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Research on the Rapid Prototyping Design and Optimization of 3D-Printed UAVs for Disaster Relief and Search-and-Rescue

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Abstract:

Natural disasters threaten the escalating threat of human security and infrastructure, highlighting the urgent need for efficient and adaptive rescue technologies. Unmanned aerial vehicles (UAVs) have become important tools for disaster response, but their extensive deployment is often limited by traditional manufacturing, such as long-term production cycles and high levels. This study studies the integration of manufacturing (3D printing) in rapid forming and optimization. Through the evaluation of the main printing process, including the Fused Deposition Modeling (FDM), Stereolithography (SLA) and Selective Laser Sintering (SLS) -- the study assessed their applicability to the lightweight, modular and task specific UAV components. The case studies on folding-wing and amphibious avs show how 3d printing can be quickly customized and functional, and structural optimization methods, such as a lattice infill and composite cement, help reduce the mechanical ability of 20-30% and enhanced. Despite the challenges associated with material durability and production scalability, additive manufacturing provides a promising way to respond with responsive, resilient, and cost-effective uav solutions.

Keywords: UAVs; Disaster relief; Additive manufacturing; 3D printing; Rapid prototyping; Structural optimization.

1. Introduction

1.1 Background of Disaster Relief and the Role of UAVs

According to the United Nations, there are more than 350 people in the world who are responsible for natural disasters every year, affecting millions of people and causing major economic losses [1]. In this case, the speed and efficiency of rescue actions often determine the outcome of survival. Traditional methods, such as helicopters or ground teams, are often limited by high costs, limited accessibility and delayed deployment [2].

UAVs have become the key to these missions. For example, a portable wing UAV can be detected in less than two minutes to quickly detect [3]. In the maritime environment, despite the bad weather, UAVs show strong adaptability through extensive search and transmission of real-time data [4]. UAV swarm technologies, which is equipped with cooperation to prevent the obstacle, further improves the operation elasticity and scalability of complex rescue tasks [5].As shown in Fig. 1 and Fig. 2, disaster scenarios such as earthquakes and wildfires highlight the urgent need for rapid aerial reconnaissance capabilities.

Fig. 1 collapsed building destroyed by an earthquake

Fig. 2 Forest wildfire spreading in a woodland area

1.2 Limitations of Traditional UAV Manufacturing

Despite their advantages, UAV deployment still faces manufacturing bottlenecks. Traditional UAV prototypes usually require a 4-8 week, which is incompatible with the urgency of the post-disaster response [1]. In addition, the UAV is adapted for a specific missions (e.g., lightweight frames for mountainous regions or waterproof designs for floods) is costly and slow, limiting flexibility [2].

By contrast, additive manufacturing allows UAV components to occur within a few days, while enabling modularity and rapid iteration [3]. This makes it possible for disaster relief teams to customize drones based on demand, which is the ability of traditional manufacturing to fail [6]. As summarized in Table 1, in terms of time, cost, customization, and deployment readiness, additive manufacturing has a significant advantage in traditional UAV production.

Table 1. Comparison between conventional UAV manufacturing and additive manufacturing (3D printing)

Criterion	Conventional Manufacturing	Additive Manufacturing (3D Printing)
Development cycle	4–8 weeks	Several days
Cost	High	Relatively low
Customization	Limited, slow	Flexible, rapid iteration
Deployment readiness	Slow	Fast

1.3 Research Objectives and Significance

This study aims to explore the integration of 3D printing technologies to quickly shape and optimize the disaster relief for UAVs. Instead of targeting performance requirements, manufacturing methods and optimization strategies as independent goals, they are seen as interrelated aspects of a unified framework. First, drones used in disaster scenarios must meet strict portability, adaptability and endurance requirements to ensure that they can be quickly deployed in different and often unpredictable situations. To address these requirements, the study has identified the applicability of mainstream 3D printing technologies, including FDM SLA and SLS-- to focus on the potential of lightweight and modular structures.

