Ensuring Straight-Line Motion of the Hexacopter in Case of One Engine Failure

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***Abstract* – It has been observed that the number of accidents due to technical malfunctions in the engines of drone-type unmanned aerial vehicles during mass production has risen significantly. When one of the aircraft's engines fails, the remaining engines must compensate to maintain the mission. This research focuses on the challenges of controlling hexacopter-type unmanned aerial vehicles with six engines in the event of a single engine failure. The paper outlines the mathematical principles for managing the hexacopter's engines so that it can continue operating as it did before the malfunction. The findings indicate that the limited power of the remaining engines may not be enough to sustain the mission without adjustments.**

***Keywords* – unmanned aerial vehicle, hexacopter, faulty engine, straight trajectory, control**

I. Introduction

The rapid development of microelectronics has recently spurred the creation of various types of unmanned aerial vehicles (UAVs). Depending on the characteristics of the tasks they perform and the operational requirements, these UAVs are equipped with different devices (such as photo-video cameras, brackets for suspending loads, relays, weapon mounts, etc.). However, in all cases, the UAV's primary task is to fly along the designated route to successfully complete the assigned mission.

As the usage of UAVs increases, so does the frequency of accidents caused by malfunctions in the engine-control system. One of the most common issues encountered is the failure of one or more engines during flight. Due to the widespread use of multi-engine drones, various types of these drones have become particularly popular, depending on their intended purpose and the demands placed on them [1-4].

Unlike single-engine drones, engine failure in multi-rotor devices can lead to safety concerns. Numerous published articles suggest addressing this issue by redesigning the control law or adjusting the control power [5, 6]. However, this approach is difficult to implement, as altering the control power of the engines often requires additional measures, including the integration of extra equipment and devices.

Most scientific and technical literature dedicated to this topic primarily focuses on quadcopters with only one engine failure. These studies mainly explore flight control based on the Euler or Krylov angles for orientation, but there is insufficient material on how to control hexacopters when one engine fails, using quaternion theory methods to describe orientation.

In this research, the possibility of controlling a hexacopter in the event of one engine failure, under conditions of limited engine power, is examined (Figure 1). The proposed approach can help ensure proper control when engine malfunctions occur and increase the likelihood of successfully performing an emergency landing maneuver.

Figure 1. General description of Əqrəb 5.0.

II. PROBLEM STATEMENT

When examining the case where there are no limitations on the hexacopter's engine power (referred to as the "normal condition" below), it becomes evident that even if two symmetrically positioned engines (Figure 2) fail, the hexacopter can still be controlled along a straight trajectory. The failure of one engine refers to a scenario where one out of the six engines on the hexacopter is not functioning. In such cases, the engine symmetrically positioned relative to the center of the hexacopter is typically turned off.

It is clear that when the number of engines decreases from six to four, it becomes necessary to increase the power of the remaining engines. When the hexacopter's flight speed is low - in other words, when the engines are operating at lower power—turning off one symmetric engine and increasing the power of the remaining four may be sufficient to maintain the required speed. However, at higher flight speeds, maintaining that speed with only four engines may not be possible due to the existing power limitations.

This raises the question of whether, in a hexacopter with engine power limitations, the failure of one engine can be compensated for by the remaining five engines. This issue is investigated in the article. Below, the mathematical formalization and solution of the problem are presented.

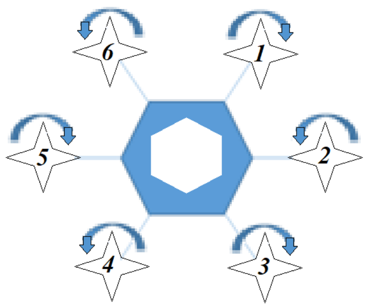

Figure 2. A schematic representation of a hexacopter

III. KEY CONDİTİONS FOR ROUTE FLİGHT CONTROL

When writing the mathematical model for controlling a UAV, two coordinate systems are often considered. These include the inertial coordinate system O_GXYZ attached to the Earth, with its origin O_G fixed at a specific point on the Earth's surface, and the local coordinate system $Oxyz$ attached to the hexacopter, with its origin located at the center of gravity of the hexacopter, used to determine its orientation in space (Figure 3).

