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;
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:

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

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

\[ F_1 = 1.04 \frac{m_{\text{ag}}}{n} \text{ [N]}. \]

Total required power is:

\[ P_r = nf(F_1) \text{ [W]}. \]

Table 1

| \( F_1, \text{ N} \) | \( P_1, \text{ W} \) |
|---------------------|-------------------|
| 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 |

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 \( m_p \leq 1500 \) g and have a flight time of
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:

- $m_{con4} = 1350\, g$ for quadcopter;
- $m_{con6} = 2700\, g$ 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 $\bar{E} = 1200\, Wh/kg$.

**Table 2**

| $m_{bat}$ g | $m_0$ g | $F_1$ N | $P$ W | $\bar{E}$ 200 | $\bar{E}$ 250 | $\bar{E}$ 1200 |
|-------------|---------|---------|-------|---------------|---------------|---------------|
| 1500        | 6277    | 16      | 437   | 41.22         | 51.53         | 247.33        |
| 1750        | 6527    | 17      | 461   | 45.52         | 56.90         | 273.12        |
| 2000        | 6777    | 17      | 486   | 49.34         | 61.67         | 296.02        |
| 2250        | 7027    | 18      | 512   | 52.73         | 65.92         | 316.40        |
| 2500        | 7277    | 19      | 538   | 55.76         | 69.70         | 334.56        |
| 2750        | 7527    | 19      | 564   | 58.46         | 73.08         | 350.77        |
| 3000        | 7777    | 20      | 591   | 60.88         | 76.10         | 365.26        |
| 3250        | 8027    | 20      | 619   | 63.04         | 78.79         | 378.22        |
| 3500        | 8277    | 21      | 646   | 64.97         | 81.21         | 389.81        |
| 3750        | 8527    | 22      | 675   | 66.70         | 83.37         | 400.18        |
| 4000        | 8777    | 22      | 703   | 68.24         | 85.31         | 409.47        |
| 4250        | 9027    | 23      | 732   | 69.63         | 87.04         | 417.77        |
| 4500        | 9277    | 24      | 762   | 70.87         | 88.58         | 425.19        |
| 4750        | 9527    | 24      | 792   | 71.97         | 89.96         | 431.82        |
| 5000        | 9777    | 25      | 822   | 72.95         | 91.19         | 437.73        |
| $m_{bat}$ (g) | $m_0$ | $F_1$ | $P$ (N·W) | $\bar{E}$ | $t$, 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 $\overline{E} = 200, 250$ and $1200 \text{ W h/kg}$

Fig. 3. Flight endurance of a quadcopter with a battery LiPo at $\overline{E} = 200$ and LiION at $\overline{E} = 250 \text{ W h/kg}$ 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 | m0     | F1 | P  | Espec |
|------|--------|----|----|-------|
| g    | g   | N  | W  | t, min |
|      |      |    |    | 200 | 250 | 1 200 |
| 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 | m0  | F1  | P   | Espec |       |       |
|------|-----|-----|-----|-------|-------|-------|
|      | g   | g   | N   | W    | 200   | 250   |
| 5 500 | 12341 | 31 | 1160 | 56.89 | 71.12 | 341.37 |
| 5 750 | 12351 | 32 | 1195 | 57.72 | 72.15 | 346.31 |
| 6 000 | 12341 | 33 | 1231 | 58.47 | 73.09 | 350.84 |
| 6 250 | 13091 | 33 | 1268 | 59.17 | 73.96 | 355.00 |
| 6 500 | 13341 | 34 | 1304 | 59.80 | 74.75 | 358.80 |
| 6 750 | 13591 | 35 | 1342 | 60.38 | 75.47 | 362.27 |
| 7 000 | 13841 | 35 | 1379 | 60.91 | 76.13 | 365.44 |
| 7 250 | 14091 | 36 | 1417 | 61.39 | 76.73 | 368.32 |
| 7 500 | 14341 | 37 | 1456 | 61.82 | 77.28 | 370.94 |
| 7 750 | 14591 | 37 | 1495 | 62.22 | 77.77 | 373.32 |
| 8 000 | 14841 | 38 | 1534 | 62.58 | 78.22 | 375.46 |
| 8 250 | 15091 | 38 | 1574 | 62.90 | 78.62 | 377.39 |
| 8 500 | 15341 | 39 | 1614 | 63.19 | 78.98 | 379.13 |
| 8 750 | 15591 | 40 | 1655 | 63.45 | 79.31 | 380.67 |
| 9 000 | 15841 | 40 | 1696 | 63.67 | 79.59 | 382.04 |
| 9 250 | 16091 | 41 | 1738 | 63.88 | 79.84 | 383.25 |
| 9 500 | 16341 | 42 | 1780 | 64.05 | 80.06 | 384.31 |
| 9 750 | 16591 | 42 | 1822 | 64.20 | 80.26 | 385.23 |
| 10 000 | 16841 | 43 | 1865 | 64.33 | 80.42 | 386.01 |
| 10 250 | 17091 | 44 | 1909 | 64.44 | 80.56 | 386.67 |
| 10 500 | 17341 | 44 | 1952 | 64.53 | 80.67 | 387.20 |
| 10 750 | 17591 | 45 | 1997 | 64.61 | 80.76 | 387.64 |
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.