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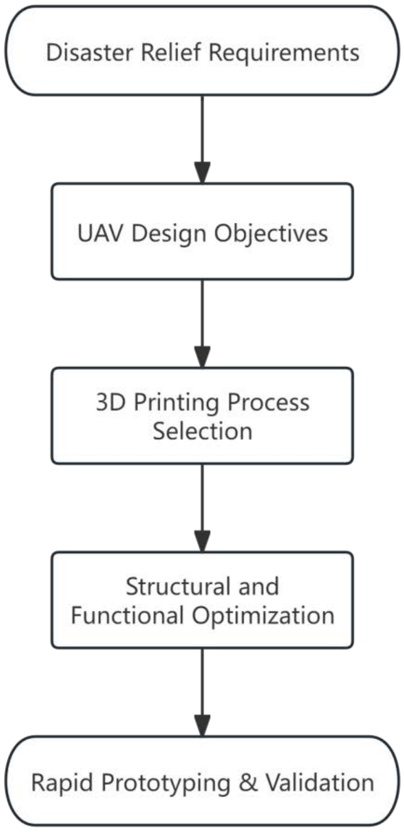

Fig. 3 Research framework for rapid prototyping of disaster-relief UAVs.

On the basis of these assessments, the optimization path is studied by combining advanced materials with structural analysis to enhance uav reliability and functional integration. By using additive manufacturing, the fuselage of the UAV is more than 30 percent of the weight of the traditional process [4]. This is directly converted into increased endurance, effective load efficiency and task response. The overall research framework is illustrated in Fig. 3, which connects disaster requirements, UAV design objectives, 3D printing processes, and structural optimization strategies.

2. Disaster Scenarios and Rapid Prototyping Requirements Analysis

2.1 Characteristics of Disaster Relief Missions

The task is characterized by emergency, unpredictability, and high risk for rescuers and victims. Research suggests the "gold 72 hours" is the most critical time window for saving life after major disasters such as earthquakes, floods or wildfires[3]. Traditional rescue teams are often blocked by collapsed infrastructure, clogged traffic routes and bad environmental conditions. These restrictions require technical solutions that can bypass terrain barriers and operate in inaccessible areas.

In this case, UAVs have proven they are flexible platforms that can perform rapid reconnaissance, real-time environmental monitoring and delivery of aid. In an earthquake, UAVs can provide air images of collapsed buildings to support decisions [1]. In the flood scenario, UAVs help to map underwater areas and identify survivors [7]. Similarly, in the field of wildfire, UAVs equipped with thermal imaging sensors have enhanced fire detection and tracking capabilities, allowing reagents to deploy fire fighting resources more effectively [8]. These examples emphasize that UAVs are not only complementary, but are also becoming the basic elements of the modern disaster management system. As illustrated in Fig. 4, These core features—urgency, complexity, risk, and multi-tasking—directly affect the design of UAVs.

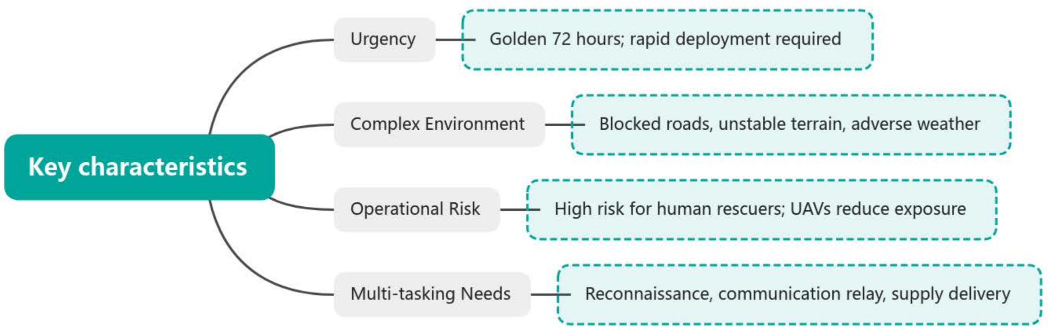

Fig. 4 Key characteristics of disaster-relief missions influencing UAV design

2.2 UAV Functional and Performance Requirements

Portable drones should remain under 5 kg to ensure that single portability is completed within less than 2-3 minutes, such as search and rescue in the prototype of the folding wing UAV [1]. Endendurance is another key factor in the 30-60-minute disaster missions. Using a simplified relation,

$$T = \frac{C}{P} \tag{1}$$

where T is the flight time (hours), C is the battery capacity (Wh), and P is the average power consumption (W), a UAV with a 99 Wh battery and average consumption of 120 W achieves approximately 50 minutes of flight. The corresponding maximum range can be estimated as

$$R = v \times T \tag{2}$$

where v is the average speed. For instance, at 36 km/h, the range is about 29 km.

