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INFLUENCE OF UNDERWING PAYLOAD ON THE FLIGHT PERFORMANCE OF A TACTICAL UAV

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Abstract: *This paper presents a performance analysis of a tactical unmanned aerial vehicle (UAV) with and without integrated rocket payload. The study is based on the application of standard flight mechanics methods combined with available experimental flight data for validation purposes. The aerodynamic characteristics of the UAV are evaluated for both configurations, taking into account the increase in mass and additional parasitic and interference drag caused by externally mounted rockets. These changes are incorporated into the equations of motion in order to estimate key performance parameters. The analysis focuses on the determination of maximum flight speed, rate of climb, endurance, and range under different flight conditions. Two calculation methodologies are applied and their results are compared with experimental data obtained during flight testing. The results show a noticeable degradation of flight performance due to rocket integration, with deviations between theoretical predictions and experimental data remaining within acceptable engineering limits. The presented approach provides a reliable basis for performance estimation of UAVs with external payload configurations.*

Keywords: *UAV, rocket payload, flight performance, flight testing.*

1. INTRODUCTION

The development of tactical unmanned aerial vehicles began during the second half of the 20th century, primarily for reconnaissance and intelligence-gathering purposes without risking human crews. During military conflicts worldwide, UAV systems were significantly improved, evolving from simple reconnaissance platforms into complex systems with greater autonomy, reliability, and operational range. At the beginning of the 21st century, intensive technological development in the fields of sensors, communication systems, and precision-guided weaponry enabled the transformation of UAV systems into multifunctional platforms. Modern tactical unmanned aerial vehicles, developed, among others, at the Military Technical Institute, represent the integration of reconnaissance and combat capabilities, offering a high degree of flexibility and relatively low operational costs. Such development further confirms their increasingly important role in modern military operations.

Medium-range unmanned aerial vehicles, such as the system considered in this paper, are designed as platforms capable of performing a wide range of tasks, including surveillance, intelligence gathering, artillery fire correction, and precision strike missions. Their ability to remain in the mission area for extended periods and transmit data in real time significantly enhances situational awareness and command efficiency. The integration of external stores further expands the operational capabilities of these systems; however, it also affects the aircraft's fundamental aerodynamic and mass characteristics. As demonstrated in previous studies, any modification of the configuration requires careful analysis of its impact on the center of gravity position, drag, and overall performance, while achieving a balance between operational efficiency and flight performance [1-3].

The integration of rocket armament enables the execution of direct fire support and reduces reaction time, thereby combining reconnaissance and combat functions within a single platform. However, the presence of external stores leads to an increase in mass and parasite drag, as well as the occurrence of additional interference drag, which directly results in reduced maximum speed, climb rate, endurance, and range. In addition, limitations on the maximum takeoff weight often require a reduction in fuel quantity, while changes in mass distribution may affect the aircraft's stability and controllability. Although aerodynamically unfavorable, such a configuration represents an operationally justified compromise in missions where combat capability takes priority over maximum flight performance.

In this context, there is a need for a reliable assessment of

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the influence of external stores on the performance of unmanned aerial vehicles. Although standard analytical methods based on the literature exist [4-6], their application to configurations with external payloads requires additional verification.

The aim of this paper is to provide a quantitative analysis of the impact of rocket armament integration on the performance of an unmanned aerial vehicle through a combination of theoretical calculations and experimental data. The analysis includes the determination of drag, required power, maximum speed, climb rate, endurance, and range, together with a comparison to the results obtained from flight tests conducted in configurations with and without rockets. Special emphasis is placed on evaluating the deviations between theoretical models and actual performance, as well as identifying the dominant factors contributing to performance degradation caused by the integration of external payloads. The obtained results are used to assess the accuracy and limitations of existing UAV performance calculation methods for configurations with external stores (rockets) through comparison with flight test results.

2. FLIGHT PERFORMANCE

The focus of this chapter is the analysis of the UAV flight performance in configurations with and without externally mounted rocket armament, with the aim of assessing the influence of external payloads on the main flight characteristics. The performance analysis was carried out using standard analytical methods for determining drag, required power, maximum speed, climb rate, range, and endurance. The obtained results will be compared with experimental data from flight tests in order to evaluate the accuracy of the applied methods and identify the dominant factors influencing UAV flight performance.

Table 1 presents some of the basic characteristics of the considered unmanned aerial vehicle shown in Figure 1.

