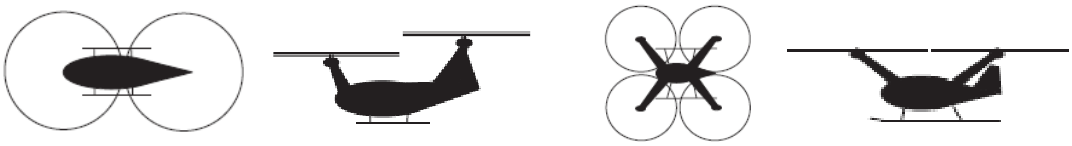
Keywords: *multicopter, brushless, Drive Calculator, software analysis.*

Acronims

C2	*-command and control*	*ISR*	*-Intelligence, surveillance and reconnaissance*
EO-IR	*-electro-optic-infrared*	*Rx/Tx*	*-receiver/transmitter*
ESC	*-electronic speed control*	*UGV*	*-unmanned ground vehicle*
USV	*-unmanned surface vehicle*	*n*	*- rotation*
v_h	*-air speed*	τ	*-torque*
I	*-amperage*	ρ	*-air density*
P	*-power*	ω	*-angular speed*
K	*- proportionality constant*	*V*	*-voltage*
F	*-traction*	*A*	*-surface*

1. INTRODUCTION

The UAVs represent, by definition, the technical system comprising a lightweight frame and a number of on-board equipment. Equipment features make a major contribution to determining global air vector capabilities (C2, performance) and mission accomplishment. The standard electronic equipment required for any type of UAV is: propulsion systems (engine, speed regulator and propeller), automatic stabilizer / autopilot, power system and C2 system (TX transmitter and RX receiver). A UAV multicopter is an aircraft similar to a traditional helicopter but with at least two lifting rotors, see Fig.1, [1].



a b

FIG. 1 UAV helicopter, a. tandem, b. multi-rotor (quad-copter), [1]

1.1. History and evolution

According to [2] the first multicopter project belonged to George Cayley designed in 1843, the air carriage was propelled by a steam engine, see Figure 2a. In 1907, Paul Cornu developed a functional flying machine capable of vertical flight (with 2 rotors), see Figure 2b.
In 1907, Flight Jaques and Louis Breguet were flown in association with Charles Richet with a quad rotor Gyroplan 1 platform, see Figure 3a, a year later, trying Gyroplane No. 2, [3].

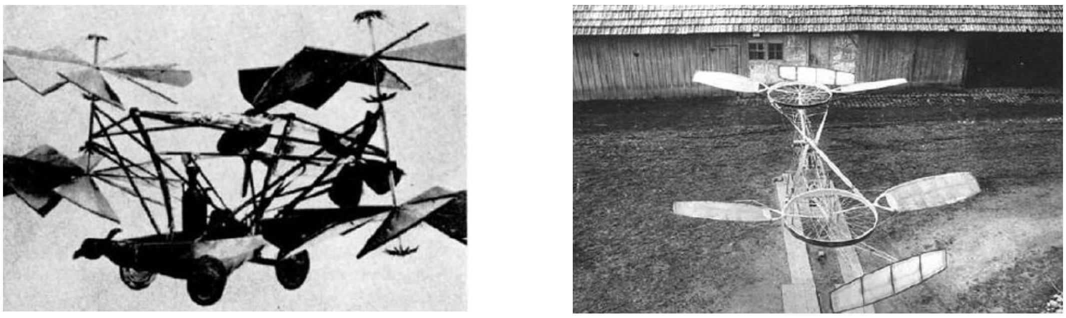
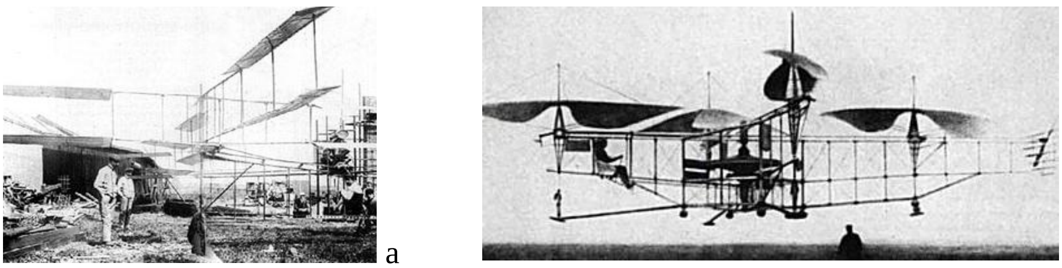