Disaster environments also demand adaptability. UAVs must resist winds up to 10–13 m/s (Beaufort scale 5–6) and operate across temperatures from –10 °C to +45 °C, as highlighted in marine rescue UAV studies [2]. Payload flexibility is equally important: UAVs should carry 0.5–2 kg of modular payloads (sensors, cameras, or small supply packages), with module changes completed in under 5 minutes. Finally, ease of operation is essential, since many first responders are not professional pilots. Semi-autonomous or fully autonomous flight modes, supported by intuitive interfaces, allow effective operation with minimal training.The core functional and performance requirements for disaster-relief UAVs are summarized in Table 2, providing both quantitative benchmarks and supporting references for design and evaluation.

Table 2. UAV Functional and Performance Requirements for Disaster Relief

Requirement	Quatitative Indicators	Notes / Source
Portability	Weight < 5 kg; deployment time < 3 min	Folding-wing UAV prototypes for rapid deployment [1]
Endurance	30–60 min typical; estimated by \[T=\frac{C}{P}\] (e.g., 99 Wh / 120 W ≈ 50 min)	Based on commercial UAVs and simplified endurance model
Range	\[R=v\times T\]; at 36 km/h × 0.8 h ≈ 29 km	Derived from flight time and average cruising speed
Environmental Adaptability	Wind resistance up to 10–13 m/s; operating temperature –10 °C to +45 °C	Marine rescue UAV studies [2]
Payload Flexibility	0.5–2 kg modular payloads (sensors, cameras, supplies); swap < 5 min	Modular UAV design concepts
Ease of Operation	Semi-/fully autonomous flight; training < 1 day	Supported by intuitive interfaces and control software

3. Overview of 3D Printing Technologies

3.1 Mainstream Processes and Material Properties

Additive manufacturing (AM), commonly referred to as 3D printing, offers diverse processes that can be applied to the rapid prototyping of disaster-relief UAVs. Three of the main methods are integrated based on the Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) to highlight the practice and availability of the engineering practice. Each method has its respective characteristics in precision, mechanical strength, surface completion and material selection. This directly affects the suitability of the UAV structural component.

Fused Deposition Modeling (FDM) is one of the most widely used technologies, which is low-cost and easy to operate. The FDM printer extrudes the thermoplastic filaments, such as PLA, ABS, or PETG to form the final geometry layer by layer. The typical layer thickness ranges from 100–300 μm, while the dimensional accuracy is around ±0.5 mm. Although the process is suitable for light and low cost components, FDM is affected by anisotropy because of weak layer bonds. For UAV applications, FDM-printed PLA or ABS can achieve tensile strengths of 40–60 MPa, sufficient for non-critical airframe components or housings [9].

In contrast, the Stereolithography (SLA) uses a UV laser or projector to cure liquid resin into solid layers. SLA parts exhibit excellent surface finish and high resolution, with layer thicknesses as fine as 25–100 μm and accuracy up to ±0.1 mm. However, SLA resins are generally brittle, with tensile strengths typically around 30–50 MPa, and

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limited resistance to high temperatures or humidity [10]. Therefore, the SLA is more suitable for use in uav components, requiring detailed geometries, such as aerodynamic fairings or sensor shells, rather than load-bearing structures.

