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Approaches to Combining Drone Sensors for Counter Unmanned Aerial Systems

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Abstract

The growing presence of asymmetric threats require effective C-UAS systems. This study addresses the challenge of integrating sensors (RF and EO/IR) onto multirotor platforms while maintaining flight endurance. Of the four scenarios developed, it analyzes Use-case B in detail, mathematically comparing six variants of hardware modifications to a heavy drone during reconnaissance of a 300×300 m area against both active and radio-silent targets. The results reveal the paradox of SWaP limits: fully equipped "All-in-One" platforms excel against active targets thanks to rapid guidance but face critical battery depletion during area-wide reconnaissance of autonomous threats. For future research, therefore, cooperation among multiple platforms, reduced energy consumption, and the integration of effectors are proposed.

KEY WORDS: *C-UAS, sensors, Use cases, sensor combination, drone simulation.*

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1. Introduction

The massive spread of Class I Unmanned Aerial Systems (UAS), specifically those in Low, Slow, Small (LSS) category, represents one of the most critical challenges for modern Surface-Based Air Defense (SBAD) and Integrated Air and Missile Defense (IAMD) systems. Current radar systems face physical limitations when detecting targets with extremely small radar cross sections that fly at low altitudes. The situation is further complicated in rugged terrain or urbanized areas, where strong ground clutter and interference occur, drastically reducing the probability of timely detection and threat classification [1].

The deployment of dedicated tactical UAS as mobile sensor platforms appears to be a promising solution. These systems make it possible to overcome terrain obstructions and get closer to the area of interest, thereby providing higher quality data for command and control (C2) systems. However, the operational deployment of these assets is limited by Size, Weight, Power and Cost (SWaP-C) parameters. This research is focused on WaP. Each additional sensor increases the platform´s total weight, which directly affects its energy consumption and reduces its maximum flight time. Developers and operators thus face a dilemma: deploy a comprehensive sensor fusion system at the cost of reduced endurance or choose a lightweight platform with limited detection capabilities [2,3].

While the currently available literature addressing C-UAS sensors [1,4,5] provides comprehensive insights into foundational sensor capabilities, and studies on coverage path planning [2,6] heavily optimize geometric constraints, these works predominantly assume stationary deployment, idealized scenarios, or do not fully quantify the synergistic effect of sensor fusion under strict operational limitations. Our approach differs by explicitly prioritizing the non-linear relationship between the weight penalty of added sensors and the required energy consumption on a highly mobile multi-rotor platform. The novelty of this model lies in its direct applicability to tactical environments, offering a practical framework that identifies the precise configurations where the rapid detection advantage of sensor fusion outweighs the critical energy drain caused by SWaP constraints [14,17].

The main objective of the research is to design and compare complex operational scenarios (Use Cases) in order to assess the real-world limits of current C-UAS platforms. By integrating mathematical modeling of sensor fusion, energy consumption, and different threat profiles, the study identifies the critical limits of these systems' deployability. The findings enable the definition of optimal hardware configurations that guarantee successful threat identification without exceeding the safety energy limits for the machine's return.

Despite the rapid development of C-UAS technologies, there is still no comprehensive methodology to quantify the impact of integrating multispectral sensors (a combination of RF and EO/IR) on overall mission efficiency from an energy perspective. Existing studies often focus either on area coverage algorithms [2] or on purely technical parameters of UAV consumption [3] but neglect the synergistic effect of sensor fusion in tactical scenarios. This article presents a simulation model, developed in Python, that analyzes the relationship between the weight penalty of sensors and the time savings achieved through more efficient detection (Slew-to Cue method). The goal is to provide a decision-making framework for the optimal configuration of C-UAS assets depending on the mission type and operational environment.