FIG. 2 Rotary wings machines, a. George Cayley – 1843; b. Paul Cornu – 1907, [2, 12]

French engineer Etienne Oehmichen in 1920 built the Oehmichen quadcopter no. 2, this platform set a new world flight record at that time, flew 360 m and stay in the air for 7 minutes and 40 seconds, see Figure 3b. Also in the same period, George de Bothezat, born in Basarabia, made the first quad-copter for the US Army [3]; and in 1936 Juan de la Cierva developed a helicopter model with tandem rotors [1].



a b

FIG. 3 Multi-copters, a. Gyro-plan no.1-1907, b. Oehmichen no. 2 [2, 3]

1.2 Classification and missions of the multi-copters

After several investigations in the UAV field, numerous classifications have been made depending on various factors, thus starting from a general classification that include all the existing UAV forms, the subsequent classification is focused on multicopter aircraft.

The most important criteria for classifying of the multi-copters are: after the number of rotors (tri-copter, quad-copter, hex-copter), see Fig.4; by flight mode (with simple GPS stabilization); according to the materials used (wood, plastic, carbon fiber, aluminum); after autonomy (small - under 10 minutes, average - between 10 and 30 minutes, high - over 30 minutes); by weight (class: micro - under 1 kg, mild between 1 and 5 kg, average between 5 and 25 kg and weight over 25 kg); after altitude (low - below 100 m, high - over 100 m).

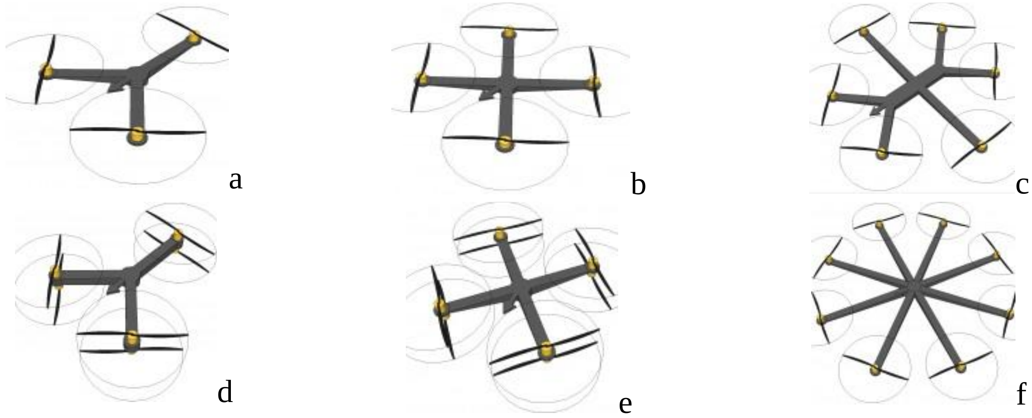


FIG. 4. Multicopter frames, a. tri-copter, b. quad-copter, c. hex-copter, d. tri-copter Y6, e. quad-copter X8, f. octopter, [12]

The most important categories of the missions that can be accomplished with multi-copters are: data acquisition (EO-IR), R&D, and transport; they can have applications in the military (ISR) and civil (industrial, agricultural, tourism), [4].

1.3. UAV multicopter capabilities

According to the literature [5, 6, 7], multi-copter air vectors possess both a set of requirements (design / fabrication, flight safety, operation / maintenance and economic) but also capabilities, including the ability to follow the map, assess the environment in which it operates, accurate navigation; mission speed (vector velocity, information processing speed, transfer, processing, centralization and dissemination); minimal radar, thermal, acoustical and magnetic mark, ability to operate in hostile areas where human factor is exposed to high risk, well-developed power system able to support the consumption of propulsion systems and secondary sensors existing on the proper vector (onboard computer, imaging equipment, sensors for processing various information, communication systems); reliability of systems in hostile environments, easy transport, launch and recovery.