Selective Laser Sintering (SLS) leverages a high-power laser to fuse powdered polymers such as Nylon (PA12) or composites. The resulting parts demonstrate relatively isotropic mechanical properties and robust durability. SLS components often exhibit tensile strengths of 45–70 MPa and elongation at break of 10–20%, outperforming FDM and SLA in terms of toughness and fatigue resistance [11]. Furthermore, SLS does not require support structures, enabling the production of complex, lightweight lattice geometries well-suited for UAV airframes and internal mounts. The main drawback is the high equipment and material cost.The compatibility of mainstream 3D printing processes with different UAV structural components is summarized in Table 3, highlighting the trade-offs between cost, accuracy, and mechanical strength.

Table 3. Compatibility of 3D Printing Processes with UAV Structural Components

UAV Component	FDM (PLA/ABS)	SLA (Resin)	SLS (Nylon/Composite)
Airframe structure	Low-cost prototyping, limited strength	High accuracy but brittle resin	Strong, durable, suitable for load-bearing
Wing components	Lightweight, but anisotropic strength	Smooth aerodynamic surfaces	High strength, suitable for complex designs
Payload mounts	Simple, rapid fabrication	Precision fits possible	Strong and modular for repeated use
Connectors/joints	Functional but weaker bonding	High detail but fragile	Robust, good fatigue resistance
Landing gear	Cheap, easy to replace	Limited toughness	High impact resistance

In summary, FDM excels in affordability and accessibility, SLA provides high resolution but limited strength, and SLS delivers a balance of strength and geometric freedom at higher cost. Understanding these characteristics is essential for selecting appropriate processes and materials for UAV rapid prototyping under disaster-response constraints.

3.2 Compatibility of 3D Printing with UAV Structural Manufacturing

When evaluating 3D printing technologies for disaster-relief UAVs, it is crucial to analyze how well different processes and materials align with the structural and functional demands of airframes. Unlike generic consumer products, UAV components must meet strict requirements of strength-to-weight ratio, dimensional accuracy, and environmental resistance, all of which directly affect flight safety and mission success.

For example, FDM printing with PLA or ABS offers rapid, low-cost prototyping of fuselage shells and structural panels. However, its layer adhesion weakness often reduces interlaminar strength to 30–40% of bulk properties, limiting use in load-bearing parts [9]. SLA printing achieves fine tolerances and smooth aerodynamic surfaces (dimensional accuracy ~±0.05 mm), making it suitable for sensor housings or wing surface prototypes, though resin brittleness constrains structural durability [10]. In contrast, SLS nylon or composite powders provide superior toughness, impact resistance, and thermal stability, supporting the production of UAV landing gears, propeller guards, or even modular wing structures [11].

Dimensional tolerance is another compatibility factor. UAV airframe assembly typically requires tolerances of ±0.1 mm for mounting holes and ±0.2 mm for structural fits. Both SLA and SLS can satisfy these requirements, while FDM often requires post-processing such as sanding or drilling to achieve precise fits [12]. Moreover, UAV structural design must account for aerodynamic efficiency and payload integration. Lightweight infill strategies (20–30% density) reduce mass by up to 25% compared to solid builds, though at the cost of reduced stiffness. Reinforcement methods—such as embedding carbon-fiber rods or using hybrid metal inserts—are therefore recommended for critical load paths [13].

In summary, FDM, SLA, and SLS each offer distinct compatibility advantages: FDM for rapid and inexpensive iterations, SLA for precision and aerodynamic form, and SLS for mechanical robustness. Selecting the appropriate process-material combination ensures that disaster-relief UAVs can be manufactured quickly without compromising safety or adaptability.As shown in Fig. 5, the three mainstream 3D printing processes—FDM, SLA, and SLS—exhibit distinct trade-offs across precision, strength, thermal resistance, weight reduction, cost, and speed, reflecting their varying suitability for UAV structural manufacturing.

