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LONG ENDURANCE ELECTRIC MULTIROTOR UNMANNED AERIAL VEHICLE

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Abstract

The article presents an algorithm for development of a Long endurance electric multirotor unmanned aerial vehicle. Calculations for usage of different types of electric batteries have been made and dependencies of flight time for different weights of batteries have been obtained. Options for quadcopter and sixcopter have been considered.

Notation

C_D – coefficient of drag force;
C_L – coefficient of lift force;
D – drag force of the aircraft;
E_{bat} – energy of the batteries;
$\overline{E_{bat}}$ – specific energy of the batteries;
F – thrust of the propulsions;
g – acceleration of gravity;
K – glade ratio;
K_e – glade ratio by maximum endurance;
K_R – glade ratio by maximum distance;
L – lift force of the aircraft;
m_0 – take-off mass;
m_p – mass of the payload;
m_{bat} – mass of the batteries;
m_{empty} – empty mass of the aircraft;
$\overline{m_{bat}}$ – specific mass of the batteries;

$\overline{\boldsymbol{m_p}}$ – specific mass of the payload;

$\overline{\boldsymbol{m_{empty}}}$ – specific mass of the empty aircraft;

$\boldsymbol{P}$ – power;

$\boldsymbol{P_1}$ – power for 1 motor;

$\boldsymbol{R}$ – distance of the flight;

$\boldsymbol{t}$ – flight time;

$\boldsymbol{t_e}$ – endurance time;

$\boldsymbol{V}$ – air speed of the aircraft;

$\boldsymbol{V_c}$ – cruise speed of the aircraft;

$\boldsymbol{W_0}$ – take-off weight;

$\boldsymbol{\rho}$ – air density.

1. State of the Art

In the past years, sales of multi-rotor unmanned aerial vehicles (UAV) (copters) represent a major part (over 90%) of total sales of such aircraft. This is due to UAV capability to perform take-off and landing on small non-equipped areas, to carry out motionless hovering, and to be easily maintained. The only disadvantage is their relatively short flight endurance due to low energy efficiency. Opportunities for improvement of their aerodynamic and thrust efficiency are almost run out. It is expected that the flight endurance will be increased by developing batteries with higher specific energy $\bar{E} = \frac{E}{m_{bat}}$.

This paper presents a simple and efficient algorithm for development of copters that fulfil customer requirements.

2. Initial Requirements

Customers most frequency requires copters with long endurance at the payload used, which are relatively cheap, that possess high level of reliability and simple maintenance [5–7].

3. Mathematical model

Basic properties and features

Copter mass can be presented as the sum of the masses of individual subsystems:

$$m_o = m_{con} + m_{prop} + m_a + m_p + m_{bat}\ [g]. \quad (1)$$

Required thrust for motionless hovering is a multiplication of required thrust of one propulsor by the number of propulsor:

(2) $F_r = F_1 n\ [N].$

Required thrust of one propulsor is calculated according to the formula by accepting that 4% of the thrust is used to limit displacements caused by air movement:

(3) $F_1 = 1.04\frac{m_o g}{n}\ [N].$

Total required power is:

(4) $P_r = nf(F_1)\ [W].$

Required power of one motor for motionless hovering depends on required thrust. This dependence is presented by manufacturers of electric motors for copters in tables with experimental data. In tables, for a specific motor, propeller and battery voltage, depending on revolutions, are presented data for power consumption and achieved thrust.

According to data by using a parabolic regression we can find the dependence:

(5) $P_1 = f(F_1)\ [W],$

(6) $E = P_r t = \bar{E} m_{bat}\ [Wh],$

(7) $t = \frac{E}{60nP_1} = \frac{\bar{E} m_{bat}}{60nP_1}\ [min].$

For the electric motor U8lite KV150, with the propeller G28*9.2CF and batteries with a voltage of 24 V, the following dependence between power consumption and required thrust can be found:

Table 1

F1, N	**P1, W**
11.54	69.6
12.13	74.4
13.27	84.0
14.37	93.6
15.31	103.2
16.17	110.4
17.51	124.8
18.69	134.4
19.68	146.4
21.12	160.8