Table 1. Key Parameters of the UAV Configuration

Internal combustion engine power [7]	38.8 kW
Propeller diameter	0.86 m
Maximal mass of UAV	265 kg
Maximal mass of usable fuel	70 kg
Wing area	4.33 m^2
Mean aerodynamic chord	0.736 m



Figure 1 Tactical UAV with rockets

The propulsion system must be properly sized to ensure the overcoming of aerodynamic drag and supplying power to all onboard systems. In this regard, it is necessary to take into account that different engines have specific optimal operating RPM ranges. The efficiency of the propeller, as an integral part of the propulsion system, depends on propeller advance ratio, which is determined using the following expression:

$$J = \frac{V}{ND} \tag{1}$$

In Equation (1), the parameter J represents the propeller advance ratio, V the flight speed, N the propeller rotational speed, and D the propeller diameter. Maximum propeller efficiency is achieved when the propeller advance ratio is within the range of 0.5 to 0.6, as illustrated in Figure 2.

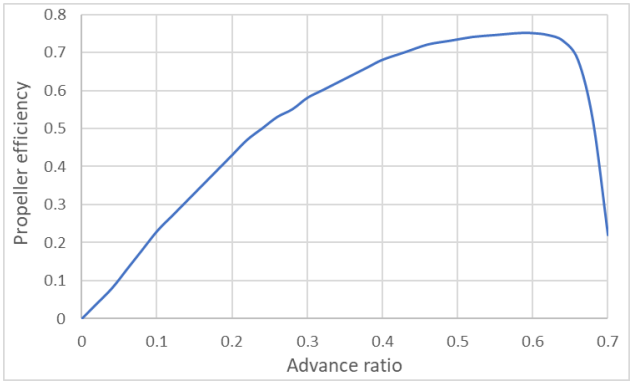


Figure 2. Propeller efficiency

For the flight speed to be optimal, it is necessary to satisfy several interrelated conditions. Depending on the mission type, the UAV must achieve an appropriate flight speed at the designated altitude in order to ensure efficient terrain surveillance, tracking of moving and stationary targets, as well as successful rocket launch and target engagement. During different flight regimes, the UAV changes its configuration, including camera deployment and retrieval, as well as variations in the amount of carried armament, which lead to changes in mass and aerodynamic characteristics, and consequently to variations in the required flight power, as shown in Figure 3 and Figure 4.

Figure 3 shows the relationship between the lift coefficient C_L and the drag coefficient C_D for several different configurations (with and without rockets) [8].

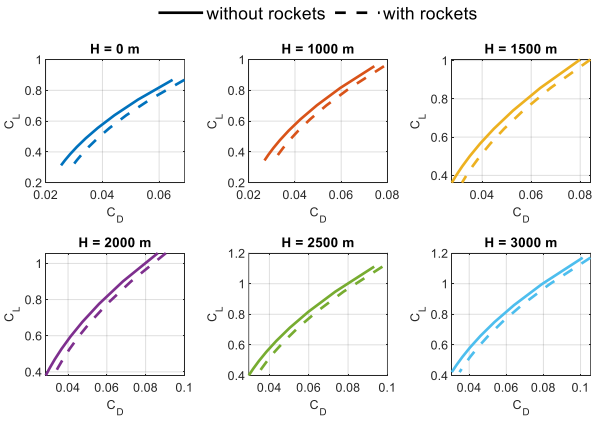


Figure 3. UAV drag polar with and without rockets

Based on the obtained drag coefficient values, the aerodynamic drag force and required flight power can be calculated using the following expressions:

$$D = C_D q S \tag{2}$$

$$P_{req} = DV \tag{3}$$

Figure 4 shows the influence of rocket integration on the required flight power, as well as the variation in available power. Figure 5 presents the maximum flight speeds as a function of altitude for configurations with and without rockets.

It should be emphasized that engine power depends on the rotational speed, throttle setting, flight regime, and atmospheric conditions. With increasing altitude, air pressure, density, and temperature decrease, resulting in reduced engine efficiency. One of the methods used to express the available engine power as a function of altitude is given by:

$$P_{avail} = P_0 \eta_{engine} \eta_{prop} \left(\frac{\rho}{\rho_0}\right)^{1.2} \tag{4}$$

where ρ is the air density at the flight altitude, while ρ_0 is the air density at sea level.