2. Methodology and Mathematical Framework

2.1. Energy Consumption Fundamentals

A key aspect of our methodology is the integration of the platform´s physical parameters into mission planning. As noted in the technical literature, most traditional research in the field of coverage path planning optimizes flight paths based purely on geometric constraints and lack comprehensive models that account for available energy and the system´s dynamic mass [6]. To overcome this shortcoming, we define the total energy consumed by mission E_{total} as the integral of the instantaneous power input $P(t)$ [15,16,18]:

$$\mathrm{E_{total}} \int_0^{\mathrm{T_{minimum}}} \mathrm{P(t)dt} \quad (1)$$

An analytical method based on rotor momentum theory was chosen for modelling the power P(t). This physical model which is based on the principles of rotor aerodynamics [9] and is applied in modern UAS communication systems [10] defines the nonlinear dependence of the required induced power (P_{req}) on the weight of the carrier (m) considering the air density (ρ), rotor disc area (A), rotor efficiency (η), avionics power ($P_{avionics}$):

$$\mathrm{P_{req}(m)} = \frac{(\mathrm{m} \times \mathrm{g})^{3/2}}{\eta \times \sqrt{2\rho \mathrm{A}}} + \mathrm{P_{avionics}} \quad (2)$$

This equation, whose validity for commercial multi-rotor drones, has been confirmed by experimental measurements [5] demonstrate what we call weight penalty in our study. The integration of a heavy sensor in use-case B increases instantaneous power consumption by 28% which is a direct consequence of the nonlinear term $m^{3/2}$ in the equation.

2.2. Simulation Environment and Sensor Fusion Logic

Development in the field of mobile C-UAS solutions is currently hampered by the lack of available open-source simulation tools that would enable realistic modeling of sensor fusion [1]. For the purposes of this study, a custom simulation environment was therefore developed in Python. This environment combines the aerodynamic model mentioned above with tactical deployment logic. The simulator continuously calculates the accumulator´s energy balance and evaluates mission success based on reaching the target time $T_{mission}$ before the accumulator capacity drops below the critical threshold for a safe return (set at 20% SoC)

2.3. Software implementation in Python environment

All mathematical calculations were performed using the Python programming language. This environment was used to precisely solve the defined equations, into which the actual hardware parameters of the tested platforms and sensors (primarily their weights and power consumption) were substituted. In addition to the data calculations themselves, Python, using standard visualization libraries (e.g. Matplotlib), was also used to generate all analytical graphs and outputs included in this work. This approach ensured accurate processing of the results and enabled a clear graphical interpretation of the identified trade-offs between hardware load, flight time and mission success.

2.4. Platform and Sensor Specifications (TTD)

In order to apply the analytical model to real-world C-UAS operations and quantify the values P_{req} and E_{total} a database of parameters for commercially available platforms and sensors, were created. The selection of platforms is based on DJI standards [7], which represent the current industry standard in the light, medium and heavy categories. For simulation purposes, these platforms were paired with corresponding types of sensor equipment, ranging from lightweight integrated cameras to dedicated radio frequency (RF) analyzers, such as the AARTOS system [8]. The tactical-technical data (TTD), which constitute the input variables ($m, P_{avionics}$, maximum battery capacity) for the simulation model in Python, are summarized in Table 1

Table 1

Tactical and technical data for reference UAS and sensor modules [7,8]

UAS model	Category	MTOW [kg]	Battery capacity [Wh]	Possible sensor load (C-UAS fusion)
DJI Mavic 3E	Light	~1.05	77	Integrated optical system (EO/IR)
DJI M30T	Medium	~3.77	131	Advanced EO/IR + Laser Rangefinder
DJI M300 RTK	Heavy	~9.00	550	Heavy RF analyzer (e.g., AARTOS) / PTZ EO/IR