F1, N	P1, W
21.85	168.0
22.90	180.0
24.03	194.4
25.01	206.4
26.74	230.4
28.22	247.2
30.89	283.2
34.13	326.4
39.81	415.2
47.86	552.0

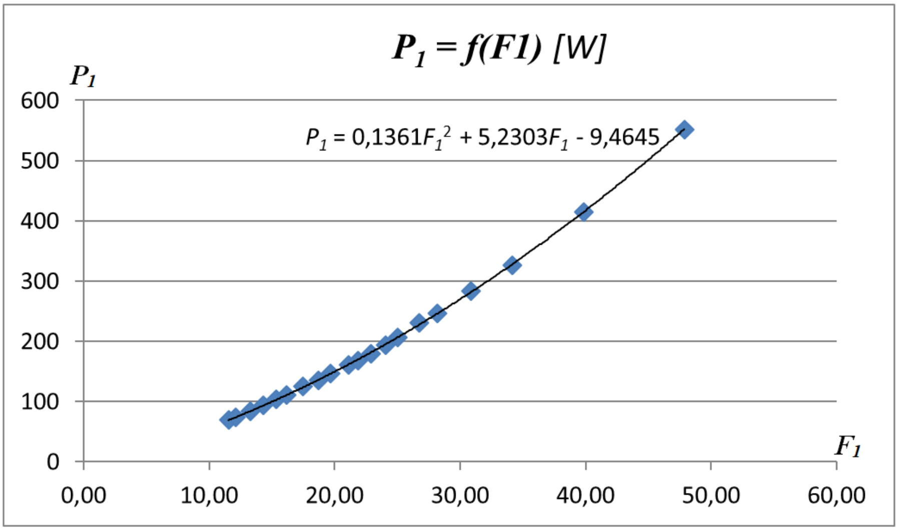

Fig. 1. Parabolic regression

For dependence between power consumption and required thrust of the electric motor U8lite KV150, with the propeller G28*9,2CF and batteries providing 24 V.

When looking at a specific example about designing of an industrial copter, some dependence can be found, which can be used for development of a copter fulfilling customer requirements.

An example is considered where a customer requires a copter capable to carry a payload with gimbal mass of $m_p \leq 1\,500$ g and have a flight time of

$t \geq 90\ min$. Calculations have been performed for two basic copter configurations with four rotors (quadcopters) and six rotors (sixcopters), which are the most frequency used for these payloads. It should be noted that this copter are able to carry higher loads at the expense of a reduced flight time.

After analysis of the masses of the structure, we accept:

- $m_{con4} = 1\ 350$ g for quadcopter;
- $m_{con6} = 2\ 700$ g for sixcopter;
- $m_a = 500$ g for avionics.

An option with a highly effective propulsion system has been considered. The system consists of brushless electric motors U8lite KV150, a propeller G28*9,2CF and batteries with a voltage of 24V. Flight times with different types of batteries and specific electric energy have been compared: ***LiPo*** with $\bar{E} = 200\ Wh/kg$, ***LiION*** with $\bar{E} = 250\ Wh/kg$ and promising batteries which are expected to be used in 2026 with $\bar{E} = 1\ 200\ Wh/kg$.

Table 2

m_{bat}	**Quadcopter**					
	m_0	F_1	P	$\bar{E}$		
				200	**250**	**1 200**
g	**g**	**N**	**W**	***t*, min**		
1 500	6 277	16	437	41.22	51.53	247.33
1 750	6 527	17	461	45.52	56.90	273.12
2 000	6 777	17	486	49.34	61.67	296.02
2 250	7 027	18	512	52.73	65.92	316.40
2 500	7 277	19	538	55.76	69.70	334.56
2 750	7 527	19	564	58.46	73.08	350.77
3 000	7 777	20	591	60.88	76.10	365.26
3 250	8 027	20	619	63.04	78.79	378.22
3 500	8 277	21	646	64.97	81.21	389.81
3 750	8 527	22	675	66.70	83.37	400.18
4 000	8 777	22	703	68.24	85.31	409.47
4 250	9 027	23	732	69.63	87.04	417.77
4 500	9 277	24	762	70.87	88.58	425.19
4 750	9 527	24	792	71.97	89.96	431.82
5 000	9 777	25	822	72.95	91.19	437.73