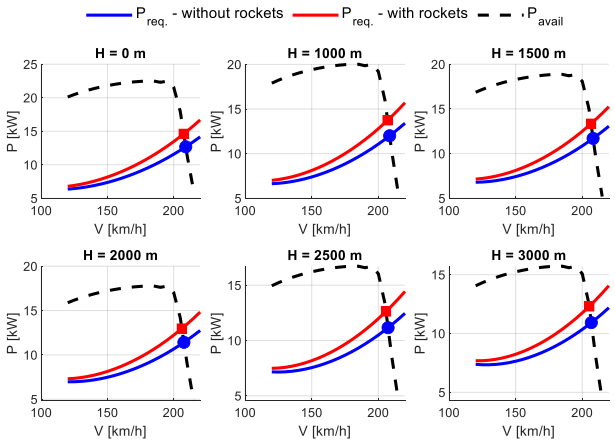


Figure 4. Required and available flight power

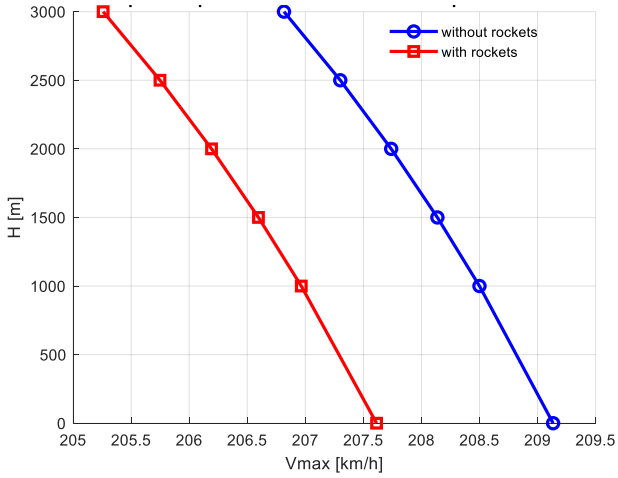


Figure 5. Maximum flight Speed as a Function of Altitude

The vertical rate of climb depends on the difference between the available and required flight power, as well as on the current aircraft weight:

$$w = \frac{P_{avail} - P_{req}}{mg} \tag{5}$$

Figure 6 illustrates the influence of rocket integration on the rate of climb at different flight speeds and altitudes.

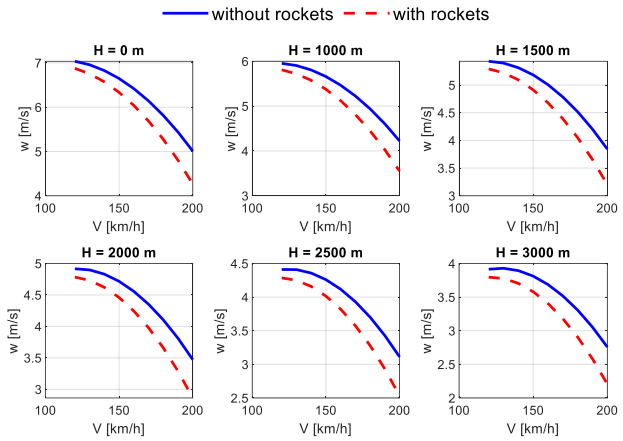


Figure 6. Rate of climb as a function of airspeed and altitude

As shown in Figure 7, with increasing flight altitude, the rate of climb gradually decreases, and for certain flight regimes and airspeeds, the climb rate approaches zero. Such behavior is a consequence of the reduction in available power and thrust with increasing altitude, as well as the increase in the power required to maintain flight under specific aircraft configurations. A similar decrease in climb rate with increasing altitude was also reported in [9] for a propeller-driven UAV operating at altitudes up to 7000 m. Depending on the mission requirements, aerodynamic configuration, and required aircraft performance, the service ceiling may be defined at certain minimum climb rate values, while the theoretical ceiling corresponds to the condition in which the rate of climb reaches 0 m/s.

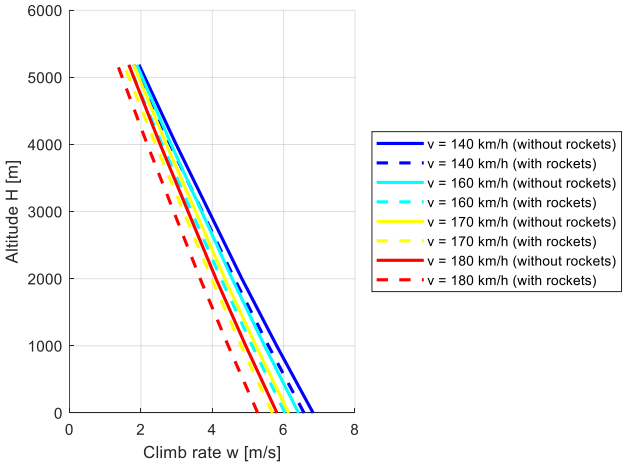


Figure 7. Rate of climb as a function of altitude

When considering flight endurance, the primary objective in the design and analysis of an unmanned aerial vehicle is to ensure the longest possible time aloft without the need for landing and refueling, which requires the optimization of multiple interdependent aerodynamic, propulsion, and mass-related parameters. In this context, one of the key requirements is achieving a high lift-to-drag ratio (L/D),