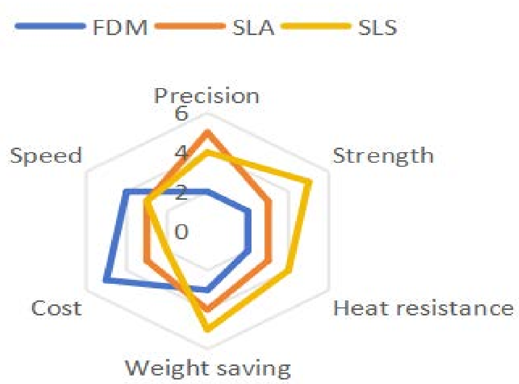

Fig. 5 Comparative radar chart of FDM, SLA, and SLS processes for UAV structural manufacturing

4. Case Studies and Application Exploration

4.1 Folding-Wing Portable UAV Case Studies

Folding-wing UAVs have become a notable solution for search-and-rescue operations due to their compactness and fast deployment. Their ability to be transported in a folded configuration and deployed within minutes makes them particularly valuable in environments where infrastructure is damaged or inaccessible. In two minutes, several folding-wing UAVs can be prepared for flight, and its total system weighs less than five kilograms, which enables single-operator portability [7]. The aerodynamic analysis further reveals the strong impact of the deployment mode on the structure load: synchronous unfolding is effective in lower airspeed, and stepwise unfolding more stability at a higher speed [14]. The multi-rotor platform of the collapsible robotic arm also shows how the compact design saves time and promotes the operation of limited disaster zones [15].

The main implication of these case studies is that the folding mechanism improves the deployment efficiency during the critical "golden time" of disaster relief. At the same time, they raise structural challenges for hinges and locking joints, which must endure repeated stresses without excessive weight penalties. In this regard, additive manufacturing offers a feasible path to producing lightweight yet customized parts such as hinges, connectors, and quick-release interfaces. This synergy suggests that folding-wing UAVs are a promising platform for the integration of 3D printing technologies in disaster-relief applications [16].

4.2 Amphibious and Marine Search-and-Rescue UAV Case Studies

In flood-prone or coastal disaster environments, UAVs that can operate across both aerial and aquatic domains have drawn attention. A recent study described a ground–air amphibious UAV based on a separation-cage structure, weighing about 1.2 kg with a 1 kg payload capacity, and demonstrating an endurance of approximately 40 minutes at 10 m/s flight speed [17]. Such dual-mode mobility allows operations where flooded terrain or collapsed infrastructure would otherwise limit accessibility.

Maritime UAV applications further highlight the importance of payload capacity relative to the overall takeoff weight. A useful index is the payload ratio:

$$\eta_p = \frac{m_{payload}}{m_{MTOW}} \tag{3}$$

where $m_{payload}$ is the payload mass and m_{MTOW} is the maximum takeoff weight. For instance, a small UAV with MTOW of 6.3 kg and payload capacity of 0.6 kg yields $\eta_p \approx 9.5\%$. Such ratios enable fair comparisons between platforms of different sizes by emphasizing the efficiency of payload integration.To further illustrate payload efficiency across different UAV types, Table 4 compares representative platforms used in disaster-relief scenarios, highlighting their maximum takeoff weight (MTOW), endurance, payload capacity, and calculated payload ratio η_p.

Table 4. Representative UAV platforms and payload ratios

Platform	Type	MTOW (kg)	Endurance (min)	Payload (kg)	Payload Ratio η_p
DJI Mavic 3T	Portable Multirotor	1.05	45	0.2	0.19
DJI Matrice 300 RTK	Industry Multirotor	6.3	55	0.6	0.1
senseFly eBee X	Fixed-wing	1.6	90	0.3	0.19
WingtraOne	VTOL Fixed-wing	4.5	60	0.8	0.18

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Cooperative systems that combine UAVs with unmanned surface vehicles (USVs) extend the coverage and communication range of maritime operations. In these arrangements, UAVs provide aerial reconnaissance and thermal imaging, while USVs serve as relays or carriers for supplies, addressing the endurance limits of UAVs operating independently [18]. These examples show that amphibious and marine UAVs significantly enhance disaster-relief capabilities, but they also demand durable waterproofing and corrosion resistance, which pose challenges for 3D-printed parts. Surface finishing, sealing, and careful material selection are therefore essential when considering additive manufacturing in such applications.

