Concept for composition of hybrid flying multi-rotor platforms with distributed load and its experimental justification

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Abstract. This paper discusses the main approaches to the development and construction of hybrid flying multi-rotor platforms with separation of lift control functions and angular stabilization functions, called by the authors "distributed load". A significant fact that limits flight time for majority of multi-rotor platforms is the energy density limit of lithium polymer batteries, which are most commonly used. To solve this problem we analyzed possible ways to increase flight time: replacing the main type of energy carrier for a more energy-intensive one and use of hybrid systems with combination of popular lithium-polymer batteries and a more energy-intensive energy carrier. The analysis was supported by experimental data.

1. Introduction

More recently various multi-rotor platforms (MRP) became popular in all spheres of life: monitoring agricultural land, exploration, searching for forest fires and transporting small goods [1]. But most multi-rotor systems have an essential drawback - the flight time is usually limited to 15-30 minutes. This limitation is associated with insufficient energy consumption of the lithium polymer batteries used in these devices. Nonetheless they are used frequently since this type of battery is the best among chemical cells [2].

The most obvious way to increase flight time is to use energy source with increased capacity. But this method is limited by the available thrust of the vehicle and the so-called "hover thrust" - the required amount of thrust to ensure that the craft is hovering in the air. The main problem with this approach is increase of weight of the battery and, consequently, decrease of payload and available thrust of the multi-rotor platform. It should be noted that dependence of the mass of the battery or the accumulated energy in it on the flight time is non-linear and depends on vehicle mass, battery capacity (its mass, as a matter of fact) and power of motors required for hovering mode [3]. To draw general equation for total vehicle flight time we note down general formulae: power on propeller $N$, battery energy $Q$ and vehicle mass $P$.

In the process of analytical research, which we cannot cite in view of the limited volume of the article, we have established:

$$N = \frac{\beta}{D \cdot \sqrt{\rho \cdot \mu}} \left(\frac{P}{\sqrt{a}}\right)^{\frac{3}{2}}$$  \hspace{1cm} (1)$$

$$Q = N \cdot t = q \cdot m_a$$  \hspace{1cm} (2)$$

$$P = m \cdot g$$  \hspace{1cm} (3)
\[ m = m_0 + m_a \]  

here \( m_a \) is the mass of the battery, \( m_0 \) is the mass of the vehicle without battery, \( m \) is the total vehicle mass, \( q \) is battery energy density, \( \rho \) is density of air, \( \alpha \) и \( \beta \) are thrust and power multiplicators correspondingly, and \( D \) is propeller diameter.

Using these equations, we can formulate vehicle flight time as

\[ t = \frac{D \cdot \sqrt[3]{\rho \cdot q \cdot m_a}}{\beta \cdot \left( m_0 + m_a \right)^\frac{3}{2} \cdot g} \]  

or

\[ t(m_a) = k \cdot \frac{m_a}{(m_0 + m_a)^\frac{3}{2}} \]  

Let’s define maximum of function:

\[ t(m_a) = k \cdot \frac{(m_0 + m_a)^3 - m_a \frac{3}{2} (m_0 + m_a)^2}{(m_0 + m_a)^3} = 0 \]

Therefore, to obtain maximum vehicle flight time we have to choose battery parameters due to equation:

\[ m_a = 2m_0 \]  

For more detailed analysis we should compare two extreme cases: \( m_a \gg m_0 \) и \( m_0 \gg m_a \)

\[ t_{m_a \gg m_0} = k \cdot \frac{m_a}{(m_0)^\frac{3}{2}} \]  

\[ t_{m_0 \gg m_a} = k \cdot \frac{1}{\sqrt{m_a}} \]  

These curves will approximate to flight time curve asymptotically (figure 1) and help us to define borders of flight time graph.

**Figure 1.** Flight time to battery mass correspondence.
In study of such question we have analyzed parameters of many different vehicles. On this base we have statistical approximation for such data. For example, with vehicle massed 400 grams maximum flight time is acquired with battery massed 687 grams (figure 2). It shows that equation (7) is estimative, and to precise calculation of these parameters we should give consideration to engine-propeller combination [4,5].

![Figure 2. Statistical data for flight time/battery capacity dependence (for energy density as 130 W*h/kg).](image)

Considering the above we decided to investigate the possibility of increasing flight time using other types of drives in multi-rotor platforms.

2. Comparison of different types of energy carriers
At present moment we have such most popular rechargeable batteries as:
- Lead batteries
  Lead batteries are quite safe and are mainly used in the automotive industry or in mobile systems, where there are no hard restrictions on the weight of the apparatus. It Not used in multi-rotor systems, but due to their high prevalence, it was decided to add them to the study. Average energy density - 0.13 MJ/kg.
- Lithium ion and lithium polymer batteries
  This type of battery is widely used in mobile devices and systems. They are less safe compared to lead batteries because they have a high heating effect when used. It should be noted that this type of battery is susceptible to fire if the protective shell is damaged. Average energy density - 0.72 MJ/kg.

Necessity to of flight time of multi-rotor vehicles necessitates for study of alternative energy sources, such as gasoline and hydrogen fuel [6].

