

SESSION A:

EARTH MOVING AND TRANSPORTATION MACHINERY

Physical analysis of forces, moments, and energy efficiency of multi-rotor unmanned aerial vehicles from the perspective of flight control

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ARTICLE INFO

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DOI: <https://doi.org/10.46793/ET26.A08Z>

PAGES: A59 – A67

ABSTRACT

Multirotor unmanned aerial vehicles (UAVs) form a specific class of aircraft in which lift is generated directly by rotor thrust rather than by fixed wings. This principle enables vertical take-off and landing, hovering and precise low-speed positioning, but it also increases energy demand and makes the flight dynamics strongly coupled. This paper analyses the physical principles that govern multirotor UAV behaviour, with emphasis on the distribution of forces, moments and energy consumption. Hovering, vertical motion, translational motion through aircraft tilt and yaw control by counter-rotating rotors are considered from the perspective of flight control. The energy model is interpreted through disk loading, induced velocity and ideal hover power. A reference numerical example for a 4 kg UAV is used to compare propeller diameters and quadrotor, hexarotor and octotorotor configurations. The results show that larger total rotor-disk area reduces induced power and can extend hover endurance, while additional rotors improve redundancy at the cost of mass, structural complexity and control allocation requirements. The analysis provides a compact basis for engineering optimisation of multirotor UAV systems.

KEYWORDS

UAV, Multirotor, Flight physics, Thrust, Moments, Disk loading, Energy efficiency, Flight control.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) are one of the most dynamic fields of contemporary aeronautics, automation and robotics. Their development has enabled aircraft of different size, mass, purpose and autonomy level, ranging from small experimental platforms to complex civil, industrial, scientific and security systems [1]. Modern UAV platforms combine aerodynamics, mechatronics, sensor systems, control algorithms, navigation and energy storage [2].

The range of UAV applications has expanded considerably in recent decades. UAVs are now used in geodesy, agriculture, infrastructure inspection, logistics, energy systems, environmental monitoring, terrain mapping, scientific research and security-related tasks [3]. This expansion has been supported by miniaturised electronics, more reliable sensors, autonomous control, improved communication systems and increasingly capable onboard computing.

The modern development of UAV systems has been further accelerated by the integration of autonomous navigation algorithms, sensor fusion techniques, and adaptive control systems. Particularly in multirotor platforms, the application of advanced state-estimation methods enables stable operation even under conditions of partial GNSS signal loss or degradation of sensor data, which is of great importance for industrial and safety-related applications in urban environments. [4].

Multirotor UAVs occupy a particularly important position within this field. Unlike fixed-wing aircraft, which generate lift primarily through aerodynamic action of the wings during forward motion, multirotor platforms generate lift directly through rotor thrust [5]. This makes vertical take-off and landing, hovering, precise positioning and manoeuvring in confined spaces possible [6].

These advantages also explain why multirotor systems are preferred when the mission requires operation at low altitude or sustained positioning above a target point.

The physical behaviour of a multirotor system is determined by the interaction of forces and moments. During flight, the aircraft is subjected to weight, rotor thrust and aerodynamic drag, while changes in the rotational speed of individual rotors modify thrust distribution and create moments about the main body axes. The basic motion modes are vertical climb and descent, roll and pitch tilting, and yaw rotation about the vertical axis [7].

A particularly important characteristic of multirotor aircraft is that translational motion is not achieved directly by a horizontal propulsive force, but rather through vehicle tilting. When the aircraft tilts, the total thrust vector is no longer directed solely in the vertical direction; instead, it is decomposed into a vertical component, which maintains altitude, and a horizontal component, which enables motion in the desired direction. Consequently, the flight control system must simultaneously regulate the vehicle attitude, total thrust, and flight stability, making a multirotor aircraft a nonlinear and dynamically coupled system.

Energy efficiency remains one of the main limitations of multirotor UAV systems. In contrast to fixed-wing aircraft, which can rely on aerodynamic lift during cruise, multirotor aircraft must continuously generate thrust to remain airborne [8]. Consequently, energy consumption is high in hover, and the endurance is strongly influenced by mass, rotor diameter, disk loading, motor efficiency, battery characteristics and mission profile.

