Methods for Protecting Unmanned Aerial Vehicles against Electromagnetic Interference in Military Applications

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Abstract: - Unmanned aerial vehicles (drones) have become an integral part of modern technological reality, operating either through remote control or through predefined navigation algorithms. They offer many advantages that include small size, low operating cost, ease of use, and high mobility. Among the various fields of applications, a prominent one emerges to be the military operations, where the protection of drones from electromagnetic interference is of vital importance. Accordingly, the present study outlines the electromagnetic threats and their counter-methods, commenting on the advantages and disadvantages of the related technology.

Key-Words: - Unmanned Aerial Vehicles, UAV, Electromagnetic Pulse, EMP, electromagnetic interference, UAV countermeasures, electromagnetic protection, ultra-wideband pulses.

Received: June 18, 2025. Revised: July 30, 2025. Accepted: October 23, 2025. Published: December 28, 2025.

1 Introduction

Unmanned aerial vehicles (UAVs) have become an integral part of modern technological reality, operating either through remote control or through predefined navigation algorithms. UAVs offer a multitude of advantages, including small size, low operating cost, ease of use, and high mobility. These characteristics have led to their widespread adoption in various fields, such as telecommunications, aerial photography, supply chain, precision agriculture, power management, natural disaster management, environmental monitoring, and fire detection [1].

However, the rapid evolution and increasing complexity of UAV systems are accompanied by increased sensitivity to complex electromagnetic environments. Particularly critical is the management of strong electromagnetic interference (EMI), which constitutes a significant threat to their safe and reliable operation. In environments with high levels of EMI, electromagnetic energy can penetrate the internal systems of UAVs through various coupling mechanisms, adversely affecting critical functions such as communication and flight control. In extreme cases, the effects can be catastrophic [2].

At the same time, the increasing illegal use of drones in activities such as terrorism, espionage, and privacy violations has intensified the need for effective methods to deal with them. Among the various proposed strategies, the application of intentional electromagnetic interference (IEMI) with an emphasis on their sensory systems has emerged as one of the most promising methods to suppress unfriendly drones. The IEMI phenomenon is characterized by the intentional production and emission of electromagnetic energy with the aim of disrupting or destroying electronic systems [3]. On the other hand, the protection of friendly UAVs from such electromagnetic pulse (EMP) attacks, especially in military applications, is becoming exceptionally important, hence being the focus of this study.

2 The Impact of EMP on UAVs

The authors in [4] focused on analyzing the effects of the pulse on the structure, communication, and wiring circuit of a surveillance drone, utilizing the “CST Microwave Studio” software and the Transmission Line Method (TLM). Electromagnetic pulses, which were initially observed during the nuclear tests of 1946, are characterized as high-frequency explosions that create strong electric fields capable of causing significant damage to electronic circuits. Drones, due to the absence of a pilot and their dependence purely on aerodynamic forces for flight, are particularly sensitive to such interference.

The research in [4] focused on the "DJI Mavic Pro", a widely used UAV, used for surveillance and aerial photography. The study thoroughly examined the impact of EMP on critical systems such as communication, flight control, propellers, microcontrollers, and sensors. In addition, the possibility of signal interference and eventual collapse was investigated under specific conditions of exposure to electromagnetic pulses.

The research methodology included both computational simulations and experimental measurements. The simulations were performed in the "CST Microwave Studio" environment, with the drone model imported in STEP format and the materials defined based on their electromagnetic properties. The configuration of the simulation parameters followed the MIL-STD464A standard, ensuring the reliability of the results. The TLM method was used to accurately calculate the electromagnetic fields, allowing for the discretization of space and time. The simulations focused on the interaction of cables with EMP fields, highlighting the importance of cable length in the sensitivity of circuits to EMP attacks.

Experimentally, the drone response was measured using an EMP generator at distances of 12, 10, and 8 meters from the radiation source. The results showed increased instability of the unmanned aerial vehicle with increasing field strength, with the vehicle becoming uncontrollable at a field strength of 24 kV/m and a distance of 8 meters from the source. Further analysis of the results revealed that the effect of EMP is more pronounced when it causes unidirectional radiation, while no significant effect was observed in bilateral radiation. Furthermore, it was found that shorter cables exhibit lower induced voltage and current, making the circuits less vulnerable to EMP attacks [4].