2. THEORETICAL

To make a multicopter used for transport is considered to optimize the take-off mass, what includes the structural elements, the propulsion system and the radio-electronic equipment, versus the power developed by the electric motors [9], Fig.5.

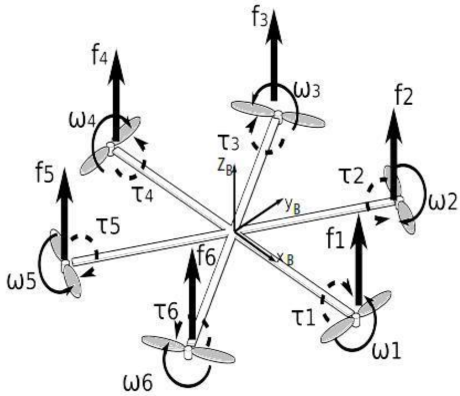


FIG. 5 Hexacopter frame, [9]

2.1. Electric motors

Generally, brushless motors are used, where the torque is:

$$\tau = K_t \cdot (I - I_0) \tag{1}$$

Where τ*- torque electric motor,*
I *–amperage intake,*
I_0 *–initial amperage in motor*
K_t *– proportionality constant torque.*

The voltage at the motor terminals is the sum of the counter-electric motor voltage (induced voltage in motor windings) and some resistive losses:

$$V = I \cdot R_m + K_\upsilon \cdot \omega \tag{2}$$

Where V *– the voltage across the motor,*
R_m *– resistance of the motor,*
ω *– Angular speed,*
K_υ *– proportionality constant, (constructive parameter of the motor).*

This motor description is used for calculate the power that the motor consumes. Power is:

$$P = I \cdot V = \frac{(\tau + K_t \cdot I_0)\cdot(K_t \cdot I_0 \cdot R_m + \tau \cdot R_m + K_t \cdot K_\upsilon \cdot \omega)}{K_t^2} \tag{3}$$

For this simple model motor resistance can be considered negligible, so the power becomes proportional to the angular velocity:

$$P \approx \frac{(\tau + K_t \cdot I_0)\cdot K_\upsilon \cdot \omega}{K_t} \tag{4}$$

To simplify it can be considered $K_t I_0 << \tau$, since I_0 is the initial motor current, therefore quite small, but this is not quite rational. But in practice this approximation is quite stable. This gives a simplified final power equation:

$$P \approx \frac{K_\upsilon}{K_t} \cdot \tau \cdot \omega \tag{5}$$

2.2. Forces and aerodynamic loads

Power is used to keep the multicopter in the air. By conserving energy, engine power consumed over a certain period of time is equal to the mechanical work done by the propeller:

$$P = F \cdot \frac{dx}{dt} \tag{6}$$

Or power is equal to the product of traction force and air velocity.

$$P = F \cdot v_h \tag{7}$$

The v_h is considered to be the air velocity while the multicopter maintains its position in the air at a stable point. It is also considered that the air velocity, v_∞, from the buffer is equal to zero. The impulse theory expresses the air velocity in the planning action of the multicopter as a traction function:

$$v_h = \sqrt{\frac{F}{2 \cdot \rho \cdot A}} \tag{8}$$

Where ρ – air density

A –propeller action area (surface).

By simplifying the equation, power is equal to:

$$P = \frac{K_\upsilon}{K_t} \cdot \tau \cdot \omega = \frac{K_\upsilon \cdot K_\tau}{K_t} \cdot F \cdot \omega = \frac{F^{\frac{3}{2}}}{\sqrt{2 \cdot \rho \cdot A}} . \tag{9}$$

In the general case $\tau = \bar{r} \times \overline{F}$, but in this case the torque is proportional to the force F by a constant rate K_t determined by the propeller blade configuration and its parameters. Simplifying the equation we obtain:

$$F = \left(\frac{K_\upsilon \cdot K_\tau \cdot \sqrt{2 \cdot \rho \cdot A}}{K_t} \cdot \omega \right)^2 = k \cdot \omega^2 \tag{10}$$

Where k – almost constant dimension.