4.3 Insights from Broader UAV-Based Search-and-Rescue Deployments

Beyond specialized folding or amphibious designs, broader deployments of UAVs in disaster relief highlight their adaptability and the value of flexible mission planning. For example, UAVs have been widely applied for post-hurricane damage assessment, where they deliver real-time situational awareness but face constraints related to weather resilience and airspace regulations [19]. In maritime contexts, UAVs have proved indispensable for providing thermal sensing, high-resolution imaging, and navigation data, even when physical rescue is carried out by manned teams [20].

A critical performance measure in these applications is coverage efficiency, expressed as the effective area surveyed per flight:

$$A = v \cdot T \cdot w \cdot (1-o) \tag{4}$$

where v is the flight speed, T is the endurance, w is the swath width of the sensor, and o is the overlap ratio required for data processing. Fixed-wing UAVs, such as the senseFly eBee X or WingtraOne, excel in this metric because their longer endurance and larger swath widths allow them to map extensive areas in a single sortie. This advantage underscores why fixed-wing and VTOL platforms are often chosen for wide-area reconnaissance in disaster scenarios.

While these platforms demonstrate promising results, increasing system complexity introduces challenges of weight, cost, and maintenance. Moreover, the long-term durability of lightweight or 3D-printed parts in harsh conditions—exposed to humidity, salt spray, and ultraviolet radiation—remains insufficiently validated. These gaps point to future opportunities for research into material optimization and hybrid manufacturing approaches.To provide a consolidated view, Fig. 6 summarizes the main UAV categories considered in disaster-relief contexts and highlights their most suitable operational tasks.

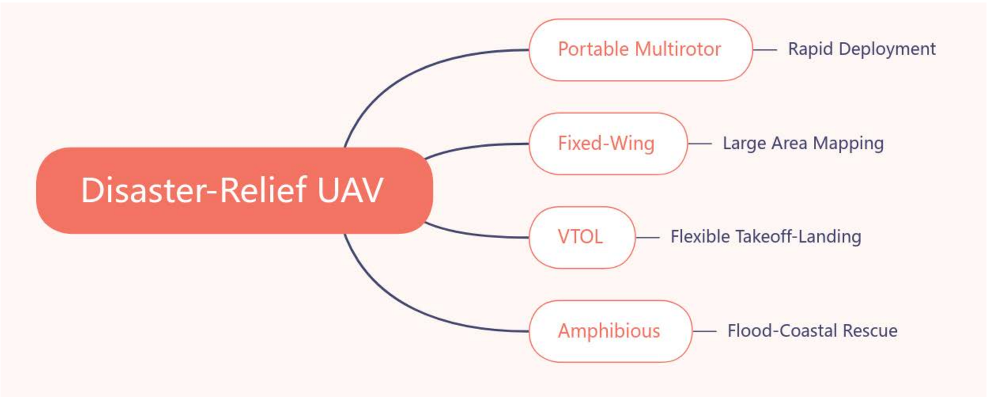

Fig. 6 UAV Types and Corresponding Disaster-Relief Tasks

5. Rapid Prototyping Validation and Optimization Analysis

5.1 Preliminary Structural Tests and Finite Element Analysis

The integration of 3D printing into UAV manufacturing has been widely evaluated through material testing and numerical simulation. Although many disaster-relief UAV prototypes remain at the conceptual stage, existing studies provide insights into how printed components perform under structural loads. For instance, tensile testing of FDM-printed PLA and ABS samples has shown strengths in the range of 40–60 MPa, but with significant anisotropy caused by weak interlayer bonding [9]. In comparison, SLS-printed nylon (PA12) exhibits higher tensile strength (up to 70 MPa) and superior impact resistance, making it more suitable for load-bearing elements such as landing gear or fuselage frames [11].

Finite element analysis (FEA) has also been employed to evaluate UAV components manufactured by additive processes. Wu et al. demonstrated that lattice-reinforced wing structures printed with nylon composites could achieve a weight reduction of 25% while maintaining equivalent stiffness [21]. Other studies have focused on stress distribution in 3D-printed joints and connectors, showing that failure typically initiates along the layer boundaries [12]. These findings underline the necessity of considering both material selection and print orientation in UAV structural design.To illustrate this phenomenon, Fig. 7 provides a schematic stress distribution near the hinge region of a folding-wing UAV, highlighting the concentration of loads around the joint area.