m_{bat}	**Quadcopter**					
	m_0	F_1	P	$\bar{E}$		
				200	**250**	**1 200**
g	**g**	**N**	**W**	***t*, min**		
5 250	10 027	26	853	73.83	92.29	442.99
5 500	10 277	26	885	74.61	93.26	447.65
5 750	10 527	27	916	75.30	94.12	451.78
6 000	10 777	27	949	75.90	94.88	455.42
6 250	11 027	28	981	76.43	95.54	458.61
6 500	11 277	29	1 014	76.90	96.12	461.39
6 750	11 527	29	1 048	77.30	96.63	463.81
7 000	11 777	30	1 082	77.65	97.06	465.88
7 250	12 027	31	1 116	77.94	97.43	467.64
7 500	12 277	31	1 151	78.19	97.73	469.12
7 750	12 527	32	1 186	78.39	97.99	470.33
8 000	12 777	33	1 222	78.55	98.19	471.30
8 250	13 027	33	1 258	78.68	98.34	472.05
8 500	13 277	34	1 295	78.77	98.46	472.60
8 750	13 527	35	1 332	78.83	98.53	472.96
9 000	13 777	35	1 370	78.86	98.57	473.15
9 250	14 027	36	1 408	78.86	98.58	473.17
9 500	14 277	36	1 446	78.84	98.55	473.06
9 750	14 527	37	1 485	78.80	98.50	472.80
10 000	14 777	38	1 524	78.74	98.42	472.43
10 250	15 027	38	1 564	78.66	98.32	471.93
10 500	15 277	39	1 604	78.56	98.20	471.34
10 750	15 527	40	1 645	78.44	98.05	470.64

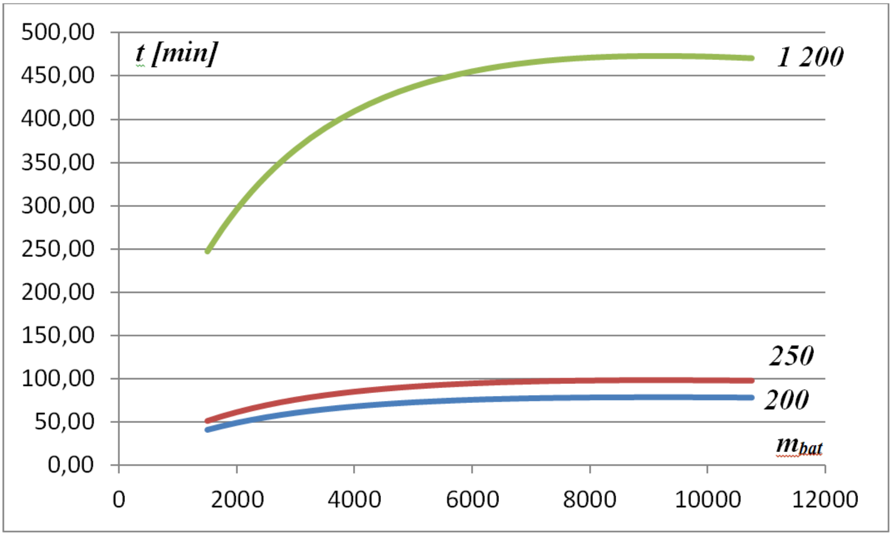

Fig. 2. Flight endurance of a quadcopter
according to the mass of batteries at $\bar{E} = 200, 250$ *and* $1200\ Wh/kg$