By summing the traction forces of all the engines, the total pulling force of the multicopter results:

$$F_B = \sum_{i=1}^{n} T_i = k \begin{bmatrix} 0 \\ 0 \\ \sum \omega_i^{\,2} \end{bmatrix} \tag{11}$$

3. SIMULATION OF THE PERFORMANCE OF AN ELECTRIC MOTOR

The hex-copter vector used (see Figure 5) in transport missions has the characteristics and performance in Table 1.

FIG. 5 Hexacopter, [10]

Table1. Hex-copter features and performances [10, 13]

Features	Value	Features	Value
Frame dimensiond	650 mm	Empty weight	1380 g
Motors	Tip 4015	Battery weight	265 g
Propeller	9x5 inch	Total weight	3000 g
ESC	40A	Used weight	1800 g
Battery 4S	4000 mA	Autonomy	15 min

In the case of a hexacopter, the optimum choice of the propulsion system takes into account both the performance of the electric motor and the battery used. We present a simulated propulsion case with a freeware Drive Calculator 3.4, [8] and analysis conditions in Table 2.

Table2. Analysis conditions

Condition	Value	Condition	Value
Constant voltage	14.8 V	Gearbox	direct drive
Altitude	0÷300 m	Max weight for test	3000 g

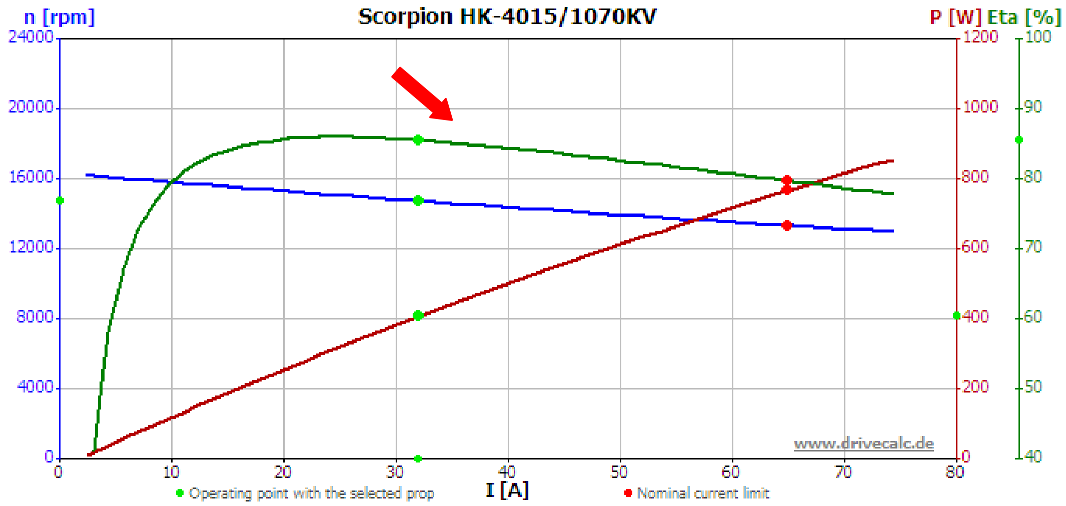


FIG. 6 Features of the 4015 electric motor at constant voltage

Fig. 6 shows the decrease in angular speed (n) but an increase in power depending on the current intensity (maximum 65 A), with a maximum efficiency between 20 and 30 A. Table 3 shows the results of the simulation of the engine operation at four altitude values. Observes an increase of the angular speed (n) with the altitude increase (14709 rot/0 m to 14740 rot/300 m) but there is a decrease of the static traction with the altitude increase (2111g /0 m at 2080/300 m).

Table3. Features of the electric motor for the altitude (constant voltage)

	0 m				100 m		
Prop speed	14719 rpm	Current	32.0 A	Prop speed	14726 rpm	Current	31.9 A
Static thrust	2111 g	Power in	474.1 W	Static thrust	2101 g	Power in	471.5 W
Vpitch	112 km/h	Power out	405.3 W	Vpitch	112 km/h	Power out	403.2 W
Thrust efficiency	4.5 g/W	Drive efficiency	85.5%	Thrust efficiency	4.5 g/W	Drive efficiency	85.5%
	200 m				300 m		
Prop speed	14734 rpm	Current	31.7 A	Prop speed	14740 rpm	Current	31.6 A
Static thrust	2090 g	Power in	469.0 W	Static thrust	2080 g	Power in	467.0 W
Vpitch	112 km/h	Power out	401.2 W	Vpitch	112 km/h	Power out	399.5 W
Thrust efficiency	4.5 g/W	Drive efficiency	85.5%	Thrust efficiency	4.5 g/W	Drive efficiency	85.5%

Fig. 7 shows a repositioning of the operating point corresponding to the currents used (about 28 A current versus 33A at constant current).