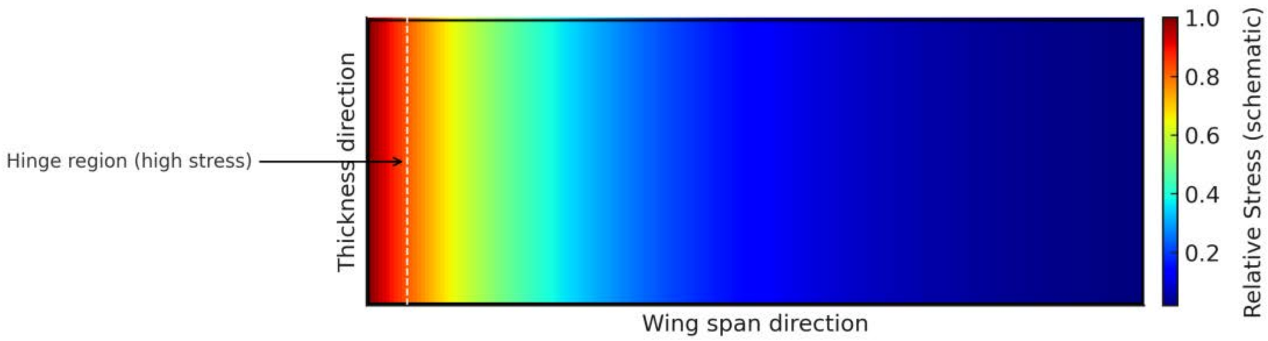

Fig. 7 Conceptual Stress Distribution in a Folding-Wing UAV

Although most experiments are conducted under controlled laboratory conditions, they provide meaningful references for disaster-relief UAV applications. They suggest that while low-cost FDM is suitable for rapid prototyping of non-critical parts, mission-critical components require either SLS printing or reinforcement strategies. The challenge remains to validate these findings in real disaster environments, where temperature, humidity, and mechanical shocks may differ significantly from laboratory conditions. To provide an overview of the validation process, Fig. 8 presents a schematic workflow for rapid prototyping, combining additive manufacturing with experimental testing and simulation prior to optimization and deployment.

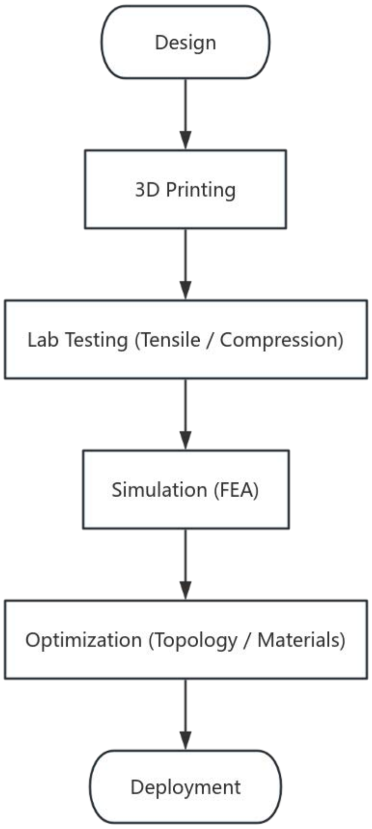

Fig. 8 Rapid Prototyping Validation Flow for UAV Components

5.2 Material and Structural Optimization Approaches

To summarize the main strategies for improving the per-

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formance of 3D-printed UAV components, Fig. 9 outlines three categories of structural optimization—lightweight design, composite reinforcement, and functional integration—each with representative methods.