From an engineering perspective, the design of a multirotor aircraft represents a compromise between stability, payload capacity, flight endurance, energy efficiency, and control complexity. A larger number of rotors may improve thrust distribution, increase payload capacity, and enhance system reliability; however, it also increases vehicle mass, the number of propulsion components, and overall structural complexity. On the other hand, simpler configurations reduce mass and energy consumption but provide lower redundancy in the event of a propulsion unit failure.

In addition to technical requirements, the development and deployment of UAV systems are also governed by the applicable regulatory framework. In civil and industrial applications, increasing importance is placed on flight safety, airspace restrictions, operation categorization, operator responsibility, and compliance with relevant regulations [9]. Therefore, the modern development of UAV technology cannot be viewed solely in terms of performance improvement, but also through the safe and controlled integration of these systems into real-world operational environments.

The aim of this paper is to analyse the physical principles that determine the behaviour of multirotor UAV systems, with special emphasis on force distribution, moment generation and energy efficiency. The paper connects theoretical models with practical aspects of flight control in order to clarify the stability, controllability and operational limitations of multirotor platforms.

2. PHYSICAL MODEL OF MULTIROTOR FLIGHT

The motion of a multirotor UAV can be analysed using classical mechanics and rotor aerodynamics. In a simplified engineering model, the aircraft is treated as a rigid body acted upon by external forces and moments. This approach makes it possible to interpret the system through basic physical quantities while still retaining a clear connection with practical flight control [5,8].

2.1. Forces and Rotor Thrust

The three dominant external forces are weight, rotor thrust and aerodynamic drag. Weight acts vertically downward and represents the basic load that the propulsion system must overcome:

$$W = mg \quad (1)$$

where W is the weight of the aircraft [N], m is the mass [kg] and g is the gravitational acceleration [m/s^2]. The total thrust generated by all rotors is the sum of individual rotor thrusts:

$$\sum_{i=1}^n T_i = T_1 + T_2 + \dots + T_n = W \quad (2)$$

In steady hover, the total thrust must balance the weight:

$$\sum T = W \quad (3)$$

If total thrust is greater than the weight, the aircraft climbs; if it is smaller, the aircraft descends. In a simplified rotor model, the thrust of the i -th rotor and its reaction torque can be approximated as follows:

$$T_i = k_T \omega_i^2 \quad (4)$$

$$Q_i = k_Q \omega_i^2 \quad (5)$$

where ω_i is the angular speed of the i -th rotor [rad/s], while k_T and k_Q are coefficients that depend on propeller geometry, air density and propulsion-system characteristics [5]. These relations show that thrust and reaction torque are nonlinear functions of rotor speed. In real flight, this nonlinearity is further affected by air-density variation, turbulence and rotor-rotor interference [10].

2.2. Moments and Attitude Control

Moments about the body axes define the rotational behaviour of the aircraft. Roll is rotation about the longitudinal axis, pitch is rotation about the lateral axis, and yaw is rotation about the vertical axis. Roll moment is generated by a thrust difference between the left and right sides of the aircraft, while pitch moment is generated by a thrust difference between the front and rear rotors [5].

Yaw moment originates from the reaction torques of the rotors. In a quadrotor, two rotors rotate clockwise (CW) and two counter-clockwise (CCW). In hover, the reaction torques cancel each other. Yaw motion is produced by increasing the speed of rotors rotating in one direction and decreasing the speed of rotors rotating in the opposite direction, while keeping the total thrust approximately constant [6,7].

