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A Conceptual Model for Eco-Friendly Low-Cost Counter-Drone Defence Using Biodegradable Sticky Microfibers

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Abstract

The increasing proliferation of uncrewed aerial vehicles (UAVs) in civilian, commercial, and potentially malicious contexts highlights the urgent need for practical, low-cost, and environmentally sustainable counter-drone solutions. Current technologies, such as radio-frequency jamming, directed energy weapons, mechanical nets, or kinetic projectiles, each provide partial responses but face significant limitations when confronted with drone swarms, cost constraints, or ecological impact. This study introduces a conceptual model based on the controlled dispersion of a cloud of biodegradable sticky microfibers designed to entangle UAV propellers and halt flight. The proposed approach emphasizes scalability—addressing multiple drones simultaneously—together with sustainability, by employing cellulose-based or biodegradable polymeric fibres coated with natural adhesive compounds. A theoretical multi-layer fibre system is outlined, adapted for different altitude ranges, from lightweight fibres for low-altitude drones to denser micro-ribbons for higher-altitude scenarios. Comparative analysis suggests that this eco-friendly method could complement existing counter-drone technologies by offering a low-cost and swarm-capable alternative. However, limitations are acknowledged, particularly regarding meteorological sensitivity, effective dispersion at high altitudes, and safety concerns related to civilian environments. Future research directions include experimental testing of candidate materials, optimization of fibre properties, and integration into broader civil airspace security systems. This work does not present an engineering prototype but rather seeks to stimulate academic discussion by opening an original research direction in sustainable counter-drone defence.

Keywords: counter-drone technology; biodegradable fibres; sticky microfiber cloud; sustainable defence; UAV neutralization; drone swarms

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1. Introduction

In the last two decades, drones have evolved from experimental equipment to widely used tools across multiple fields, including agriculture, logistics, infrastructure inspection, express deliveries, and entertainment and photography. This democratization of UAV (Unmanned Aerial Vehicle) technology has brought major benefits, but has also generated serious challenges regarding public security and safety.

The main risks include:

- exceeding the maximum legal altitude of 120 m, which may interfere with civil air traffic;
- unauthorised transportation of objects (drugs, weapons, contraband), given that many commercial drones can lift over 500 g;
- use for industrial espionage or for violating citizens' privacy, an aspect with direct implications for GDPR and data protection [1];
- possible coordinated attacks with drone swarms, in which individual neutralization becomes ineffective.

Current countermeasures include radio or GPS jamming, the use of lasers, microwave systems, or interceptor drones equipped with nets. However, all of these have important limitations: high costs, high energy consumption, vulnerability to weather conditions, and low effectiveness against a large number of drones launched simultaneously. As recent literature on anti-drone technologies shows, there is no universal, effective and sustainable solution against swarms [2–4].

In this context, the present work proposes an **original conceptual approach**: the use of a *cloud of biodegradable textile microfibers with sticky properties* to neutralize drones. The central idea is that, once dispersed in the proximity of detected UAVs, the cloud will cling to their propellers and block their propulsion mechanism. While net solutions are effective for capturing a single drone, a cloud of microfibers could cover a large area, making it possible to neutralize several drones simultaneously [3–9].

The innovative nature of this proposal consists of:

- **scalability** – the ability to act on drone swarms;
- **sustainability** – biodegradable textiles reduce environmental impact;
- **low cost** – compared to advanced energy systems or classic ammunition;
- **adaptability** – possible use of several types of fibres, calibrated for different altitudes.

The contribution of this study is conceptual in nature. We do not present a technical prototype, but an idea that opens a new research direction and may inspire future developments in the field of civil aviation security.

2. Literature Review

The increasing use of drones in civil and commercial space has led to the emergence of a growing number of technological solutions aimed at countering them. Currently, existing approaches are mainly based on four directions: electromagnetic jamming, energy weapons, mechanical capture and conventional kinetic methods [3–8].

Electromagnetic jamming aims to disrupt radio signals used for control or satellite navigation signals. Recent studies have shown that these methods have low efficiency on autonomous drones with inertial navigation [5–7]. This solution has the advantage of being able to act on multiple drones simultaneously and without direct contact. However, its efficiency is limited in the case of drones operating autonomously, on pre-programmed routes, and it can also affect other electronic equipment in the area, which raises safety concerns [8–14].