2.1 Impacts of Strong EMPs

The study by [5] presents a systematic analysis of the potential strong EMIs that UAVs may encounter during their flight. The study focuses on three critical subsystems: the data transmission system, the flight control and navigation system, and the power supply system. The EMIs that affect UAVs during their flight can be categorized into two main groups: internal and external.

The study by [5] focuses exclusively on external EMI, originating from the operating environment. The term "strong EMI" refers to the presence of high-amplitude electromagnetic disturbance signals that occur during the operation of electronic devices or systems. These signals are evaluated in relation to the typical operating environment of the systems and have the potential to significantly affect their functionality. Strong EMI includes a wide range of waveforms, including continuous waves (CW), high-altitude electromagnetic pulses (HEMPs), lightning electromagnetic pulses (LEMPs), ultra-wideband pulses (UW-EMPs), and high-power microwaves (HPMs).

UAVs, as highly integrated electronic systems, are composed of a multitude of electronic components. From a systems perspective, the UAV system can be divided into two main circuits: the signal circuit and the power circuit [6]. The signal circuit acts as the data transmission channel between the individual components of the UAV or between the UAV and the ground control station, while the power circuit represents the internal power supply circuits of the system. Strong EMI can couple to any of these circuits, potentially affecting the internal electronics and exposing the UAV to varying degrees of interference and potential damage.

2.1.1 Impact on the Data Transmission System

The data transmission system of a UAV is a critical two-way communication channel between the unmanned aircraft and the ground control station. It is based on wireless communication and includes an uplink for transmitting remote control signals and a downlink for relaying status data and visual information. However, the antenna of the data interface system not only functions as a receiver of control signals from the ground station, but also constitutes a potential gateway for unwanted strong electromagnetic energy into the system. This intrusion can occur through two main coupling mechanisms: (a) *Front-door coupling* (the entry of high-power microwaves through antennas and similar elements; (b) *Back-door coupling* (the penetration of microwave energy through holes and slots in the device's casing).

The damage processes of unmanned aerial systems by high-power microwaves include three stages: (a) *Radiation* (microwave energy is radiated onto the target surface); (b) *Coupling* (energy enters the system through the aforementioned mechanisms); (c) *Destruction* (damage is caused to the electronic systems through thermal effects or strong electric and magnetic fields).

The internal circuits of the UAV's data interface system include sensitive components such as low-noise amplifiers, mixers, and digital signal processors (DSPs). These components are particularly vulnerable to strong electromagnetic interference, which can lead to a wide range of malfunctions, from transient performance degradation to permanent component failure.

Continuous wave coupling is the most common form of EMI, operating primarily at low frequencies. In this case, the UAV antenna is the primary coupling path for the data link system. Electromagnetic pulses, on the other hand, can cause serious, even permanent, damage to the internal electronics of the UAV. The effect of high-power microwaves depends largely on the operating frequency of the data link system.

The sensitivity of the data interface system to EMI is affected by several critical factors. One of them is the interference frequency. When the frequency of the interfering signal approaches the frequency of the remote-control signal, the isolation of the interfering signals from the radio frequency (RF) front-end becomes insufficient. In addition, the polarization of the electromagnetic field plays an important role, as the polarization direction significantly affects the degree of interference.

Field strength is another determining factor, especially when it comes to electromagnetic pulses and their impact on UAVs. In cases of narrow-band strong EMPs, the frequency of the pulses also plays a critical role in the impact on the data link system.

To better understand these phenomena, extensive simulations and analyses have been performed. In particular, simulations using MATLAB have demonstrated the relationship between the signal-to-noise ratio (SNR) and the bit error rate (BER) in a single-frequency interference environment. Simulations using SIMULINK have confirmed the effect of HPMs on the data interconnection system, with the results agreeing with the experimental radiation tests.

Recent research has also focused on analyzing the effect of various waveforms on the image transmission quality in the downlink data channel. The findings show that Gaussian noise, square pulses, and spike pulses exhibit the greatest impact on the data transmission system. Furthermore, it has been observed that the image transmission quality is significantly affected when the BER values are similar, regardless of the waveform. The data transmission system of UAVs has emerged as one of the most vulnerable subsystems to strong EMI and is the subject of intensive research activity [7].