2.5. Sensor Payloads and SWaP-C Parameters

Table 2

Platform and Sensor Specifications (TTD)Sensor Payloads and WaP-C Parameters

Sensor type	Ref. model	Weight (m_{sensor}) [kg]	Power consumption (P_{sensor}) [W]	Detection ability	Key ability inside C-UAS
RF – 1	Epiq Solutions Matchstiq Z3u	0.15	5	Spectre analysis (70MHz – 6GHz, short range	Close-range signal detection Suitable for light and medium-sized drones.
RF – 2	AARONIA IsoLOG 3D Mobile	1.2	25	3D tracking (9 kHz – 6 GHz). Range: 1–2 km (air-to-air)	Guidage azimutal « Slew-to-Cue
EO - 1	DJI Zenmuse H20	0.67	10	20 MP Zoom (23x Hybrid), Laser (1200 m)	Visual identification during the day
EO – 2	DJI Zenmuse H20 N	0.88	15	Dual thermovision, Starlight night-vision	Identification 24/7, also in adverse conditions (fog, night)

3. Simulation results and performance analysis

To validate the designed mathematical model and assess the impact of sensor fusion on the mission´s energy balance, two use-cases (Use-case A-B) were defined and another two cases (Use-case C-D) were considered for future research. All scenarios operate within an area of interest of 300 x 300 meters, using a heavy class platform (DJI Matrice 300 RTK) as the reference UAS carrier.

When evaluating the performance and effectiveness of a defense drone (C-UAS), we cannot rely only on the parameters of the platform itself. We always have to consider that we are up against, because that plays a crucial role. Each threat has different characteristics, ranging from emitting radio signals (e.g. commercial drones) to complete radio silence. These characteristics directly determine whether it is even possible to detect this target using specific modifications of the defense drone. Based on the parameters of these targets, a preliminary decision can be made regarding the abilities of the early detection and find the drone or whether our platform will have to search the entire area [14,17].

Regarding the areas of application for individual sensors, we continued to build on the results of our previous study [11-13].

3.1. Theoretical detection speed within the target area

The system´s ability to respond in a timely manner to a threat within a 300x300 m area of interest is critically dependent on the chosen detection method and the target´s signature. An analysis of two diametrically opposed threat profiles reveals significant differences in theoretical detection times [14]:

Detection of commercial drone (Target 1). For a standard threat emitting a strong communication signal, the most significant difference between sensors occurs. The use of RF fusion reduces detection time to an absolute minimum, typically to 2 to 5 seconds. The RF antenna passively monitors the radio spectrum and performs immediate directional triangulation the momenta transmission is detected. On the other hand, relying entirely on optical sensors is ineffective in this case. Without knowledge of the initial azimuth, the camera must systematically scan the sky. Since its field of view (FOV) covers only a fraction of the area at any given moment, the average detection time can increase to 4 to 8 minutes.

Detection of an autonomous UAV with radio silence (Target 2). In the case of an asymmetric threat flying along a pre-programmed route and emitting no active RF signature, the tactical advantage is reversed. The RF fusion method fails completely in this scenario. The passive directional antenna has no source signal to track, thereby preventing the initiation of the Slew-to-Cue process and becoming a useless platform load. The only functional alternative thus remains the deployment of purely EO/IR sensors. The detection time remains at a slow rate of 4 to 8 minutes, as with the first target, however against a “silent” threat, this is the only physically possible way to detect it. The defense system must accept the high energy and time demands of a lengthy, area-wide search in order to detect the target base on its inevitable thermal signature [18].

3.2. Operational parameters

Table 3

Physical and electromagnetic characteristics of potential targets

Evaluation Criteria	Target 1 Commercial drone	Target 2 Autonomous UAV
Type of platform	Quadcopter with active remote control	Fixed-wing
Typical dimensions	~0.35x0.35 m	~0.5-1.5 m
Kinematic profile	Slow flight (5 to 15 m/s), hovering for observation purposes	High speed flight (15-30 m/s), via pre-programmed route
Emitting RF signal	High; transmits telemetry and video in standard bands (2.4/5.8 GHz)	None, receives GPS, does not generate an active RF signature
EO/IR cross section (thermal signature)	Medium; small visual silhouette, but clearly heat signature from the rotors and battery	High; easily detectable heat from engines

3.3. Use-case A

Use case A serves as a baseline for evaluating the energy consumption of standard C-UAS target detection methods. In this case, a Heavy-class platform (DJI Matrice 300 RTK) is used, equipped only with a standard electro-optical (EO) sensor. Since the platform does not carry additional heavy sensors, the takeoff mass m remains at its base value, and there is no significant increase in instantaneous power consumption $P(t)$ due to weight penalties. The mission´s objective is a complete survey of the area of interest, measuring 300 x 300 meters. Due to the absence of prior directional guidance (Slew-to Cue), the operator must select a “lawnmower” search pattern, which ensures 100% coverage of the area by the visual sensor. This approach is often criticized in the literature for its energy inefficiency during large-scale operations.