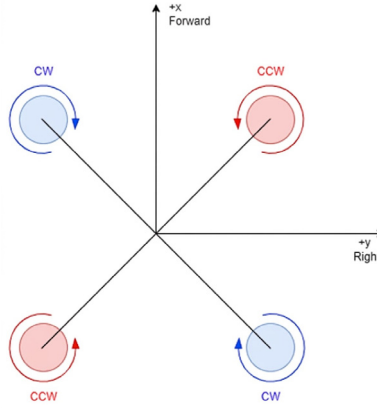


Figure 1: Quadrotor geometry and CW/CCW rotor directions

2.3. Translational Motion and Drag

A multirotor aircraft does not produce horizontal motion by using a separate horizontal propulsive force. Instead, the aircraft tilts, and the total thrust vector is decomposed into vertical and horizontal components. For a small tilt angle α , the components can be written as:

$$T_v = \sum T \cos \alpha \quad (6)$$

$$T_h = \sum_{i=1}^n T_i \sin \alpha \quad (7)$$

The horizontal component enables motion in the desired direction, while the vertical component must still support the weight of the aircraft. To maintain altitude during tilted flight, the required total thrust becomes:

$$\sum T = \frac{W}{\cos \alpha} \quad (8)$$

This relation explains why aggressive maneuvers and large tilt angles reduce endurance: an increase in tilt requires an increase in total thrust and therefore greater power consumption [8]. Aerodynamic drag acts opposite to the direction of motion and becomes more important in translational flight than in hover:

$$D = \frac{1}{2} \rho C_D A v^2 \quad (9)$$

where D is the drag force [N], ρ is air density [kg/m^3], C_D is the drag coefficient, A is the reference area [m^2] and v is the flight speed [m/s]. Drag has a direct influence on energy consumption, particularly at higher speeds and during longer missions.

Table 1: Command interpretation for a quadrotor in X configuration

Command	Increase ω	Decrease ω	Main effect
Forward	Rear pair	Front pair	Thrust vector tilts toward +X; forward motion
Backward	Front pair	Rear pair	Thrust vector tilts toward -X; backward motion
Right	Left pair	Right pair	Thrust vector tilts toward +Y; right motion
Left	Right pair	Left pair	Thrust vector tilts toward -Y; left motion
Yaw right	CW group	CCW group	Rotation about +Z with small change in ΣT
Yaw left	CCW group	CW group	Rotation about -Z with small change in ΣT

From the control perspective, the controller must transform desired translational and rotational motion into rotor-speed commands. Because every change in rotor speed affects both force and moment distribution, multirotor stabilisation requires fast sensors, robust state estimation and continuous feedback control [4,10].

The presented control allocation scheme shows that a multirotor system achieves control through differential variation of the thrust generated by individual rotors. Such a principle enables highly precise control of the aircraft attitude and position; however, it also increases the demands placed on the control algorithm, sensor response time, and the onboard energy system [4].

This model demonstrates that a multirotor aircraft does not achieve translational motion in the same manner as a conventional aircraft. In fixed-wing aircraft, horizontal motion is achieved through a combination of propulsion and aerodynamic lift generated by the wings, whereas in multirotor aircraft motion is obtained by changing the orientation of the thrust vector. Consequently, thrust in a multirotor system serves a dual purpose: it provides lift while simultaneously enabling vehicle control and maneuvering [6].

Under real flight conditions, system behavior additionally depends on aircraft mass, center-of-gravity location, rotor arrangement geometry, propeller characteristics, environmental conditions, and the quality of the sensor system. If the center of gravity is not properly positioned relative to the rotor plane, additional moments may arise, making stabilization more difficult. Therefore, the design of multirotor systems requires a symmetrical mass distribution and proper sizing of propulsion components [7].

An additional source of system complexity arises from the strong coupling between flight dynamics and control. Any change in the thrust generated by an individual rotor affects not only translational motion but also the distribution of moments about all aircraft axes. As a result, stabilization of multirotor platforms requires continuous control-command adjustments and accurate real-time processing of sensor data [10].

The basic physical model indicates that a multirotor unmanned aircraft is a complex nonlinear system in which small variations in the rotational speed of individual rotors can significantly alter the overall distribution of forces and moments. Consequently, stable flight requires continuous thrust correction, measurement of attitude and velocity, and closed-loop feedback provided by sensors such as gyroscopes, accelerometers, and state-estimation systems [5]. This close interaction between the physical model and the flight control system forms the basis for the further analysis of multirotor UAV systems presented in this paper [6].