2.1.2 Impact on the Flight & Navigation System

The flight and navigation system is the core of an unmanned aerial vehicle, playing a crucial role in the smooth operation and control of the vehicle. The structure of this system includes three basic elements: (a) the inertial measurement unit (IMU) that incorporates specialized sensors that accurately measure the three-axis attitude angle and motion parameters of the UAV; (b) an *embedded microcomputer* that acts as the brain of the system, processing the signals and making critical flight decisions; (c) a GPS receiver that provides precise information about the vehicle's position and direction.

The flight and navigation system is significantly vulnerable to strong electromagnetic interference. Electromagnetic fields can drastically affect the accuracy of gyroscopes and magnetic compasses, leading to incorrect estimation of the aircraft's attitude and reduced flight stability. In addition, EMI has the potential to distort the command signals transmitted by the microcomputer, causing abnormal operation of the UAV. The GPS receiver is particularly vulnerable to EMI due to the high sensitivity required for its accurate operation.

The conclusions of the study highlight the significant impact of strong electromagnetic waves on the critical systems of UAVs. The findings highlight the urgent need to develop advanced shielding and protection techniques for UAV electronic systems. In addition, it is necessary to design robust control algorithms that can effectively compensate for the effects of EMI.

Future research directions should include further investigation of the impact of different types of EMI in combination with various environmental factors. In addition, the development of advanced testing and certification methods to assess the EMI resilience of UAVs is a critical aspect of future research [5].

2.1.3 Impact on the Power System

The power system is vital for the flight of UAVs and consists of four basic components: battery, motor, electronic stability control (ESC), and propeller. The motor and ESC are critical for flight stability. In an environment of strong electromagnetic interference, the power system may suffer from malfunctions. Interference can enter the circuit through coupling on the printed circuit board (PCB) or affect the pulse width modulation (PWM) through cable coupling. Research [5] has shown that:

- Strong electromagnetic pulses can cause ESC MOSFET failure.
- Strong magnetic fields significantly increase the peak current of motors and affect their speed, depending on the control algorithm.
- HPMs can damage motors and ESCs, leading to a UAV crash.
- The cables between the flight control model, ESC, and motor are the main coupling path for HPM energy.
- HPM pulses can affect PWM signals, causing sudden changes in motor speed.

2.2 Impact of UW-EMPs

Unmanned aerial vehicles have emerged as a critical element of modern military forces, due to their multiple advantages, such as high flexibility, minimizing the risk of personnel losses, and comparatively low operating costs. However, the limited space inside the UAVs requires the concentration of multiple electronic systems in a small volume, which increases their sensitivity to strong electromagnetic fields. This vulnerability makes it imperative to study extensively and develop effective protection measures.

The study in [8] examines the critical importance of data connectivity for the effective operation of UAVs in combat conditions, with particular emphasis on their resilience against UW-EMPs, which emerge as a significant source of interference due to their high power, wide frequency range, and extensive area of effect.

To assess the reliability of UAV communication systems under the influence of UW radiation, a series of radiation experiments was conducted. The analysis focused on the phenomenon of "loss of lock", a critical issue for communications security. The results demonstrated a clear correlation between the intensity of UW radiation and the probability of "loss-of-lock" of the communication system. Specifically, a critical intensity threshold was observed at 140 kV/m, above which the probability of permanent damage increased exponentially [8].

Experimental data demonstrated a clear correlation between the intensity and frequency of UW-EMPs and the functional integrity of the UAV data link system. In more detail [8]:

- *Single pulses*: Their application, regardless of distance and irradiation point, did not result in a "lost lock" of the data link system; this indicates a degree of resilience of the system to short-term electromagnetic disturbances.
- *Critical parameters*: It was observed that for distances less than or equal to 4 meters and radiation frequencies above 5Hz, the system exhibited significant data loss and inability to restore communication; the critical radiation intensity threshold for causing this malfunction was determined to be 140 kV/m.
- *Correlation with distance*: The observed dependence on distance indicates the existence of a spatial threshold, beyond which the field attenuation is sufficient to prevent catastrophic effects on the system.