Such alternatives are hydrogen fuel and gasoline. These types of energy carriers have an average energy density much higher than the previously mentioned types of storage devices. For hydrogen fuel the average energy density is 120 MJ/kg, and for gasoline fuel it is 40 MJ/kg.

But a significant disadvantage is the difficulty in converting stored energy into electrical energy. In the case of hydrogen fuel, actual fuel cells use platinum and rare-earth metal catalysts so have very high price. Also it necessitates hydrogen with low impurities. Usage of other types of catalyst lowers cell efficiency. Moreover, the fuel cells have low speed of chemical reaction within so it can't provide necessary power on peak load without additional energy accumulator. Also, hydrogen is an explosive substance, which imposes restrictions on the use and certification of devices.

When using hydrocarbon fuel, for example gasoline, as the main type of energy storage for multi-rotor vehicles, the method of using an internal combustion engine (ICE) to convert fuel combustion energy into mechanical energy and using this energy to rotate the generator shaft is quite popular. Taking into account the high energy consumption of gasoline, it should be noted the efficiency of the internal
combustion engine (about 50-60%) and the efficiency of the generator (70-90%). Thus, at the output of such a system, we get an efficiency of about 35-55%. But even with this ratio, we get the energy density much higher than that of lithium-polymer batteries - 0.72 MJ/kg versus 14-22 MJ/kg (figure 3).

Figure 3. Energy density in various storage devices.

3. Using hybrid systems to increase flight time

As it was recognized above, the problem of increasing flight time can be solved by using alternative energy sources. Most available and popular kind of hydrocarbon fuel is petroleum. At the present time there are some vehicles those have hybrid power system.

For example, there is an engineering design that uses 4 internal combustion engines [7], coaxially connected to low-inertia electric motors. Authors idea is that electric motors should accelerate or decelerate the internal combustion engines to ensure angular stabilization. This scheme, in our opinion, has a significant drawback - part of the available power of the internal combustion engine is lost when the engine is braking.

There is a more optimized and popular option in which the internal combustion engine is connected to a generator [8,9]. In this case, the internal combustion engine operates at the most efficient mode, and the available energy from the generator is constant.

But as mentioned above, with such a scheme, we have an additional efficiency loss in internal combustion engine-generator combination, and an additional 10-30% of energy is lost. Therefore, we proposed a scheme in which the output power from the internal combustion engine is used to rotate the "power propellers", which provide 70-90% of the vehicle thrust, and for angular stabilization we use low-inertia electric motors, those supply the remaining percentage of thrust [10,11]. To implement this transmission method, a special transmission was developed using a reduction gear and a belt drive.

When analyzing the capabilities of a hybrid multi-rotor platform, an important place takes up the issue of assessing the time it spends in the air and the factors those have an effect for its increase. For simplicity we will consider the mode of "hovering" of the MRP over the earth's surface in the absence of wind. It is this approach that is being investigated when setting records for the time spent in the air for devices of this class.

Let us use the well-known formulae for the thrust $T_1$ of one of the MRP lift rotor and the power $N_1$ supplied to the propeller [12]:

$$T_1 = \alpha \rho n_1^2 D_1^4,$$

(11)
\[ N_t = \beta \rho n_s^2 D_1^5, \]  
(12)

where \( \rho \) is the air density, \( n_s \) is the rotational speed of the propeller (rps); \( \alpha \) and \( \beta \) are the thrust and power coefficients, respectively; \( D_1 \) - diameter of one propeller.

After excluding \( n_s \) from (11) and (12) we will have:

\[ N_t = \beta \left( \frac{T_1}{\alpha} \right)^{\frac{3}{2}}. \]  
(13)

therefore, the power required to rotate the propeller increases with increasing thrust less intensively than the linear dependence, which is constructively favorable.

If we divide (11) by (12), we obtain the equation for thrust and power, which is important for the design of the MRP:

\[ \frac{T_1}{N_t} = \frac{\alpha \cdot \pi}{\beta} \cdot \frac{1}{V_1}. \]  
(14)

where \( V_1 = n_s \cdot \pi \cdot D_1 \) is the linear speed of the tip of the propeller blade during rotation. Ratio \( \frac{T_1}{N_t} \) characterizes the propulsive quality of the rotor motor group MRP - the less mechanical power per unit of thrust \( T_1 \) of one propeller, the higher the quality.

Formula (14) shows that a radical means of the ratio of the power of the power plant to the value of the specific fuel consumption is a decrease in the linear speed \( V_1 \). This is possible according to (13) by increasing the diameter \( D_1 \) of each of the propellers However, this is due to the growth of the entire structure, therefore, in addition to the trend reflected in equation (14) other factors have to be taken into account also.

Let's approach the estimation of the flight time. We will assume that the starting mass of the MRP is equal to \( m_0 \), the fuel stock is equal to \( m_f \). By the end of the flight, the mass of the MRP will obviously be equal to \( m_f = m_0 - m_f \). Let us also assume that the power of the internal combustion engine \( N_E \) is transferred to the four main rotors of MRP with the efficiency \( \eta \). As a result, we have:

\[ N_E \cdot \eta = 4m g \cdot \frac{\beta}{\alpha \pi} \cdot V_1, \]  
(15)

where \( m \) is the mass of the MRP, \( g = 9.8 \frac{m}{s^2} \) is the acceleration of gravity.