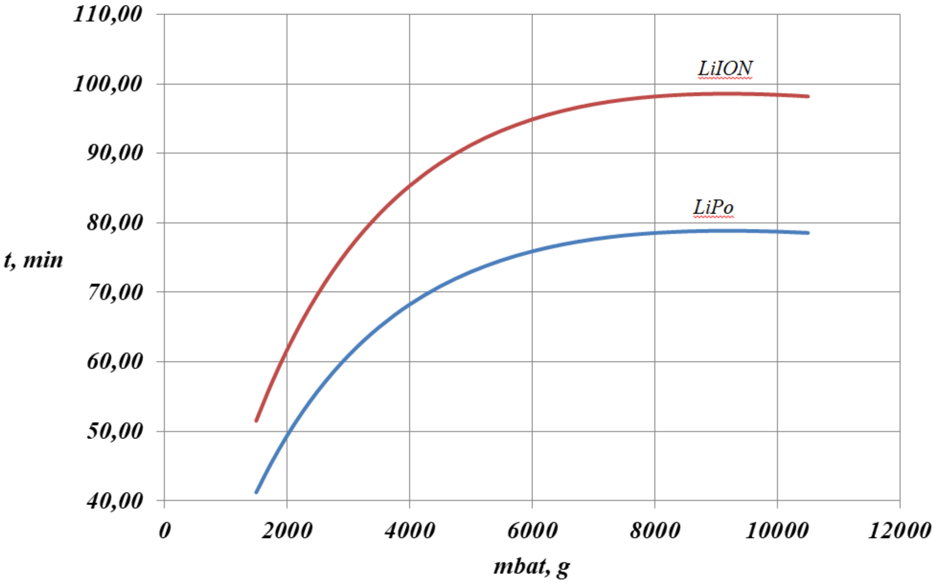

Fig. 3. Flight endurance of a quadcopter
with a battery ***LiPo*** *at* $\bar{E} = 200$ *and* ***LiION*** *at* $\bar{E} = 250 Wh/kg$
according to the mass of batteries

Following conclusions can be drawn according to table data and figures:

- The maximum endurance with *LiPo* batteries is less than 80 min which do not fulfill customer requirements;
- Required flight time can be only achieved when using ***LiION*** batteries with a mass of $m_{bat} = 5\ 000$ g and $m_0 = 9\ 777$ g. By using these types of batteries with a higher mass, the flight endurance increases slightly. Maximum endurance of 98,58 min is reached by using batteries with a mass of $m_{bat} = 9\ 850$ g and $m_0 = 14\ 027$ g;
- With promising batteries, the required endurance will be achieved at $m_{bat} \leq 1\ 500$ g and $m_0 \leq 6\ 000$ g. Promising batteries will provide flight endurance over 8.5 hours so that the usage of other sources of energy will be inefficient.

When designing, several copter configurations should be explored in order to achieve the best solution. In this case, the scheme of a sixcopter is considered.

Table 3

mbat	**Sixcopter**					
	m0	**F1**	**P**	**Espec**		
				200	**250**	**1 200**
g	**g**	**N**	**W**	**t, min**		
1 500	8 341	21	654	27.54	34.42	165.24
1 750	8 591	22	682	30.79	38.49	184.77
2 000	8 841	23	711	33.77	42.21	202.61
2 250	9 091	23	740	36.49	45.61	218.94
2 500	9 341	24	770	38.98	48.73	233.89
2 750	9 591	24	800	41.27	51.58	247.59
3 000	9 841	25	830	43.36	54.20	260.17
3 250	10 091	26	861	45.28	56.61	271.71
3 500	10 341	26	893	47.05	58.81	282.30
3 750	10 591	27	925	48.67	60.84	292.04
4 000	10 841	28	957	50.16	62.71	300.99
4 250	11 091	28	990	51.54	64.42	309.21
4 500	11 341	29	1 023	52.80	65.99	316.78
4 750	11 591	30	1 056	53.95	67.44	323.73
5 000	11 841	30	1 091	55.02	68.77	330.11
5 250	12 091	31	1 125	56.00	70.00	335.98