A thorough analysis of the loss-of-lock phenomenon revealed the following mechanism [8]:

- *Primary coupling*: The UW-EMP is primarily coupled to the drone's receiving system through its antenna; this coupling is the main entry point for electromagnetic disturbances into the system.
- *Communication interference*: The incoming electromagnetic energy causes significant interference to the communication system, affecting the integrity of the transmitted data.
- *Inability to recover*: Prolonged exposure to high-intensity UW-EMPs leads to the system's inability to restore communication; this phenomenon can be attributed to two possible scenarios of anomaly, either of the transmitting signal or of the receiving one.
- *Identification of the source of the failure*: Through a thorough investigation, the possibility of an anomaly in the transmission signal was ruled out; the analysis showed that the main cause of the loss-of-lock is the failure of the low-noise amplifier in the UAV receiver.

3 Protection Methods

The viability and effectiveness of the protection methods in the research of [2] have been documented through in-depth examples and case studies, providing innovative directions for the development of advanced protection systems. These methods aim to enhance the safety and reliability of UAVs under conditions of intense electromagnetic interference. The research focused on five main axes of technological approaches, which are analyzed as follows [2]:

Modal Filtration: This technology is an innovative approach to breaking up short-duration conductive pulses into sequences of smaller-amplitude pulses. Its application is based on the utilization of existing interconnections of electronic and electrical devices, including the housing as a ground return plane, the available space on the circuit board, the existing cables, and the printed conductors. This method achieves a significant reduction in electromagnetic interference without the need for additional components, thus optimizing the weight and cost of the system.

Hollow and Thin Passive Conductors Method: Experimental data demonstrate that replacing conventional solid passive conductors with hollow, angular, or thin conductors brings significant benefits, in terms of reduction of output voltage, significant weight savings, and maintenance of the desired pulse distribution in shorter sequences. This approach contributes to the optimization of the performance-to-weight ratio, a critical parameter for UAV systems.

Magnetodielectrics in Modally Bound Structures: The integration of magnetodielectric materials, combined with the application of the Theory of Inventive Problem Solving (TRIZ) methodology, has led to the development of devices with triple modal binding. These devices exhibit excellent performance in enhancing protection against EMI and suppressing the emission of hazardous currents. This approach offers a multi-layered solution to address complex electromagnetic challenges.

Evaluation of Ultrashort Pulse Attenuation: The method of symmetric filtration through successive stages has proven to be particularly effective in reducing the intensity of Ultrashort Pulses (USPs). This technique is ideal for applications where strict compliance with the dimensions of the UAVs is required, and also the preservation of the basic characteristics of the UAV systems. This approach allows for effective protection without significantly affecting the design or functionality of the UAV.

Use of Nonlinear Filters for USP Protection: Further enhancement of USP attenuation is achieved through adding additional conductors, introducing asymmetry into the system, and developing hybrid structures combining modal techniques. The application of the TRIZ approach in this context leads to innovative technical solutions for achieving Electromagnetic Compatibility (EMC) in advanced UAV countermeasure systems.

The various strategies and methods for protecting UAVs against various types of EMI are analyzed next.

3.1 Protection against Strong EMI

The integration of innovative technologies, such as Frequency Selective Surface (FSS) and Energy Storage System (ESS), as well as the use of advanced containment devices, are decisive steps towards enhancing the resilience of UAVs in demanding electromagnetic environments. Strong EMI includes a wide range of waveforms, including continuous waves (CW), high-altitude electromagnetic pulses (HEMPs), lightning electromagnetic pulses (LEMPs), ultra-wideband pulses (UWB EMPs), and high-power microwaves (HPMs) [5]. The protection measures against strong EMI consider backdoor coupling, shielding in general, cable shielding, and conduction protection.

3.1.1 Protection against Backdoor Coupling

Protection against backdoor coupling is a critical issue in the electromagnetic shielding of UAVs. This phenomenon involves the entry of electromagnetic energy into the interior of an electronic system through various paths, such as openings, grounds, power lines, or direct penetration. This penetration creates a complex electromagnetic field distribution, which can adversely affect sensitive circuits or components, preventing the smooth operation of the system. The protection strategy against this interference primarily focuses on reducing the energy of the incoming electromagnetic field by applying different techniques depending on the coupling paths [5].

3.1.2 Shielding Protection

Electromagnetic shielding (Shielding Protection) is a fundamental technique for limiting the propagation of EMI in space. This method is implemented by surrounding the device or circuit with special materials that cause attenuation of the interference signal, either through reflection or absorption. In the context of strong electromagnetic protection of UAVs, the main applications of shielding focus on the shell and cables.