3. CONFIGURATION AND CONTROL MODEL

The configuration of a multirotor UAV is defined by the number of rotors, their geometric arrangement and the corresponding control-allocation logic. A quadrotor is the simplest and most common configuration, while hexarotors and octorotors are used when higher payload capacity, greater stability or partial fault tolerance is required [6].

3.1. Vertical Motion and Control Allocation

Vertical motion is governed by the balance between total thrust and weight. Hover corresponds to $\sum T_i = W$ and $h = \text{const}$; climb occurs when $\sum T_i > W$; and descent occurs when $\sum T_i < W$ [5]. The flight controller coordinates rotor speeds so that total thrust and body moments satisfy the desired motion. For a quadrotor in X configuration, a simplified linear control allocation can be expressed as:

$$T_1 = \frac{1}{4}u_T + \frac{1}{2}u_\phi + \frac{1}{2}u_\theta - \frac{1}{2}u_\psi \quad (10)$$

$$T_2 = \frac{1}{4}u_T - \frac{1}{2}u_\phi + \frac{1}{2}u_\theta + \frac{1}{2}u_\psi \quad (11)$$

$$T_3 = \frac{1}{4}u_T - \frac{1}{2}u_\phi - \frac{1}{2}u_\theta - \frac{1}{2}u_\psi \quad (12)$$

$$T_4 = \frac{1}{4}u_T + \frac{1}{2}u_\phi - \frac{1}{2}u_\theta + \frac{1}{2}u_\psi \quad (13)$$

where u_T is the total-thrust command and u_ϕ , u_θ and u_ψ are the roll, pitch and yaw control commands. This formulation is an approximation, but it clearly shows that attitude and thrust commands are distributed to individual rotors rather than applied independently.

3.2. Rotor Configurations and Redundancy

Increasing the number of rotors does not only increase payload potential; it also changes the redundancy and complexity of the system. A quadrotor has limited tolerance to a motor failure because the loss of one propulsion unit directly disturbs both force and moment balance. Hexarotors and octorotors introduce additional actuators and therefore allow partial thrust redistribution in some failure scenarios [7].

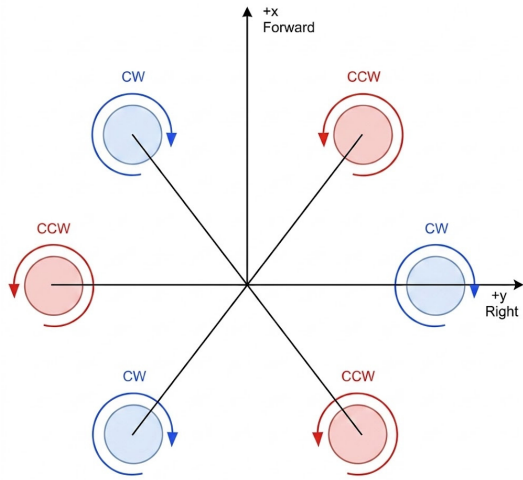


Figure 2: Hexarotor geometry and alternating rotor directions

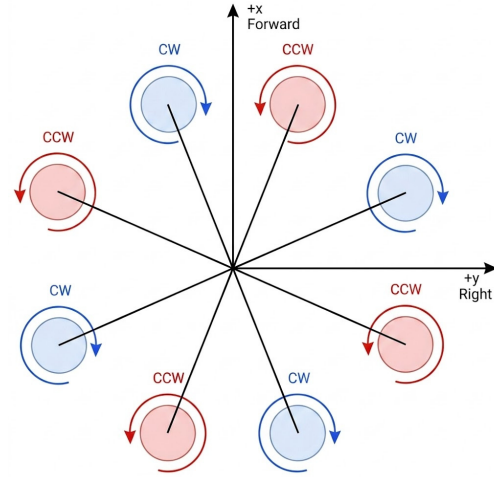


Figure 3: Octorotor geometry and alternating rotor directions

The advantage of additional rotors is not automatic. The remaining motors must have enough thrust reserve, the structure must be able to withstand redistributed loads, and the controller must solve the allocation problem in real time while respecting motor limits and available battery power.