mbat	**Sixcopter**					
	m0	**F1**	**P**	**Espec**		
				200	**250**	**1 200**
g	**g**	**N**	**W**	**t, min**		
5 500	12 341	31	1 160	56.89	71.12	341.37
5 750	12 591	32	1 195	57.72	72.15	346.31
6 000	12 841	33	1 231	58.47	73.09	350.84
6 250	13 091	33	1 268	59.17	73.96	355.00
6 500	13 341	34	1 304	59.80	74.75	358.80
6 750	13 591	35	1 342	60.38	75.47	362.27
7 000	13 841	35	1 379	60.91	76.13	365.44
7 250	14 091	36	1 417	61.39	76.73	368.32
7 500	14 341	37	1 456	61.82	77.28	370.94
7 750	14 591	37	1 495	62.22	77.77	373.32
8 000	14 841	38	1 534	62.58	78.22	375.46
8 250	15 091	38	1 574	62.90	78.62	377.39
8 500	15 341	39	1 614	63.19	78.98	379.13
8 750	15 591	40	1 655	63.45	79.31	380.67
9 000	15 841	40	1 696	63.67	79.59	382.04
9 250	16 091	41	1 738	63.88	79.84	383.25
9 500	16 341	42	1 780	64.05	80.06	384.31
9 750	16 591	42	1 822	64.20	80.26	385.23
10 000	16 841	43	1 865	64.33	80.42	386.01
10 250	17 091	44	1 909	64.44	80.56	386.67
10 500	17 341	44	1 952	64.53	80.67	387.20
10 750	17 591	45	1 997	64.61	80.76	387.64

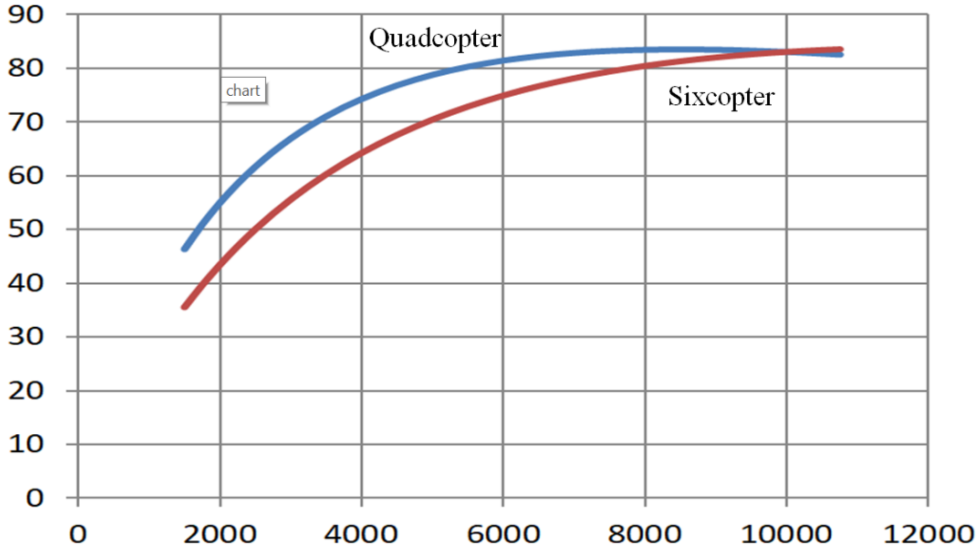

Fig. 4. Flight endurance of a quadcopter and sixcopter according to the mass of batteries at $\bar{E} = 200\ Wh/kg$

The tables and diagrams show that a sixcopter is not able to provide the required flight endurance.

Conclusion

The algorithm allows to find options that fulfil customer requirements and to eliminate options which do not fulfil these requirements and also are not competitive.

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МНОГОРОТОРЕН БЕЗПИЛОТЕН ЛЕТАТЕЛЕН АПАРАТ С ГОЛЯМА ПРОДЪЛЖИТЕЛНОСТ НА ПОЛЕТА

Д. Зафиров

Резюме

В тази статия се предлага алгоритъм за проектиране на многороторен безпилотен летателен апарат с голяма продължителност на полета. Направени са пресмятания за използването на различни видове батерии, като са получени зависимости на полетното време за различни техни маси. Разгледани са варианти за четирироторен и шестроторен безпилотни летателни апарати.