which directly reduces the power required for sustained level flight, while minimum drag is achieved through optimization of the aircraft configuration and external stores. At the same time, low specific fuel consumption of the propulsion system is of crucial importance, as it enables more efficient utilization of the available energy through the selection of an engine operating within its optimal regime and providing a favorable balance between power output and fuel consumption. The propeller efficiency, as a key element of the propulsion system, must also be maximized in order to convert the largest possible portion of the engine's mechanical power into useful thrust. In addition, the total amount of fuel that the UAV can carry represents a significant factor, although it is constrained by structural and operational requirements such as maximum takeoff weight and load distribution. Therefore, optimal endurance is achieved through a careful balance between aerodynamic efficiency, propulsion system performance, and available energy resources, while taking into account all limitations of the actual operational environment.

Depending on the flight regime, range and endurance can be classified into the following cruise conditions:

- Constant Airspeed/Constant Altitude Cruise.
- Constant Attitude/Constant Altitude Cruise.
- Constant Airspeed/Constant Attitude Cruise.
- Constant Weight Cruise.

This paper presents range and endurance values for steady flight at constant speed and constant altitude, without considering takeoff, climb to cruise altitude, descent, and landing phases. Table 2 presents the corresponding range and endurance expressions, which yield identical results.

Table 2. Analytical expressions for range and endurance

Range [10]	$R = 3600\frac{\eta}{q}\sqrt{\frac{\pi\lambda_e}{C_{Dmin}}}\arctan\frac{m_g}{\frac{\delta V^2}{16}S\sqrt{C_{Dmin}\pi\lambda_e}+\frac{m_o(m_o-m_g)}{\frac{\delta V^2}{16}S\sqrt{C_{Dmin}\pi\lambda_e}}}$
Endurance [10]	$E = \frac{R}{V}$
Range [11]	$R = \frac{V}{c_t\sqrt{kC_{Dmin}}}\left[tan^{-1}\left(\frac{2\sqrt{k}}{\rho V^2 S\sqrt{C_{Dmin}}}W_{ini}\right) - tan^{-1}\left(\frac{2\sqrt{k}}{\rho V^2 S\sqrt{C_{Dmin}}}W_{fin}\right)\right]$
Endurance [11]	$E = \frac{1}{c_t\sqrt{kC_{Dmin}}}\left[tan^{-1}\left(\frac{2\sqrt{k}}{\rho V^2 S\sqrt{C_{Dmin}}}W_{ini}\right) - tan^{-1}\left(\frac{2\sqrt{k}}{\rho V^2 S\sqrt{C_{Dmin}}}W_{fin}\right)\right]$

Figure 8 and Figure 9 present the range and endurance of the analyzed UAV for different flight regimes in configurations with and without rockets. The results show that the UAV configuration with rockets has lower range and endurance compared with the configuration without rockets. This reduction is mainly attributed to the decrease in available fuel capacity caused by rocket instalation, which limits both the total flight time and the achievable range.