3.3. Failure-Case Thrust Model

The preservation of flight after a propulsion-unit failure can be interpreted as a control-allocation problem. The controller must maintain the total thrust required for weight compensation and, at the same time, generate stabilising moments:

$$\sum_{i=1}^n T_i = W \quad (14)$$

$$M = BT \quad (15)$$

where B is the allocation matrix that maps individual rotor thrusts into the resulting moments. Its structure depends on rotor geometry and the selected multirotor configuration [7]. For a system with n rotors and one failed rotor, a minimum thrust condition is:

$$(n - 1)T_{max} \geq W \quad (16)$$

For practical controllability, however, this condition is not sufficient. A thrust reserve is required, and a common engineering criterion is that the maximum thrust per rotor should be at least twice the hover thrust:

$$T_{max} \geq 2T_{hover} \quad (17)$$

This criterion provides margin for disturbance rejection, attitude correction and emergency maneuvers, but it also increases the requirements placed on motors, propellers and the battery system.

4. ENERGY MODEL AND DISK LOADING

Energy efficiency is a critical parameter that defines mission endurance, operational radius and useful payload. Multirotor platforms consume significant energy even in stationary flight because the rotors must continuously accelerate air downward in order to balance the aircraft weight. Therefore, energy modelling is central to multirotor design and mission planning [10,11].

4.1. Disk Loading

Disk loading is a basic parameter of rotor aerodynamic efficiency. It is defined as the ratio between aircraft weight and total effective rotor-disk area:

$$DL = \frac{W}{\Sigma A_i} \quad (18)$$

Lower disk loading generally improves hover efficiency because the required thrust is produced by accelerating a larger mass of air to a lower induced velocity. This is why larger propellers can reduce the power required for hover. At the same time, larger propellers increase aircraft dimensions, may require stiffer arms and can limit use in urban or confined spaces [3,12].

4.2. Induced Velocity, Ideal Power and Endurance

From momentum theory, the induced velocity through the i -th rotor disk can be approximated as:

$$v_i = \sqrt{\frac{T_i}{2\rho A_i}} \quad (19)$$

For the complete aircraft in hover, ideal induced power can be written in compact form as:

$$P_{ideal} = \sqrt{\frac{W^3}{2\rho\Sigma A_i}} \quad (20)$$

The relation shows that an increase in aircraft weight has a strong influence on hover power. Even a relatively small mass increase due to sensors, payload or batteries can noticeably reduce flight endurance [13]. A practical estimate of endurance is:

$$t = \frac{E_{bat}\eta}{P_{prosek}} \quad (21)$$

where E_{bat} is the usable battery energy [Wh], η is the total system-efficiency coefficient and $P_{el,avg}$ is the average electrical power [W]. In real operation, energy reserves must also be planned for wind, manoeuvres, landing, sensor operation and unexpected mission changes [14,15].

5. NUMERICAL ANALYSIS OF A REFERENCE UAV SYSTEM

A reference numerical analysis was carried out to quantify the influence of rotor diameter and propulsion configuration on energy efficiency. The analysed system is a medium-size multirotor platform intended for civil and industrial applications. The adopted mass is $m = 4$ kg, which gives $W \approx 39.24$ N.

5.1. Baseline Thrust Calculation

In steady hover, the total thrust equals the aircraft weight. For a quadrotor configuration, the required thrust per rotor is:

$$T_i = \frac{W}{4} = \frac{39,24}{4} \approx 9.81 \text{ N} \quad (22)$$

This value is only the theoretical minimum required to maintain altitude. It does not include thrust reserve for stabilisation, acceleration, disturbance compensation or emergency manoeuvres. For this reason, a total thrust-to-weight ratio $T/W \geq 2$ is often used as a practical design target for reliable control.

5.2. Influence of Propeller Diameter

The influence of propeller diameter was analysed for a constant aircraft mass of 4 kg and four rotors. The comparison includes propellers of 10 in, 12 in and 15 in. The numerical results are summarised in Table 2.