If we know the specific fuel consumption \( c_e \) per power unit then for the fuel consumption \( G_T \) we will have:

\[ G_T = c_e \cdot N_E. \]  
(16)

Taking into account that the derivative of the mass of the MRP with fuel consumption has a negative value, we can write:

\[ \dot{m}(t) = -c_e \cdot N_E. \]  
(17)

Eliminating \( N_E \) from (15) and (17), we arrive at the differential equation

\[ -\frac{\dot{m}(t)}{c_e} = \frac{4 \cdot \beta \cdot g \cdot V_1}{\eta \cdot \alpha \cdot \pi} \cdot m(t), \]  
(18)

or

\[ \tau \cdot \dot{m}(t) + m(t) = 0, \]  
(19)

\[ m(t) = m_0 e^{-\frac{t}{\tau}}, \]  
(20)

where \( \tau = \frac{\eta \alpha \pi}{c_e 4 \beta g V_1} \) is the time constant of the investigated dynamic system.
As it is known, the solution to equation (19) is an exponential dependence of the form (20), the graph of which is shown in figure 3.

For clarity, let us compare a device using a hybrid system based on an internal combustion engine generator and a device using only a lithium polymer battery (figure 4). Graph shows amount of energy W(t) and We(t) expended for flight by hybrid and classic quadcopter designs correspondingly. As it can be seen from the graphs, a system with a hybrid system is 300% more efficient.

![Figure 4. Change in stored energy amount during flight for classic and hybrid designs](image)

To compare flight times, draw a tangent line to the point where the required amount of engine power is less than idle power. In other words, to hover the vehicle power required is less than the minimum output power of the internal combustion engine. In addition, a system with a hybrid propulsion system has a minimum weight of more than 5 kg, while the mass of batteries in electric versions of MRP usually does not exceed 4.5-5 kg.

When considering this it becomes obvious that there is an optimal flight time for vehicles using various energy carriers: for vehicles using lithium polymer batteries, the flight time is up to 1-2 hours, and for hybrid vehicles, 1.5 hours and more [13] (figure 5).

![Figure 5. Research of the optimality of the choice of the main energy carrier on multi-rotor apparatus.](image)
4. “Distributed load” concept

As it was mentioned above, the bulk of modern hybrid systems are built on the principle of transferring power of internal combustion engine to electric power with the generator [14]. With this scheme, the efficiency of the system will be approximately equal to 35-55%. We have proposed a scheme with an efficiency of the order of 45-56%, which we called a “distributed load system” (figure 6).

![Figure 6. Comparison of different schemes for increasing the flight time of MRP.](image)

The essence of this system is to distribute the function of providing the main part of the thrust and angular stabilization. The main part of the thrust is provided with the internal combustion engine, the torque of which is transmitted to the gearbox, from which, with a belt drive, it is subsequently transmitted to the "lifting propellers". This approach allows unloading the control rotor up to 10% of the main thrust, which provides the necessary moments for stable angular stabilization [15]. Such composition requires to take in account joint effect of lifting and control propellers to eliminate possibility of satiation in control propellers system that leads to vehicle control failure. Tests confirmed that angular stabilization requires 10% of thrust. When thrust becomes higher than 90% if maximum, angular stabilization becomes unstable (figure 7).

![Figure 7. Experimental data for dependence of engine thrust and reference signal.](image)
In the course of the experiments, it was found that due to the increase in the inertia of the design, the standard yaw angle control scheme using unbalanced angular velocities is not enough. Therefore, it was decided to exclude the participation of control motors in the yaw angle control loop and to equip the MRP with aerodynamic rudders (figure 8).

**Figure 8.** External view of MRP with distributed load. 1 - mounting frame, 2 - landing gear, 3 - control motors, 4 – control propellers, 5 - flight controller, 6 – rechargeable battery, 7 - rudders, 8 – rudders servo, 9 - power propellers, 10 - internal combustion, 11 - electricity generator, 12 - throttle actuator, 13 - reduction gear, 14 - output shafts, 15 - belt transmission.

5. Conclusion

At the moment, there is a problem of increasing the flight time of multi-rotor systems. To solve it, the existing limitations and possible ways to increase the flight time were analyzed. The analysis revealed the dependence of the battery mass on the vehicle mass to achieve the maximum flight duration.

Also, existing solutions and developed options were found using hybrid power plants based on a combination of internal combustion engines and a generator. For vehicles with a flight time of less than 1-1.5 hours, it is more profitable to use lithium polymer batteries, and for a longer flight time, you should use schemes using hybrid power plants.

We have proposed a concept of load distributing, which is 10-15% more effective than a scheme using a generator. When using the principle of distributing the load on the MRP of the classical yaw angle control scheme by unbalancing the angular velocities of the motors, it is not enough, and it becomes necessary to equip the apparatus with additional aerodynamic rudders for yaw angle control.

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