An analysis of the baseline area survey clearly demonstrates the limitations of the traditional geometric approach to C-UAS mission planning. Although the platform operated with a minimum payload, the need for visual coverage of the entire area disproportionately extended the exposure time ($T_A = 16.0\ min$). In the context of the mission´s total energy balance ($E_{total} = \int P(t)dt$), it was confirmed that flight time is the dominant factor, outweighing even the advantage of a lightweight platform. A residual battery capacity of 22.9% represents an unacceptable risk in a real tactical environment. With such a low reserve, almost approaching the critical limit of 20%, the operator would not have sufficient energy to handle unexpected events, such as compensating for strong headwinds, extended hovering for target identification or safe return from the farthest point of area of interest. This finding highlights the need to seek ways to radically reduce flight time, even at the cost of violating the strict weight restrictions.

Due to the simplicity of this use case, it was not explored further, and the use case is discussed and commented only on the general information basis.

3.4. Use-case B

As a part of use case B, we decided to test the capabilities of a “heavy” platform (specifically the DJI Matrice 300 RTK) when searching for a target within a 300 x 300 m area, as well as in the use-case A.

The main purpose of this use case is to find the ideal balance, to determine which combination of sensors will ensure the target is detected as quickly as possible without unnecessarily draining the battery.

3.4.1. The Evaluation Methodology

To find an optimal balance, we do not test only the most complex configuration possible. Instead of that, we decided to use 2 examples of RF sensors and 2 examples of EO sensors. Main parameters of these examples are mentioned in Table 2. Using these specific models, we created six logical combinations. These variants can theoretically cover everything from the sensors themselves to full sensor fusion.

The specific variants are designed with a view to gradually expanding the platform´s capabilities. The first two variants (V1 and V2) use only standalone RF sensors, either a lightweight analyzer (RF-1) or its heavier (RF-2), directional alternative. Their purpose is to test whether knowing the target´s radio position alone, without subsequent visual confirmation, is sufficient for successfully completing the mission. The next step is represented by variants (V3 and V5), which expand the system with a lightweight daytime camera (EO-1). The primary goal of this fusion is to reduce the total payload weight and thus lower power consumption, but at the cost of relying strictly on visual detection. The final pair of variants (V4 and V6) then represent full sensor fusion, in which the RF modules are paired with a heavier thermal imaging camera (EO-2).More detailed information on possible targets is provided in the Table 3.

3.4.2. Modifications and Tactical Filtering

To test the platform, six test variants were assembled from the available hardware. However, prior to the actual power evaluation, four of them were eliminated due to their inability to meet the minimum tactical requirements for operations in a complex environment:

- Platform in variants 1 and 2 (RF sensors only) carry only radio equipment and lacks an optical channel. Although these are the lightest configurations, they do not allow for visual target confirmation, which is not an acceptable criterion for us in C-UAS operations.
- Configuration equipped only with EO sensors (V3 and V5) is primarily designed to reduce weight by using lightweight daytime camera. However, due to visual noise in the environment, such as forest or urban areas, standard optics are unable to detect the target.