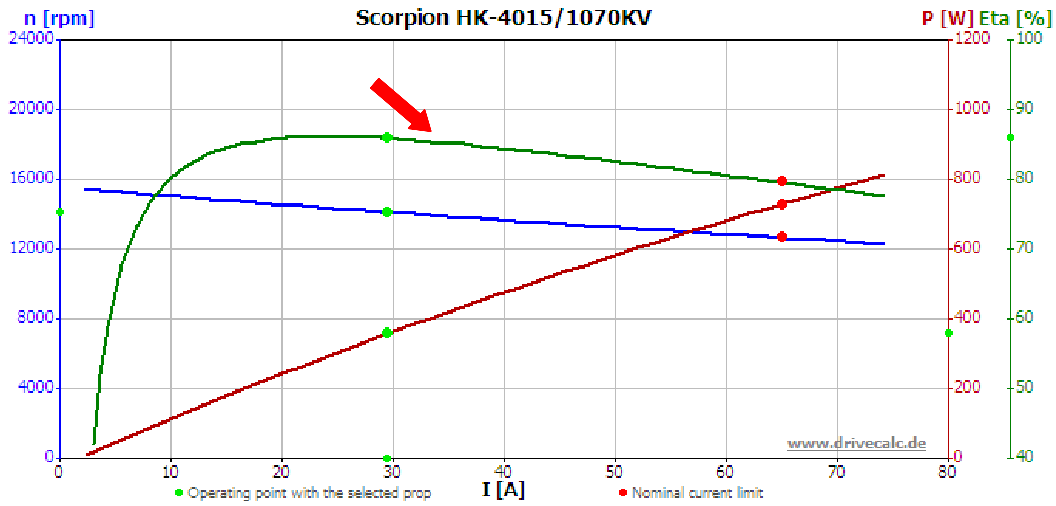


FIG. 7 Features of the 4015 electric motor at the variable voltage

Table 4 shows an increase in angular speed (n) with increasing flight altitude, but also a decrease in power consumption and effective static power (1931 g/ 0 m at 1904 g/ 300 m).

Table 4. Features of the electric motor for the altitude (variable voltage)

0 m				100 m			
Prop speed	14110 rpm	Current	29.5 A	Prop speed	14120 rpm	Current	29.4 A
Static thrust	1931 g	Power in	415.9 W	Static thrust	1922 g	Power in	414.1 W
Vpitch	108 km/h	Power out	357.0 W	Vpitch	108 km/h	Power out	355.5 W
Thrust efficiency	4.6 g/W	Drive efficiency	85.9%	Thrust efficiency	4.6 g/W	Drive efficiency	85.9%
200 m				300 m			
Prop speed	14129 rpm	Current	29.2 A	Prop speed	14139 rpm	Current	29.1 A
Static thrust	1913 g	Power in	412.2 W	Static thrust	1904 g	Power in	410.4 W
Vpitch	108 km/h	Power out	354.0 W	Vpitch	108 km/h	Power out	352.5 W
Thrust efficiency	4.6 g/W	Drive efficiency	85.9%	Thrust efficiency	4.6 g/W	Drive efficiency	85.9%

Table 5 shows the variation in operating characteristics at 0 m depending on the ambient temperature. The speed characteristic increases with temperature increase (14610 rpm / -10^o at 14814 rpm / 40^o) and static traction decreases as the temperature rises (2275g / -10^o at 1969g / 40^o).