Table 2: Influence of propeller diameter on ideal hover power ($m = 4$ kg, four rotors)

Case	Propeller	A_i [m ²]	ΣA_i [m ²]	v_i [m/s]	$P_{ideal,tot}$ [W]
A	12 in (0.305 m)	0.07298	0.2919	7.42	291
B	10 in (0.254 m)	0.05070	0.2028	8.87	348
C	15 in (0.381 m)	0.11400	0.4560	5.93	233

Increasing the diameter from 12 in to 15 in reduces ideal hover power by about 20%, while reducing the diameter to 10 in increases it by about 19.5%. The reason is the change in total disk area and induced velocity. However, the largest propeller is not necessarily the best practical solution, because it increases the aircraft envelope and structural requirements.

5.3. Rotor Configuration and Hover Endurance

The performance of quadrotor, hexarotor and octorotor configurations was compared using 12 in propellers and a 6S 10 Ah battery system with usable energy of approximately 178 Wh. The results are given in Table 3.

Table 3: Comparison of rotor configurations (12 in propellers, $m = 4$ kg)

Configuration	Rotors	DL [N/m ²]	$P_{el,hover}$ [W]	Hover time [min]
Quadrotor	4	134.4	≈ 420	≈ 25.4
Hexarotor	6	89.6	≈ 343	≈ 31.1
Octorotor	8	67.2	≈ 297	≈ 35.9

At identical mass and propeller diameter, the octorotor configuration gives approximately 41% longer hover time than the quadrotor. This result confirms the importance of total rotor-disk area. Nevertheless, in a real design, additional rotors increase mass, cost, wiring complexity, maintenance requirements and the complexity of the flight-control allocation problem.

5.4. Practical Interpretation

The most energy-efficient operating condition is hover or mild translational motion with small tilt angles. A tilt of 10° already creates a useful horizontal thrust component, but it also requires an increase in total thrust to maintain altitude. Therefore, aggressive maneuvers, abrupt direction changes and large tilt angles directly increase power consumption and reduce endurance. The results indicate that mass optimisation, propeller selection, rotor configuration and mission-profile planning must be treated as a coupled design problem.

For fault-tolerant operation, rotor count alone is not sufficient. After a motor failure, the remaining propulsion units must generate enough thrust and stabilising moments. For example, in a hexarotor with one failed motor and $W = 39.24$ N, the remaining five rotors must generate at least 7.85 N each only to compensate for weight. Additional margin is still necessary for attitude stabilisation and yaw-moment compensation.

6. PERFORMANCE AND APPLICATIONS OF MULTIROTOR UAV SYSTEMS

The previous analysis shows that the performance of multirotor UAV systems cannot be assessed through a single design parameter. Endurance, payload capacity, stability, controllability and operational safety are the result of a coupled interaction between aircraft mass, rotor configuration, propeller diameter, disk loading, thrust reserve, propulsion efficiency and mission profile. Therefore, the selection of a multirotor platform should not be reduced to the number of rotors or battery capacity alone, but should be treated as an integrated engineering optimisation problem.

From the performance perspective, quadrotor configurations offer the simplest and lightest solution. They have fewer propulsion units, lower structural complexity, reduced maintenance requirements and simpler control allocation. These advantages make quadrotors suitable for compact platforms, short-duration missions, educational applications, visual inspection, mapping of smaller areas and general monitoring tasks. However, their simplicity is accompanied by limited redundancy. Since each rotor has a critical role in both lift generation and attitude control, the failure of a single motor or propeller usually causes a major loss of stability and controllability.

Hexarotor and octorotor configurations provide a different balance between efficiency, redundancy and complexity. By increasing the number of rotors, the total rotor-disk area is increased, disk loading is reduced and the required induced velocity in hover becomes lower. This can improve hover efficiency and provide greater possibilities for thrust redistribution. Such configurations are therefore more suitable for missions that require higher payload capacity, improved stability, safer operation or partial tolerance to propulsion-unit failure. Typical examples include industrial inspection, professional photogrammetry, environmental monitoring, emergency response and missions above sensitive or inaccessible areas.