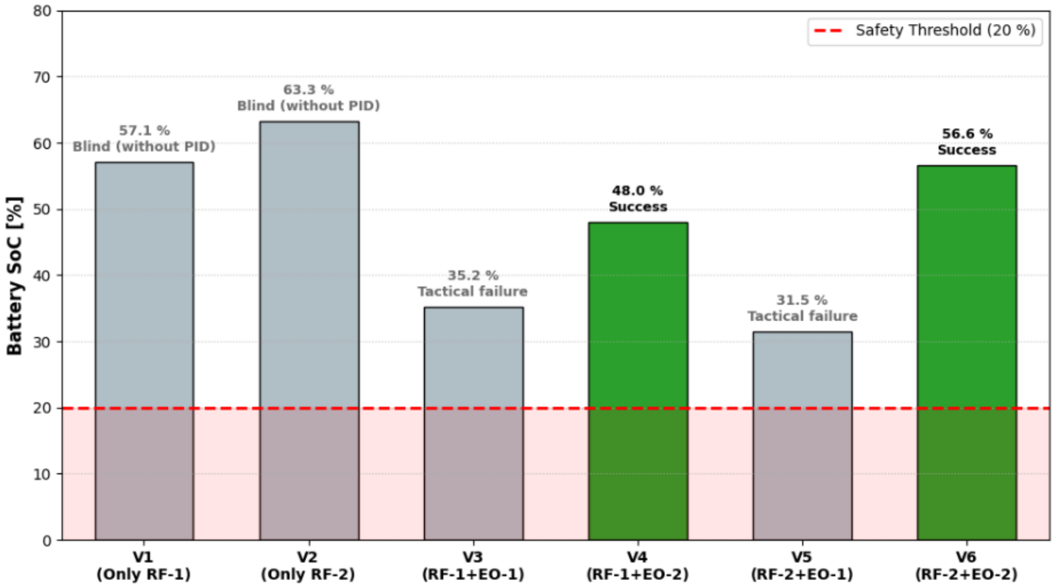

Fig. 1. Target 1 - Battery Balance and Tactical Success.

Figure 1 ilustrates the energy and tactical balance of the platforms against a standard emitting a RF signal. Although variants V1 and V2 have the highest remaining battery charge (over 57%), they are unable to identify the target due to the absence of optics and the mission fails. In variants V3 and V5, the limitations of the daytime camera become apparent. The drone approaches the target, but due to high visual noise in the environment, it takes much more time to clear the area, which unnecessarily drains energy without any guarantee of success. Focus narrows to configurations with thermal vision. Unexpectedly, the heaviest variant (V6) performs best in the overall survey, it flies the shortest possible route thanks to the guided heavy RF sensor, thereby compensating for its high-power consumption and returning with a 56.6% battery reserve.

Results in Figure 2 reveal the limitations of sensor architecture when a target does not emit an RF signal and the platforms are forced to initiate a systematic area search. Here, the precise mathematical impact of the optical parameters is fully evident. Configurations V3 and V5, which rely on a day camera, must drastically narrow their field of view to detect the target. The time required to scan the perimeter mathematically increases to over 90 minutes, leading to complete battery drainage (SoC 0%) and a potential crash.

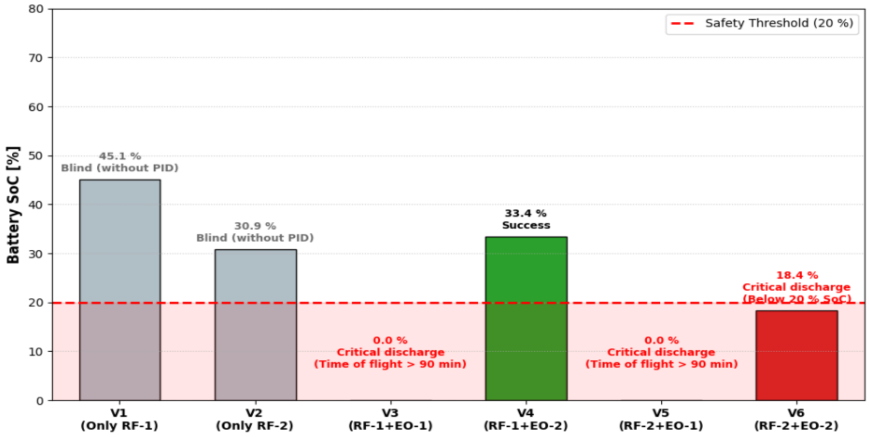

Fig. 2. Target 2 - Battery Balance and Tactical Success.