Table5. Features of the electric motor for the temperature (variable voltage at 0 m)

-10^o				0^o			
Prop speed	14610 rpm	Current	34.4 A	Prop speed	14656 rpm	Current	33.4 A
Static thrust	2275 g	Power in	509.3 W	Static thrust	2207 g	Power in	494.2 W
Vpitch	111 km/h	Power out	434.0 W	Vpitch	112 km/h	Power out	421.8 W
Thrust efficiency	4.5 g/W	Drive efficiency	85.2%	Thrust efficiency	4.5 g/W	Drive efficiency	85.3%
10^o				20^o			
Prop speed	14700 rpm	Current	32.4 A	Prop speed	14740 rpm	Current	31.6 A
Static thrust	2142 g	Power in	480.1 W	Static thrust	2081 g	Power in	467.0 W
Vpitch	112 km/h	Power out	410.2 W	Vpitch	112 km/h	Power out	399.5 W
Thrust efficiency	4.5 g/W	Drive efficiency	85.5%	Thrust efficiency	4.5 g/W	Drive efficiency	85.5%
30^o				40^o			
Prop speed	14778 rpm	Current	30.7 A	Prop speed	14814 rpm	Current	30.0 A
Static thrust	2023 g	Power in	454.9 W	Static thrust	1969 g	Power in	443.3 W
Vpitch	113 km/h	Power out	389.5 W	Vpitch	113 km/h	Power out	379.9 W
Thrust efficiency	4.4 g/W	Drive efficiency	85.6%	Thrust efficiency	4.4 g/W	Drive efficiency	85.7%

Fig. 8 and Table 6 show an increase in operating time depending on the current supplied by the battery and battery mass.

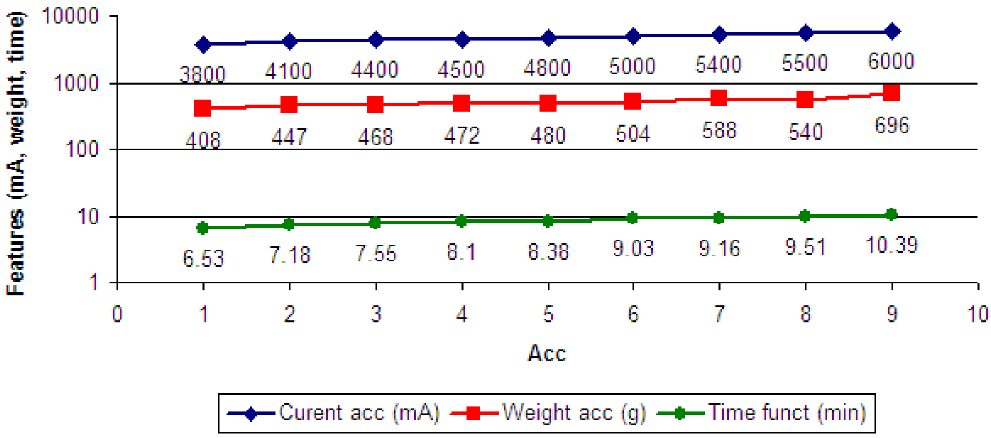


FIG. 8 Autonomy versus battery amperage

Tabelul 6. Flight autonomy simulation

Nr. crt.	Amperage battery (mA)	Battery weight (g)	Time (min)	Nr. crt	Amperage battery (mA)	Battery weight (g)	Time (min)
1	3800	408	6.53	6	5000	504	9.03
2	4100	447	7.18	7	5400	588	9.16
3	4400	468	7.55	8	5500	540	9.51
4	4500	472	8.10	9	6000	696	10.39
5	4800	480	8.38				

4. CONCLUSIONS

The propulsion equipment used in the operation of a multicopter will have a major impact on the payload and the maximum flight mass, which the multicopter type UAV can have with direct implications for total autonomy. The use of multicopter operation simulations used in transport missions during the pre-project phase can provide a picture of how to capture useful tasks with direct implications for flight stability and mission success. Due to the miniaturization of the radio-electronics and propulsion equipment on board multi-copters, we can also talk about a reduction in total drive power consumption and an increase in flight autonomy as we approach a multi-level multilevel constructive concept (two conjugated engines).

The approach to innovative constructive concepts (morphing, multiagent, UAV-UGV-USV hybrid vectors) can generate significant increases in flight characteristics and performance (autonomy, stability / maneuverability).

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