Energy weapons, such as lasers or microwave systems, offer the possibility of quickly neutralizing targets by destroying sensitive components or damaging electronic circuits. However, these systems involve high operating costs and significant energy consumption, and are vulnerable to adverse weather conditions, such as fog or rain [10–12].

Mechanical capture methods, based on nets, cables or interceptor drones, have the advantage of neutralizing the drone intact, allowing its analysis after capture. However, their efficiency is reduced when it comes to simultaneously neutralizing multiple targets, and the degree of complexity of implementation increases considerably in dynamic scenarios [3–7].

Finally, traditional kinetic methods, such as the use of bullets or projectiles, continue to be used in specific contexts, but they pose significant risks to the environment and civilian infrastructure. For this reason, they are increasingly less accepted in urban environments or congested areas.

The analysis of these approaches shows that none of the current solutions manages to satisfactorily combine efficiency against drone swarms, low costs and minimal environmental impact. This gap justifies alternative approaches and the exploration of new, more sustainable and accessible directions, such as the concept proposed in this paper – the dispersion of a cloud of sticky biodegradable microfibers to neutralize unauthorized drones.

3. Materials and Methodology

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The present work does not aim to develop a functional prototype, but to formulate and analyze a conceptual model for neutralizing unauthorized drones by means of a cloud of sticky biodegradable microfibers. In this section, the candidate materials, the operating principles and the criteria used for the comparative evaluation of the method are presented. The choice of materials is based on the properties of advanced textile fibres, which have been analyzed in the specialized literature on the mechanical behaviour and dimensional stability of textile structures [6]. These aspects are consistent with the current directions in green materials and functional textiles.

Candidate materials. The proposed concept is based on the use of textile microfibers obtained from biodegradable materials with adhesive properties. Among the options considered are: cellulose microfibers with coatings based on natural polymers (gum arabic, modified starch), polylactide (PLA) or polyhydroxyalkanoate (PHA) filaments with a bio-adhesive resin layer, respectively micro-ribbons made of vegetable fibres (hemp, cotton) treated with natural tackifying compounds. The choice of materials is guided by criteria such as biodegradability, specific density, behaviour under various atmospheric conditions and environmental safety. These considerations are in line with recent directions in the development of bio-based polymers for sustainable engineering applications [6,10–13].

Operating principle. After detecting drones by radar or other optical systems, a controlled dispersion of a cloud of microfibers in the vicinity of the targets is assumed. The sticky fibres, carried by air currents, cling to the drone propellers, causing the propulsion mechanism to jam and loss of stability in flight. Unlike a classic net, which can capture a single drone, the cloud has the advantage of covering an extended area, offering the possibility of simultaneously neutralizing several drones. The principle of fiber dispersion can be conceptually compared to the dynamics of oscillating pneumatic systems, where the control of air flows plays an essential role [13–17].

Representative parameters and cloud sizing.

In order to realistically estimate the efficiency, we adopted representative dimensions for microfibers of the order of **5–20 μm** in diameter and **2–10 cm** in length, values compatible with cellulose or biopolymer fibers (PLA/PHA) coated with natural adhesives [6]. In this dimensional range, **the specific mass per fibre** is of the order of **0.0006–0.047 mg/fib**re, which translates into **~2×10^4 – ~1.7×10^6 fibres/gram** depending on the geometry. The operational target at low altitude (<500 m) is that the rotor of a commercial drone (≈20 cm diameter) encounters a sufficient number of fibers per second to generate progressive entanglement; calculations show that an **air density of ~3,000–7,000 fibers/m^3** is adequate, equivalent to only **~0.02–0.08 g fibers/m^3** (for ~10 μm × 5 cm microfibers). Thus, a local cloud **r≈8–12 m** (diameter 16–24 m) covers an area of **~200–450 m^2** and has a volume of **~2,100–7,200 m^3** , requiring on average **~40–580 g** of material to reach the target density; for **r=10 m** (≈4,190 m^3) this results in **~0.08–0.34 kg** . In windy conditions, an ellipsoidal "plume" of ~20×20×10 m (semi-axes 10,10.5 m) has a volume of ≈ **2,094 m^3** and requires **~40–170 g** at the same density. These orders of magnitude confirm the **low-mass/low-cost nature** of the approach and justify the focus on low altitudes, where the cloud remains sufficiently coherent for effective interaction with the rotor [6,10,11].