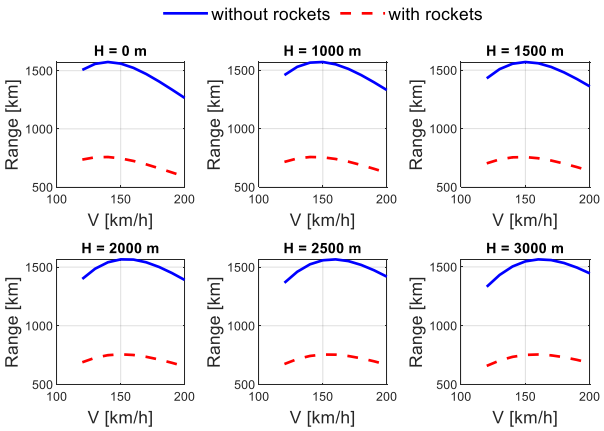


Figure 8. Range as a function of airspeed

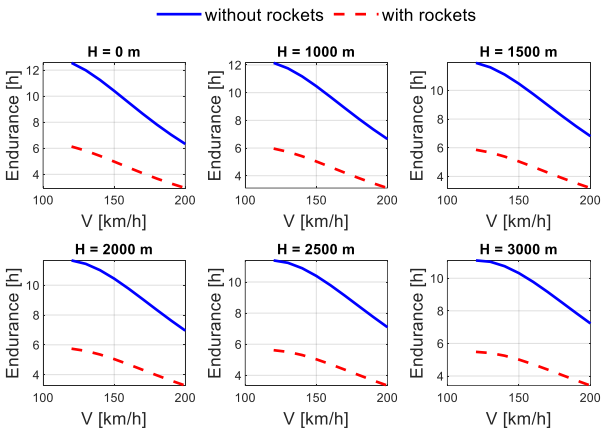


Figure 9. Endurance as a function of airspeed

2.1. Flight test results

The maximum flight speed was evaluated following stabilization at the cruise altitude of 2000 m, where the UAV was operated at a throttle setting of 90% for a duration of three minutes. The UAV was then climbed to an altitude of 3000 m, and the same test procedure was repeated. In order to minimize the influence of wind on the

measurement results, the tests were conducted in both flight directions at each altitude. Table 3 provides a comparison between the calculated performance values and the results obtained during flight testing. It should be noted that the objective of the flight tests was not to determine the maximum attainable flight speed, but rather to verify compliance with the required operational speeds specified in the technical requirements, namely 180 km/h for the configuration without rockets and 160 km/h for the configuration with rockets.

Table 3. Comparison of calculated and measured maximum flight speeds

Without rockets		
H (m)	$V_{calculated}\ (km/h)$	$V_{test}\ (km/h)$
2000	207.74	190.8
3000	206.82	192.6
With rockets		
H (m)	$V_{calculated}\ (km/h)$	$V_{test}\ (km/h)$
2000	206.19	186.01
3000	205.26	187.09

Table 4 presents a comparison between the calculated and experimentally measured rates of climb. For the configuration without rockets, the deviations between the calculated and measured values were below 10%, with a maximum difference of 8.1%, indicating good agreement between the analytical model and flight test results. Larger deviations were observed for the configuration with rockets. These discrepancies are attributed to differences in the conditions under which the flight tests were conducted, since the flight tests in the configuration with rockets and the flight tests in the configuration without rockets were performed on different days. As a result, variations in atmospheric conditions, including turbulence encountered during cloudy weather, affected the measured rates of climb.

Table 4. Comparison of maximum rates of climb

Without rockets		
H (m)	$w_{calculated}\ (m/s)$	$w_{test}\ (m/s)$
1000	5.95	6.33
2400	4.92	4.52
With rockets		
H (m)	$w_{calculated}\ (m/s)$	$w_{test}\ (m/s)$
1000	5.77	6.62
2200	4.82	6.78

The service ceiling was evaluated by climbing the UAV to an altitude of 5000 m above sea level in the configuration without rockets and to 4000 m in the configuration with rockets, while maintaining a stable flight condition for a duration of three minutes in both cases. The calculated dependence of rate of climb on altitude is presented in Figure 7, while Table 5 presents the corresponding flight test results. It should be noted that the objective of the flight tests was not to determine the maximum attainable altitude, but rather to verify compliance with the required operational ceiling specified in the technical requirements, namely 5000 m for the configuration without rockets and 4000 m for the configuration with rockets. Consequently, the measured values differ from the calculated results, particularly in the configuration with rockets.

Table 5. Service ceiling comparison

H (m)	$w_{cal.}\ (m/s)$	$w_{test}\ (m/s)$	Rockets
5188	1.95	2	without
4029	2.3	1	with

Endurance was one of the critical requirements that the aircraft had to satisfy during flight testing. Since the UAV successfully met the required flight endurance criteria, maximum range testing was not performed. In order to determine the range and endurance, it is first necessary to evaluate the fuel consumption during ground engine operation, climb, descent, landing, and taxiing. When the required navigation reserve is additionally considered, the remaining available fuel quantity for steady level flight at the prescribed cruise altitude can be determined.

In this study, the endurance values were compared exclusively for the flight segment extending from reaching the target flight altitude to the initiation of descent, with the flight conducted at an average throttle setting of 30%.