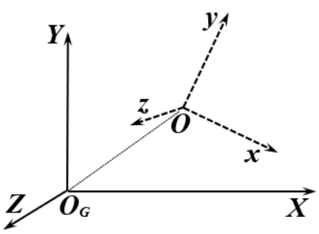

Figure 3. The local and inertial coordinate systems.

We will assume that the Ox axis lies along the first arm of the hexacopter, the Oz axis is perpendicular to the Ox axis within the plane where the arms are positioned, and the Oy axis is directed along the symmetry plane, perpendicular to the Oxy. It is considered that in the horizontal stationary state, the Oy axis is directed upwards, and the $Oxyz$ system is a positively oriented coordinate system.

For the hexacopter to fly along a straight line relative to the Earth's coordinate system O_GXYZ, it is first oriented appropriately by adjusting the rotational speeds of its propellers, achieving the necessary pitch. Once this orientation is established, the hexacopter is controlled along the desired trajectory using the engines, which continue to operate at the appropriate rotational speeds.

It should be noted that this article does not address the calculation of propeller rotation speeds for changing the UAV's orientation.

The UAV's flight along the straight segments of the route differs mainly in terms of direction and how the altitude changes along these segments. Therefore, to determine the solution principle for finding the control parameters of the flight along the route, each straight segment of the route can be considered separately.

Therefore, without loss of generality, it can be assumed that the hexacopter is designed to fly at a specific speed along a straight line connecting two points, $A(x_a, z_a, 0)$ and $B(x_b, z_b, 0)$, within a given plane.

It should be noted that if the hexacopter had a tilt (roll), it would not be able to maintain a straight flight. The non-zero angle formed between the engine's rotational axis and the flight plane would generate a moment that would force the hexacopter to deviate from that plane. Additionally, the pitch of the hexacopter must be adjusted so that the thrust from the engines compensates for the combined forces of gravity and aerodynamic drag along the O_GZ axis.

This ensures the hexacopter remains on the intended straight path, avoiding deviations due to roll or misaligned thrust.

As illustrated in Figure 1, the rotational axes of the engines in the examined type of hexacopters are aligned parallel to the Oy axis and form a right angle with the Oxz plane. For the hexacopter to progress along the designated AB trajectory, it must adjust its spatial orientation by an angle φ so that the thrust produced by the engines can counterbalance the gravitational force and the aerodynamic drag from the air.

The value of angle φ is determined based on the hexacopter's design (aerodynamic properties) and mass [7]. In this research, the angle a is assumed to be known.

Therefore, it is necessary to determine the rotational frequencies $\omega_1, \ldots, \omega_6$ of the engines in such a way that the UAV flies along a specific AB trajectory at a certain speed $v_0 = (v_x, v_y, 0)$ relative to the $OXYZ$ coordinate system, while maintaining a constant spatial orientation.

Taking this into account in the hexacopter's equations of motion, and in accordance with [7], the following can be written:

$$\begin{cases} -\omega_2^2 + \omega_3^2 + \omega_5^2 - \omega_6^2 = 0, \\ \omega_1^2 - \frac{1}{2}\omega_2^2 + \omega_3^2 - \omega_4^2 + \frac{1}{2}\omega_5^2 - \omega_6^2 = 0, \\ \omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2 + \omega_5^2 - \omega_6^2 = 0, \end{cases} \quad (1)$$

$$\sum_{i=1}^{6} \omega_i^2 = f_0. \quad (2)$$

Here $f_0 = c_A|\boldsymbol{v}_0|v_z + mg\cos\varphi$, m -hexacopter's mass and c_A - aerodynamic drag coefficient.

Thus, the quantities $\omega_1, \ldots, \omega_6$ that meet the proposed requirements must satisfy the system of equations (1)-(2).

IV. ENSURİNG CONTROL İN NORMAL OPERATİNG MODE

Let's assume that all motors of the hexacopter are functioning properly. In this case, we will investigate the determination of the quantities $\omega_1, \ldots, \omega_6$ that satisfy the system of equations (1)-(2).

For each k denote ω_k^2 as ξ_k, $k = 1, 2, \ldots, 6$.