To limit premature agglomeration in the container, **the adhesive layer** is treated as **a bio PSA** (resin/rosin esters with food plasticizers) with **predominantly contact tack , or a two-step dispersion** is applied (dry fibres + ultrafine mist of natural adhesive sprayed simultaneously in volume), both solutions maintaining the biodegradable character. The targeted thermal stability is **0–60/80 °C** and **low Tg** , to preserve the elasticity of the film in relatively dry and drafty air; at very low altitudes, alternatives based on **hygroscopic polysaccharides** (starch/gum arabic) can quickly activate adhesion through ambient humidity. From the perspective of mechanical interaction, optimized fibers **10–30 μm** in diameter and **5–20 cm** long (regenerated cellulose or thin PLA) offer a compromise between environmentally **controlled fragility** and **the ability to agglomerate** at the rotor: blocking does not depend on the strength of a single fiber, but on **the cumulative effect** of thousands of fibers which, at the mentioned density, progressively coil up to form clumps capable of stopping propulsion.

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Altitude adaptation. The conceptual model considers three categories of fibres calibrated for different altitudes: ultralight fibres, similar to plant fluff, for altitudes below 500 m; medium-density fibres for intermediate altitudes, around 5000 m; and heavier fibres, shaped like micro-ribbons, for theoretical scenarios up to 10,000 m. This stratification aims to maintain the balance between the ability of the fibres to remain suspended in the air and the need to withstand the stronger atmospheric currents encountered at high altitudes [16–19]. A key issue, still at the hypothesis stage, is the optimal mode of dispersion. The paper does not propose a specific mechanism, but possible options include compressed air cannons, dedicated dispersion drones, or projectiles with controlled micro-explosive charges. The optimal choice should be evaluated through simulations and tests to guarantee the appropriate targeting and density of the cloud.

Analysis criteria. In the absence of practical experiments, the method was evaluated conceptually by reference to four major criteria:

- **ecological sustainability**, determined by the degree of biodegradability of the fibers and the minimal impact on the environment;
- **potential costs** , compared to jamming systems or energy weapons;
- **theoretical effectiveness against swarms**, through the possibility of simultaneously covering a larger volume of airspace;
- **resistance to atmospheric conditions**, including variations in air density, humidity and temperature.

Conceptual scheme. The proposed action flow consists of the following steps: detection of unauthorized drones; guidance of a dispersion vector to the target area; release of a cloud of sticky microfibers; interaction of the fibres with the UAV propellers; loss of lift and their neutralization.

Trebuie menționat că lucrarea are caracter conceptual și nu include încă teste experimentale sau prototipuri funcționale. Următorul pas firesc ar fi construcția unui prototip la scară redusă și testarea în condiții controlate, pentru a valida ipotezele prezentate și a rafina parametrii de funcționare.

4. Results and Discussions

Given the conceptual nature of the proposed method, the “results” presented do not consist of experimental data, but rather theoretical evaluations and comparisons with existing solutions. The analysis focuses on the potential advantages of the sticky biodegradable microfiber cloud, as well as the limitations that need to be recognized.

A first notable result of this approach is **scalability**. While traditional mechanical methods, such as nets, can only neutralize a single drone at a time, the cloud can cover a larger air area simultaneously. This gives it great potential in scenarios involving swarms of drones, where individual neutralization becomes ineffective.

Secondly, the method brings a clear benefit in terms of **environmental sustainability**. The use of biodegradable fibers and adhesive compounds of natural origin minimizes the impact on the environment, in contrast to classic ammunition or energy systems that can generate hazardous residues.

From an economic point of view, the proposed approach falls into the category of **low-cost solutions**. The candidate materials are cheap and easy to obtain, and the operating principle does not require massive energy consumption. In comparison, laser or microwave systems involve high acquisition and operating costs, which limit their widespread use.