In contrast, the heavy V6, which has the best results in a previous comparison, completes the visual reconnaissance in 16 minutes, but due to constantly carrying an unused heavy radio, its battery capacity drops to 18.4 %. This is below the 20% safety limit and the platform risks crashing on the return back. The only universally reliable variant that can capture both targets and safely return to base with a sufficient V4 modification.

4. Conclusions

This research presented a comparative analysis of scenarios (use-cases A to D) to evaluate the operational and energy limits of multirotor C-UAS platforms. The main output examined throughout the research was a continuous energy-time balance mapped against the tactical success of various sensor fusions in a complex environment.

A critical review of the generated data outputs reveals a fundamental weakness in the current "All in One" paradigm (all sensors on a single drone). The data outputs clearly demonstrated a nonlinear operational paradox, maximizing hardware capabilities results in a positive energy balance only if it guarantees immediate guidance (Slew-to-Cue). The results demonstrated that as soon as the target changes its profile to radio-silent, this hardware advantage turns into a critical disadvantage, which, due to the extended reconnaissance time, drains the battery below the 20% safety threshold. Furthermore, the results definitively ruled out the usability of standard daytime optic (EO-1) in complex environments, with data showing that the narrowing of the field of view required for positive identification demands so much energy that it exceeds the battery´s physical capacity. The results from the challenging scenarios (adverse weather etc.) ultimately confirmed that a single platform is physically incapable of covering the entire C-UAS kill chain. Based on the analysis of these results, it is clear that future tactical deployments must transition to distributed cooperative systems. For this reason, we are considering future research with another two use-cases (C-D)

Use-case C. Concept of use-case C is based on the principle of multi-platform cooperation. It therefore moves away from the idea of using a single "all in one" drone and distributes these capabilities across two or more platforms. These drones communicate with one another and share the tasks assigned to them. The logic is that the area of interest can be divided, allowing the advantages of specific sensors to be used to explore certain parts of the area. Tasks can be defined according to needs: for example, one drone can be used as a scout with higher speed and the ability to locate a target, while the second drone may be equipped with heavy equipment and arrive at the site only after a threat has been positively identified (e.g., deployment of effectors, etc.). The advantages of this use would certainly include synergy and speed, as we can utilize parallel scanning, which reduces the time required to scan the entire area; and last, but not least, redundancy for example if one drone fails, is jammed or is destroyed, the first drone could be capable of at least partially completing the assigned task. On the other hand, this use-case may be more demanding in terms of control complexity, particularly in more advanced cross-platform software, or in terms of increased requirements for personnel and infrastructure, which would be necessary when deploying multiple platforms.

Use-case D. This experiment would undoubtedly provide us with the most realistic results, as it theoretically models reality. In practice, drone platforms rarely operate over perfectly flat terrain under ideal weather conditions. In this case, we are considering deploying the platform in an urban environment or under adverse weather conditions, with the goal of determining how the platform will behave when its sensors close their optimal range. Buildings or fog impair the camera´s visibility and obstacles also block the radio signal, potentially creating blind spots or false radio reflections. This use-case is useful for identifying real-world limitations, as we obtain clear data from the deployed drones and know in advance where we can and cannot rely on them in practice. It also allows us to assess state-of-the-art technology and consider theoretical innovations for equipping these platforms. The disadvantage is that drone has to fly at lower altitudes and speeds to compensate for the unfavorable conditions in which they must operate. There is also a significant risk that the drone´s battery will not last due to the demanding nature of the mission.

As the results from use-case C demonstrated, distributing detection and mitigation tasks among cooperating platforms is the only proven method for minimizing individual flight times, ensuring target neutralization and maintaining a high level of energy security.

Way Ahead. Based on this research, it would be worth applying these findings in future and verify their real-world applicability on drone platforms with similar physical parameters, thereby validating the simulated results. Further research could also involve modifying sensor platforms by adding effectors.

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