Experimental studies have demonstrated the effectiveness of various shielding materials. For example, the use of aluminum foil in the shell of a UAV was shown to be particularly effective against lightning EMP (LEMP), reducing the peak voltage inside the UAV cabin to just 1 V under 150 kV lightning pulse conditions. Additionally, research has evaluated the performance of advanced materials, such as carbon fiber composites and graphene oxide, in electromagnetic wave shielding applications, confirming their suitability for use in UAVs.

Simulations conducted with “COMSOL Multiphysics” software have provided valuable information on the effect of LEMP on various parts of the UAV, including the fuselage and wings. The results of these simulations demonstrate that appropriate coating of the shell surface with electrically conductive materials can effectively prevent lightning from entering the UAV. In addition, these studies have highlighted the significant impact that the positions of the openings in the shell and the polarization direction of the incoming electromagnetic field have on the shielding performance [5].

3.1.3 Cable Shielding

Cables, as the main conductors for transmitting information and power between UAV electronic systems, are particularly vulnerable to electromagnetic interference due to their direct exposure to complex electromagnetic environments. Cable shielding is a critical technique for reducing the electromagnetic energy coupled into them, thus enhancing their resistance to external EMI.

Extensive research has shown that the effectiveness of cable shielding depends on multiple factors, including the type of EMI and the structural parameters of the shielding. In addition, the spatial arrangement of cables within the UAV has been shown to significantly affect the shielding performance. Based on these findings, strategies are proposed to optimize protection, which include careful design of cable routing and the implementation of advanced grounding methods.

High-precision simulations have shown the significant impact of cable layout and type on induced voltages in high-EMP environments. These findings highlight the importance of a holistic approach to UAV cabling design, considering both electrical and geometric parameters [5].

3.1.4 Conduction Protection

In environments with intense electromagnetic activity, conductors within UAVs, including cables, can act as coupling agents for electromagnetic energy, transferring unwanted voltages or currents to internal systems. Conduction protection aims to address this phenomenon by strategically placing nonlinear circuit elements along the UAV cables. These elements operate by either limiting the voltage or releasing the current, in order to reduce the effects of interference.

The main methods of conduction protection include containment and filtering techniques. Unlike front-door coupling protection, where containment technologies are mainly applied to the receiving systems, in conduction protection, protection technologies are applied to the internal cables of the UAV. The goal is to prevent the propagation of interference into the internal system of the drone [5].

3.2 Protection against UW-EMP

The research of [8] highlighted two main axes for enhancing the protection of UAVs against UW-EMPs. The first one is reducing the coupling of pulse energy from the antenna by:

- applying electromagnetic shielding to the front part of the UAV antenna;
- using a selective frequency surface to spatially limit the pulse input;
- integrating sophisticated filters and limiters before sensitive electronic components;
- utilizing advanced technologies such as PIN limiters, plasma gas limiters, ultra-fast microwave switches, ferrites, and superconducting limits.

The second axis includes the following three techniques for reducing the pulse energy reaching the front part of the radio frequency circuit.

3.2.1 Reducing Antenna Coupling with the EMP

The application of electromagnetic shielding to the front part of the UAV antenna is an effective method to reduce the coupling with the UW-EMP. The selective frequency surface emerges as a particularly promising technology for this purpose. It is a two-dimensional or three-dimensional metallic periodic structure, which allows the passage of electromagnetic waves within the passband, while strongly reflecting the waves outside it. The selective coupling offered by the FSS can significantly reduce the energy of the UW-EMP coupled to the antenna, without affecting the functionality of the communication system [8].

3.2.2 Reducing the Energy of the EMP in the Front End of the RF Circuit

The addition of sophisticated filters and limiters before the sensitive electronic components of a UAV is a critical element of the protection strategy. Particular emphasis is placed on the use of a PIN limiter. Such a device consists of a PIN diode with three regions - heavily doped P+, heavily doped N+, and a lightly doped intermediate region I. When this device is activated, the charge carriers pass through the intermediate region and recombine. The result of this recombination is the discharge of the energy of the UW-EMP to the ground, providing effective electromagnetic protection. It is usually placed at the front end of the RF circuit to protect the low-noise amplifier and mixer against high-power electromagnetic pulses [8].