An important aspect is the interaction between the mechanical strength of the fibers and their functionality. Fibres that are too fragile would break immediately upon contact with the rotor, while fibres that are too resistant would pose ecological risks. For this reason, the proposed conceptual solution consists of using microfibers with a diameter of 10–30 μm and a length of 5–20 cm, made of regenerated cellulose or PLA biopolymers. These have the flexibility not to cause damage to birds or animals, but they can agglomerate in the rotor by the simultaneous accumulation of thousands of fibres, which leads to the formation of clumps capable of blocking the propulsion mechanism. In

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addition, biodegradable materials ensure rapid degradation in the natural environment, limiting the accumulation of residues.

The mechanical behaviour of fibres depends not only on the material, but also on the geometric structure and the way they interact upon contact, an aspect also discussed in studies dedicated to knitted structures [11].

However, the analysis also highlights some **important limitations**. Meteorological conditions strongly influence the efficiency of the cloud. Strong wind, rain or high humidity can disperse the fibres or reduce their adhesion. In addition, the applicability at high altitudes is limited, as thin air and atmospheric currents accelerate the dissipation of the cloud. Therefore, the method is promising for low and medium altitudes, where most civil and commercial drones operate, but it is less suitable for large UAVs. The efficiency of the microfiber cloud is sensitive to meteorological factors such as wind, rain and high humidity. These can prematurely disperse the fibers or reduce their bonding ability. To optimize the performance, CFD simulations and experimental studies of the behavior in different atmospheric scenarios would be required.

Another discussion concerns **the safety of use**. Even if the proposed materials are biodegradable and non-toxic, additional assessment is needed regarding the risk that the fibres will affect other equipment in the area (ventilation, sensors) or cause discomfort to the population in the event of accidental dispersion.

By conceptually comparing the proposed method with existing solutions, a clearer picture emerges: electromagnetic jamming remains effective against communication-dependent drones, but does not act on autonomous ones; energy weapons are fast, but expensive and environmentally sensitive; mechanical capture is precise, but limited to a single UAV; kinetic methods present significant collateral risks. In this landscape, the biodegradable microfiber cloud appears as a complementary alternative, capable of specifically addressing scenarios with low-altitude drone swarms. This is also confirmed by recent comparative analyses [12,13]. Recent studies confirm that the future of anti-UAV technologies will depend on hybrid solutions, combining efficiency with low costs and low ecological impact [18,19]. The impact on civil safety must also be considered. Even if the materials are biodegradable and non-toxic, accidental dispersion in populated areas could cause discomfort or unwanted interactions with other equipment. Thus, additional environmental and civil impact assessments become essential.

For high-altitude drones, where the air is thinner and the atmospheric currents are stronger, the method would require significant adaptations or could become ineffective. For this reason, practical applicability remains focused on low and medium altitudes, where most commercial drones operate.

5. Conclusions

This paper proposed an innovative conceptual model for neutralizing unauthorized drones by using a cloud of biodegradable textile microfibers with sticky properties. In contrast to established methods – electromagnetic jamming, energy weapons, mechanical capture or kinetic solutions – this approach aims to combine the advantages of low cost, environmental sustainability and the possibility of acting on multiple drones simultaneously.

The comparative analysis carried out in the paper highlighted that current methods, although effective in certain scenarios, have major limitations when it comes to drone swarms, implementation costs or environmental impact. In this context, the microfiber cloud emerges as a complementary solution, able to better respond to situations in which existing technologies become ineffective or prohibitive.

At the same time, the main limitations of the concept were also identified: the dependence on meteorological conditions, the difficulty of maintaining cloud density at high altitudes, and the need for additional assessments regarding the safety of fibre dispersion in civilian environments. These aspects show that the method cannot be considered universally applicable, but rather directed towards security scenarios at low and medium altitudes, where most commercial and hobby drones operate.

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Looking ahead, future research should focus on experimental testing of candidate materials, optimising fibre properties (density, adhesion, buoyancy time), and developing controlled dispersion mechanisms. It would also be necessary to integrate the concept into a broader civil aviation security framework, along with detection and monitoring systems, to achieve efficient, safe, and environmentally friendly solutions.

Thus, the contribution of this paper lies not in presenting a completed technology but in opening a new research direction with the potential to inspire further developments in a rapidly expanding field. In an era where drones are becoming increasingly powerful and accessible, innovative and sustainable ideas can play an essential role in ensuring the balance between technological progress and the protection of society.

3D modelling of natural and technical structures has proven helpful in other research areas, such as the case of automated olive harvesting [14], which suggests that, in our case too, simulations could be a future step.

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