The numerical results obtained in this paper confirm the importance of total rotor-disk area. For the same aircraft mass and propeller diameter, configurations with more rotors can achieve lower disk loading and lower hover power. However, this result must be interpreted with caution. In a real UAV system, additional rotors also introduce additional motor mass, arms, wiring, electronic speed controllers, structural reinforcements and control complexity. Consequently, the theoretical improvement in hover efficiency can be partially reduced or even cancelled if the added components significantly increase the total aircraft mass. This is why the optimal configuration depends strongly on the intended mission rather than on aerodynamic efficiency alone.

Propeller diameter has a similarly important but constrained influence. Larger propellers reduce induced power because they increase the effective disk area and accelerate a larger mass of air at a lower velocity. This improves hover efficiency and can extend endurance. At the same time, larger propellers increase the overall aircraft dimensions, require longer and stiffer arms, reduce compactness and may limit operation in narrow, urban or indoor environments. For this reason, the most efficient propeller from the energy point of view is not always the most practical solution from the operational point of view.

Another important conclusion is that increasing battery capacity does not automatically increase endurance in a proportional way. Although a larger battery stores more energy, it also increases aircraft mass. This additional mass increases the thrust required for hover and therefore raises power consumption. A poorly balanced design with an oversized battery may have only a small endurance improvement, or in some cases no meaningful improvement at all. Effective endurance optimisation therefore requires simultaneous consideration of battery energy, aircraft mass, propulsion efficiency and mission power demand.

In practical applications, multirotor UAVs are especially valuable when the mission requires vertical take-off and landing, stable hovering, precise positioning and low-speed manoeuvring. These characteristics make them useful for infrastructure inspection, geodetic surveying, agricultural monitoring, terrain mapping, environmental observation, search-and-rescue operations and industrial diagnostics. In such missions, the main advantage of a multirotor UAV is not maximum

forward-flight efficiency, but the ability to remain accurately positioned above or near a target while carrying sensors, cameras or measuring equipment.

For infrastructure and industrial inspection, multirotor UAVs can approach bridges, roofs, towers, chimneys, power lines and other structures without the need for scaffolding, cranes or direct human access. In agriculture and environmental monitoring, they can provide spatially distributed data on vegetation, soil condition, irrigation, erosion, pollution or flood risk. In emergency-response scenarios, they can rapidly collect visual or thermal information from areas that may be unsafe for people, such as fire zones, collapsed structures, flooded terrain or chemically contaminated locations.

The use of multirotor UAVs in public-safety and emergency-response systems also highlights the importance of reliability and fail-safe behaviour. In these applications, flight failure may not only result in equipment loss, but may also create additional risk for people and property. Therefore, platforms intended for such missions require sufficient thrust reserve, robust communication, reliable navigation, emergency landing logic and, where necessary, partial propulsion redundancy. The choice between quadrotor, hexarotor and octorotor configurations should therefore be made according to the acceptable level of operational risk.

From the flight-control perspective, the practical performance of a multirotor UAV depends on how effectively the controller transforms desired motion into rotor-speed commands. Since the same rotors are responsible for lift, attitude control and yaw control, every manoeuvre affects both force and moment balance. This becomes particularly important during aggressive motion, wind disturbances, payload variation or partial actuator degradation. Advanced control algorithms, sensor fusion and adaptive control methods can improve stability and robustness, but they also require accurate modelling and reliable onboard computation.

Overall, the application potential of multirotor UAV systems is highest in missions where manoeuvrability, hovering ability, spatial precision and operational flexibility are more important than long-range aerodynamic efficiency. Their main limitations remain endurance, sensitivity to mass increase, wind influence, battery constraints and system complexity. Future development should therefore focus on lighter structures, more efficient propulsion systems, improved batteries, accurate energy prediction, fault-tolerant control and autonomous mission adaptation in realistic operating environments.