During the flight tests conducted in the configuration without rockets, the unmanned aerial vehicle remained airborne for 9.42 hours at an average cruise altitude of 2500 m and an average flight speed of 150 km/h, consuming 46 kg of fuel, as shown in Figure 10. The calculated endurance for the corresponding flight regime was 10.14 hours.

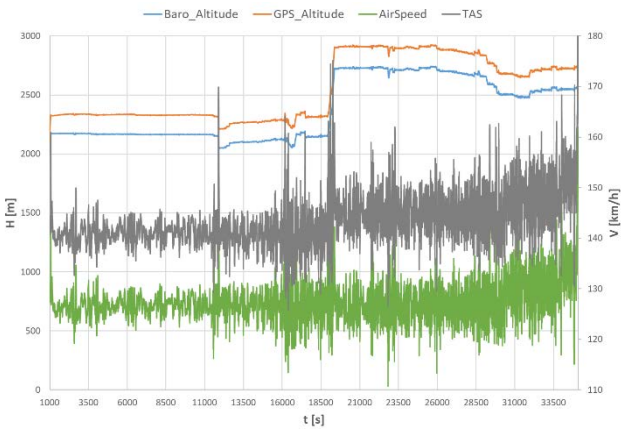


Figure 10. UAV Endurance in the configuration without rockets [12]

During the flight tests conducted in the configuration with rockets, the unmanned aerial vehicle remained airborne for 5.39 hours at an average cruise altitude of 2000 m and an average flight speed of 140 km/h, consuming 26 kg of fuel, as shown in **Figure 11**. The calculated endurance for the corresponding flight regime was 5.35 hours.

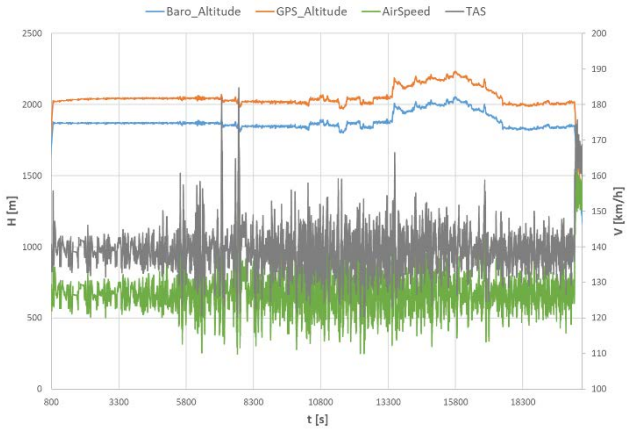


Figure 11. UAV Endurance in the configuration with rockets [12]

3. CONCLUSION

The paper presented a comparative analysis of the flight performance of a tactical unmanned aerial vehicle in configurations with and without external rocket stores. The analysis included the determination of maximum flight speed, rate of climb, endurance, and range through the application of standard analytical flight performance methods, followed by comparison with the results obtained during flight testing.

The obtained results indicate that rocket integration has a relatively small influence on maximum flight speed and rate of climb. Although the presence of external stores leads to an increase in aerodynamic drag and aircraft mass, the corresponding degradation of these performance parameters remained comparatively low under the analyzed flight conditions. In contrast, a significantly greater impact was observed in terms of endurance and range. The primary reason for this reduction was not the increase in aerodynamic drag itself, but rather the decrease in available fuel quantity required to satisfy the maximum takeoff mass limitation in the armed configuration.

A comparison between the calculated and experimentally obtained results showed good agreement across all analyzed cases, confirming that conventional analytical flight performance methods provide sufficiently accurate predictions even for UAV configurations with external stores. This demonstrates that relatively simple analytical approaches can still serve as reliable tools during preliminary design and operational performance assessment.

It should also be noted that flight testing of UAV performance is inherently influenced by atmospheric conditions, which may vary significantly during the execution of the tests. Sudden wind gusts and local atmospheric disturbances can affect the measured flight parameters, potentially contributing to deviations between calculated and experimentally obtained results, even under carefully controlled test conditions.

Future research may include the investigation of advanced endurance enhancement methods for tactical UAVs, such as autonomous soaring, atmospheric energy harvesting, and energy-efficient trajectory optimization techniques presented in recent studies [13].

Finally, despite the reduction in endurance and range, the capability to integrate rocket armament represents a major operational advantage. Modern combat operations increasingly emphasize the importance of unmanned platforms capable of combining reconnaissance and strike functions within a single system, making armed UAV systems an increasingly important component of contemporary military operations.

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