3.2.3 Multiple Protection Methods

The complexity of the threat posed by UW-EMPs makes it imperative to develop advanced electromagnetic protection methods. However, due to the aforementioned characteristics of the UW-EMP, complete protection of the sensitive components of a UAV with a single protection method is considered insufficient and technically unfeasible. Therefore, it is recommended to simultaneously implement multiple, complementary electromagnetic protection methods. These may include:

- Advanced electromagnetic shielding with materials of high conductivity and magnetic permeability.
- Implementation of circuit topologies resistant to electromagnetic interference.
- Use of advanced surge protection devices, such as fast-response diodes and varistors.
- Optimization of grounding and electromagnetic compatibility of the overall system.
- Incorporation of self-recovery algorithms in case of temporary malfunction.

The combined application of these methods aims to significantly improve the survivability of drones in the increasingly complex electromagnetic environment of modern and future battlefields. Research in this area is considered vital, as the increasing reliance on UAVs in both military and civilian applications requires ensuring their reliability and resilience against advanced electromagnetic threats [8].

3.3 New Technologies for Strong Electromagnetic Protection

The rapid evolution of the electromagnetic environment, combined with the increasing complexity and miniaturization of electronic systems, has created new challenges in the field of electromagnetic protection of UAVs. Traditional protection methods often prove insufficient to meet modern requirements, while the development of innovative technologies and materials is required [5]. In this respect, three different directions are considered, regarding new materials and technologies, innovative software solutions, and specialized approaches by UAV-type and flight scenarios.

3.3.1 New Materials and Technologies for Electromagnetic Protection

Advanced Electromagnetic Shielding Materials: Recent research has led to the development of new composite materials with excellent electromagnetic shielding properties. Graphene-based nanocomposites have demonstrated excellent performance in absorbing electromagnetic waves over a wide range of frequencies. These materials offer significant advantages in terms of weight and flexibility, making them ideal for applications in UAVs.

Electromagnetic Bionic Technology: Inspired by biological systems, electromagnetic bionic technology leverages structures and mechanisms found in nature to improve electromagnetic shielding. For example, metamaterials that mimic the structure of butterfly wings have been shown to be effective in absorbing electromagnetic radiation in specific frequency bands.

Adaptive Electromagnetic Protection: Adaptive electromagnetic protection systems use advanced algorithms and smart materials to dynamically adapt shielding to changing electromagnetic conditions. This approach allows for real-time protection optimization, significantly increasing the effectiveness and efficiency of protection systems.

3.3.2 Innovative Software Solutions

Automatic Restart and Recovery: Recent studies have led to the development of sophisticated software solutions that allow the automatic restart and recovery of UAV flight and navigation systems after strong EMI. These solutions are based on advanced error detection algorithms and fast recovery mechanisms, ensuring that downtime is minimized.

Narrowband Interference Suppression Techniques: The application of narrowband interference suppression techniques, based on advanced signal processing algorithms such as the fast Fourier transform, has proven to be highly effective. These techniques allow for the accurate identification and elimination of specific EMI, significantly improving the quality of communications in UAV networks.

Cognitive Communication for UAV Swarms: Innovative anti-EMI methods based on cognitive communication technologies have been developed specifically for UAV swarm communication. These methods leverage techniques such as dynamic spectrum scanning and adaptive spectrum access, enabling effective communication even in environments with intense EMI.

3.3.3 Specialized Approaches by UAV-Type and Flight Scenarios

Electromagnetic protection of UAVs requires tailored approaches, depending on the type of aircraft and the flight scenario:

Rotary-wing UAVs: Due to their complex structure with multiple rotating engines and high device integration, rotary UAVs require holistic protection solutions. These include:

- Advanced shielding schemes to minimize interactions between internal components.
- Sophisticated filtering systems to address electromagnetic emissions from the engines.
- Active noise control techniques to reduce EMI caused by rotating parts.

Fixed-wing UAVs: Fixed-wing UAVs, with their simpler structure, focus primarily on protecting critical communication and navigation systems. Specialized solutions include:

- Advanced antenna systems with integrated electromagnetic shielding.
- Differential signal reception techniques for improved immunity to EMI.
- Application of adaptive filtering algorithms.