7. CONCLUSION

This paper presented a physical and engineering analysis of multirotor unmanned aerial vehicles, with emphasis on the relationship between force generation, moment control and energy efficiency. The analysis confirmed that multirotor UAVs are highly coupled dynamic systems in which lift, attitude control, yaw motion and power consumption cannot be considered independently. Every change in rotor speed affects not only the total thrust, but also the distribution of moments and the energetic state of the aircraft.

The force analysis showed that hover is governed by the balance between total rotor thrust and aircraft weight, while climb and descent are achieved by changing this balance. Translational motion is obtained by tilting the aircraft and redirecting the thrust vector, rather than by generating a separate horizontal propulsive force. This means that forward, backward or lateral motion always introduces a compromise between horizontal acceleration and vertical lift. As the tilt angle increases, additional thrust is required to maintain altitude, which directly increases power demand and reduces endurance.

The moment analysis demonstrated that roll, pitch and yaw control are generated through controlled differences in rotor thrust and reaction torque. Roll and pitch motion depend on asymmetric thrust distribution between opposite sides of the aircraft, while yaw motion depends on the torque imbalance between clockwise and counter-clockwise rotating rotors. These principles explain why the flight controller must continuously solve a control-allocation problem: it must distribute commands to individual rotors while simultaneously satisfying requirements for lift, attitude stabilisation and yaw control.

The energy analysis confirmed that disk loading is one of the key parameters of multirotor efficiency. A larger total rotor-disk area reduces induced velocity and ideal hover power, while higher aircraft mass strongly increases the required power. The numerical example for a 4 kg UAV showed that increasing propeller diameter can significantly reduce ideal hover power, and that increasing the number of rotors can reduce disk loading when the total mass is kept constant. However, these results must not be interpreted mechanically. In real UAV design, larger propellers and additional rotors also increase size, structural demands, mass, cost and control complexity.

The comparison of quadrotor, hexarotor and octorotor configurations showed that no configuration is universally optimal. A quadrotor is usually the most rational choice when simplicity, compactness, low mass and low cost are dominant requirements. Hexarotor and octorotor configurations become more appropriate when the mission requires higher payload capacity, improved stability, greater thrust reserve or partial fault tolerance. The selection of the configuration must therefore be based on the mission profile, payload, safety requirements, operating environment and available energy, rather than on rotor number alone.

One of the most important engineering conclusions is that endurance cannot be improved by isolated component changes. Increasing battery capacity, propeller diameter or rotor number may improve one aspect of performance, but each of these changes also affects mass, geometry, structural stiffness, power consumption and control allocation. For this reason, multirotor UAV design must be understood as a coupled optimisation problem involving propulsion, structure, control system, battery selection and mission planning.

The practical implication of the analysis is that multirotor UAVs are most effective in missions where hovering, vertical take-off and landing, precise positioning and low-speed manoeuvrability are more important than long-range aerodynamic efficiency. Their advantages are especially relevant in inspection, mapping, monitoring, emergency response and operations in hazardous or inaccessible environments. At the same time, their main limitations remain short endurance, sensitivity to payload increase, wind influence, battery constraints and dependence on reliable control systems.

Future research should move from simplified analytical models toward experimentally validated performance models. This includes detailed measurement of propulsion efficiency, battery behaviour under variable load, rotor-rotor aerodynamic interference, influence of wind and manoeuvres, and energy consumption during realistic mission profiles. Special attention should also be given to fault-tolerant control, adaptive control allocation and autonomous decision-making under degraded operating conditions.

Overall, the study confirms that efficient and reliable multirotor UAV design requires an integrated approach. The best solution is not the aircraft with the largest battery, the greatest number of rotors or the largest propellers, but the platform in which mass, thrust, disk area, control authority, energy reserve and mission requirements are properly balanced. This balance represents the central engineering challenge in the development of modern multirotor UAV systems.

ACKNOWLEDGEMENTS

This research has been supported by the Ministry of Science, Technological Development and Innovation (Contract No. 451-03-34/2026-03/200156) and the Faculty of Technical Sciences, University of Novi Sad through project “Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the Faculty of Technical Sciences, University of Novi Sad 2026” (No. 01-3609/1).

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