Thus, the system of equations (1)-(2) can be rewritten as follows:

$$\begin{cases} -\xi_2 + \xi_3 + \xi_5 - \xi_6 = 0, \\ 2\xi_1 - \xi_2 + 2\xi_3 - 2\xi_4 + \xi_5 - 2\xi_6 = 0, \\ \xi_1 - \xi_2 + \xi_3 - \xi_4 + \xi_5 - \xi_6 = 0, \\ \xi_1 + \xi_2 + \xi_3 + \xi_4 + \xi_5 + \xi_6 = f_0. \end{cases} \quad (3)$$

As can be seen, equation system (3) is a linear system written with respect to six unknowns, and its rank is equal to four. Therefore, this system has infinitely many distinct solutions.

To choose the most suitable solution from the set of possible solutions, in accordance with the essence of the problem, let's introduce the following optimality criterion:

We seek to minimize the variation in the angular velocities of the motors, ensuring that the hexacopter operates efficiently and maintains stable flight.

This optimality criterion can be formulated as a cost function that seeks to equalize or minimize the deviations in motor performance, ensuring the overall stability and balance of the hexacopter's movement along its intended trajectory.

$$\Im \equiv \sum_{i \neq j} \left(\xi_i - \xi_j\right)^2 \to \min, \qquad i, j = 1, 2, \ldots, 6. \quad (4)$$

The minimization of the $\Im$ functional essentially requires that the values of ξ_i and ultimately the rotational frequencies ω_k^2 be as close to each other as possible. This requirement is justified by the fact that during the straight-line movement of the UAV, its motors should ideally be evenly loaded.

From a mathematical perspective, this problem is one of conditional extremum. Various approaches can be applied to solve this problem [8]. In the course of the study, the Kuhn-Tucker method was applied [9-11]. The solution to the conditional extremum problem formulated by equations (3)-(4) yields the following result:

$$\xi_1 = \xi_2 = \xi_3 = \xi_4 = \xi_5 = \xi_6 \approx 0{,}166 f_0.$$

Based on the obtained values of the $\xi_1, \ldots, \xi_6$ quantities, the following values are derived for the rotational frequencies of the propellers:

$$\omega_1 = \omega_2 = \cdots = \omega_6 \approx 0{,}4\sqrt{f_0}. \quad (5)$$

Thus, for the hexacopter to fly in a straight line, it is first oriented appropriately by adjusting the rotational frequencies of the propellers to achieve the desired pitch. Subsequently, it is controlled along the trajectory according to the specified rotational frequencies (5).

V. ENSURİNG CONTROL WHEN ONE OF THE ENGİNES FAİL

When all engines are functioning normally, optimal control for straight-line flight is achieved by having all the propellers rotate at the same speed. Suppose one of the hexacopter's engines, for instance, the 6th engine, has malfunctioned.

Without loss of generality, we assume the failure is in the 6th engine.

In the case where there are no constraints on the rotational speeds of the remaining engines, the control of the hexacopter's movement has been studied in [5], showing that straight-line control is possible if $\omega_3 = 0$.

This raises the question: if the engine power is limited and the remaining engines cannot maintain the necessary rotational speeds, is it possible to control the hexacopter with the five remaining engines in the same manner?

If a solution exists, it must satisfy all the minimums determined by each additional constraint imposed on the system. Clearly, the same result can be obtained if engines 2, 3, or 5 malfunction instead.

If we consider the case where the 1st engine, rather than the 6th, fails, the system can be solved analogously, and again, we arrive at the conclusion that when the engines' power is limited, controlling the hexacopter with five engines is not possible [12].

It should also be noted that the same results are obtained if the 4th engine fails.

Thus, it can be concluded that under the given constraints, it is not feasible to control the hexacopter along a straight trajectory using only five engines.

VI. CONCLUSİON

Research has shown that when one of the hexacopter's engines fails, it can still continue moving along its original trajectory using the other engines, except for the one symmetrically opposite to the failed engine. In this case, if there are no technical power limitations on the engines, it is necessary to increase the rotation speed of the propellers to maintain the previous flight speed.

However, if there are power constraints, continuing along the trajectory would require a reduction in flight speed. Furthermore, it has been mathematically justified that under such power limitations, the shortage of power across four engines cannot be compensated by the fifth engine to maintain the hexacopter's previous speed along a straight-line trajectory.

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