Specialization by Flight Scenario:

- UAVs for Aerial Photography and Logistics; Emphasis given on internal electromagnetic radiation using advanced isolation and filtering techniques to ensure the accuracy of sensors and imaging systems.
- UAVs for Power Surveys; Implementation of multi-layered protection strategies, including the use of advanced shielding materials and active interference suppression systems.
- UAVs for High Altitude Flights; Development of specialized solutions to address the unique challenges posed by the ionospheric environment, such as the use of adaptive error correction algorithms and signal enhancement techniques.

4 Discussion

This study demonstrates the increasing vulnerability of UAVs to strong EMI, a phenomenon that has become particularly evident with the rapid expansion of the drone market, the ever-increasing complexity of their embedded systems, and the combination of technologies for countering potential threats by their usage [9]. Systematic analysis of experimental data revealed that:

- The loss of lock of the data link system is primarily due to the failure of the low-noise amplifier (LNA) in the UAV internal circuits. This finding highlights the criticality of the LNA as a sensitive point in the UAV architecture.
- UWB pulses have been shown to be particularly damaging to UAVs, due to their extremely fast rise time (on the order of picoseconds) and high radiated power (which can reach gigawatts). These characteristics allow UWB pulses to bypass conventional shielding methods and induce high voltages in internal circuits, leading to catastrophic damage to semiconductors.
- Conventional shielding techniques often fail to adequately meet modern requirements for protection against strong EMI. The application of innovative shielding materials and technologies, although promising, is still in the early research stage and has not been substantially integrated into the design and manufacturing process of UAVs.

While conventional high and low power EMI methods are primarily based on RFs, their effectiveness can be limited by the characteristics of the targeted systems. Particularly in the case of modern digital integrated circuits, the tiny dimensions and high operating voltage levels often make RF interference ineffective [10].

5 Conclusion

The conclusions of the present study can be summarized as follows [10]. The complete protection of sensitive UAV components with a single protection method is considered insufficient and technically unfeasible, due to the complexity of UW-EMPs. The existing experimental methodologies may not fully capture the correlation between macroscopic phenomena and underlying microscopic mechanisms caused by electronic interference. The current simulation models may not adequately consider all the specific structural and material parameters of UAVs. The analysis of failure mechanisms has not yet been fully systematized, limiting the understanding of the relationship between damage to individual components and the overall failure of the UAV system.

Considering the findings and limitations of the present methods, the following directions for future research are suggested: The development of practical and cost-effective protection methods, including, for example, the application of 3D printing techniques for the fabrication of specialized protective structures; The investigation of the application of the proposed methods to a wider range of electronic systems, beyond UAVs; The development of standards and guidelines for the application of these techniques in real operating conditions; The incorporation of self-recovery algorithms in case of temporary malfunction; The strengthening of experimental methodologies through:

- Integrating advanced monitoring techniques, such as the use of high-precision sensors.
- Applying non-destructive testing techniques.
- Improving simulation models through: (a) developing more sophisticated algorithms that consider the specific structural and material parameters of UAVs; (b) using machine learning and artificial intelligence techniques to improve the accuracy of simulations; (c) integrating multi-physics models that combine electromagnetic, thermal, and mechanical phenomena.
- Developing and integrating innovative protection technologies, such as: (a) using advanced metamaterials; (b) developing active protection systems; (c) applying self-healing techniques to address the effects of strong EMI.
- Systematization of failure mechanism analysis through: (a) development of comprehensive models that describe the relationship between damage to individual components and overall failure of the UAV system; (b) conducting detailed reliability analyses; (c) development of advanced fault diagnosis and prediction techniques.

In conclusion, continuous research and development in the field of electromagnetic protection of UAVs is critical to ensuring their reliability and safety in an increasingly complex electromagnetic environment.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used Google Translate services in order to improve the readability and language of their manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Vasileios Karpetas conducted the survey.
Christos Papakitsos wrote the text and assessed the materials aspects.
Nikolaos Laskaris assessed the electronics aspects.
Michail Papoutsidakis assessed the automation engineering aspects.
Evangelos Papakitsos assessed the software engineering aspects and structured the research process.
Dionysios E. Mouzakis assessed the research methodology and supervised the project.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.