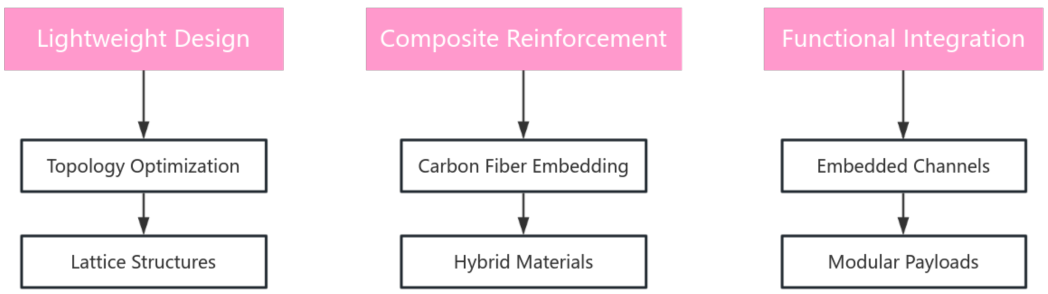

Fig. 9 Structural Optimization Methods for 3D-Printed UAVs

Optimization strategies for UAVs manufactured through additive processes can be broadly categorized into lightweight design, composite reinforcement, and functional integration. Lightweight optimization is often achieved through topology optimization and lattice structures, which allow material to be distributed only where necessary. Research indicates that lattice-infilled airframes can reduce mass by 20–30% while preserving stiffness and natural frequency characteristics [21]. This design directly improves the endurance and portability of the disaster relief environment.

The composite reinforcement is also a promising approach. Embedding carbon-fiber rods into the FDM printer, or using nylon powder reinforced with fiber in SLS printing, can significantly improve fatigue resistance and impact tolerance [10]. These hybrid strategies allow UAVs to withstand bad running conditions, such as strong winds or bumpy landing in the disaster area.

Function integration represents another optimization direction. In addition to the processing of UAV structures and systems, 3D printing can also insert sensor shells, wiring channels and modular payload directly into the fuselage [22]. This reduces the complexity of assembly and allows novices to quickly reconfigure UAVs for different tasks, such as switching between thermal imaging and supply delivery.

Despite these advantages, the challenge remains. There is no sufficient research on the durability of the material in ultraviolet radiation, moisture absorption and heat cycle. Additionally, the cost and time of producing large structural parts with high-resolution printing remain obstacles to scalability. Solving these restrictions requires further cooperation between materials and UAV engineering technology. However, the review optimization method shows that addition manufacturing provides a reliable way to build a UAV, which is lighter, stronger and more suitable for disaster relief tasks.

6. Conclusion

6.1 Research Summary

This thesis studies the feasibility of applying additive manufacturing in the development of UAVs. Through the review of existing technologies, it is indicated that 3D printing provides an advantage in rapid forming, light structure and modular adaptability. These features are often valuable in time-tense relief missions, and portability and customization are essential.

Case studies have shown that amphibious UAVs have expanded their operations to floods and coastal environments, and the UAV–USV system has strengthened maritime rescue. The analysis of material testing and finite element simulation shows that although low cost FDM printing is applicable to non-critical components, but high performance methods, such as SLS or enhanced composite materials, are more suitable for structural components. Throughout the optimization strategies such as lightweight design, composite reinforcement and functional integration, visible addition manufacturing can directly support the design of a particular task.

In summary, this research highlighted the potential role of 3D printing as an enabling technology for disaster-relief UAVs, providing both technical feasibility and practical adaptability.

6.2 Limitations and Future Directions

Although the findings are encouraging, several limitations remain. The present study relied primarily on literature review and conceptual analysis, without experimental verification of UAV prototypes. As a result, endurance calculations, payload ratios, and structural performance indicators were derived from simplified models and reported specifications rather than real-world data. Additionally, issues such as environmental durability of printed parts, large-scale production efficiency, and compliance with aviation regulations were beyond the scope of this thesis. Future work should focus on bridging these gaps. First, controlled experiments under realistic conditions—such as high humidity, strong winds, and thermal cycling—are required to validate the structural reliability of 3D-printed UAV components. Second, hybrid manufacturing approaches that integrate additive manufacturing with traditional composites could address trade-offs between weight and strength. Third, research should expand to system-level integration, where UAVs operate collaboratively with ground and surface vehicles to create multi-domain disaster-response networks. Finally, further exploration of design automation, including AI-assisted topology optimization, may accelerate the customization of UAVs for specific missions.To provide a clearer overview of potential research paths, Fig. 10 presents a schematic mind map highlighting three main directions: experimental validation, materials and hybrid manufacturing, and system-level integration.

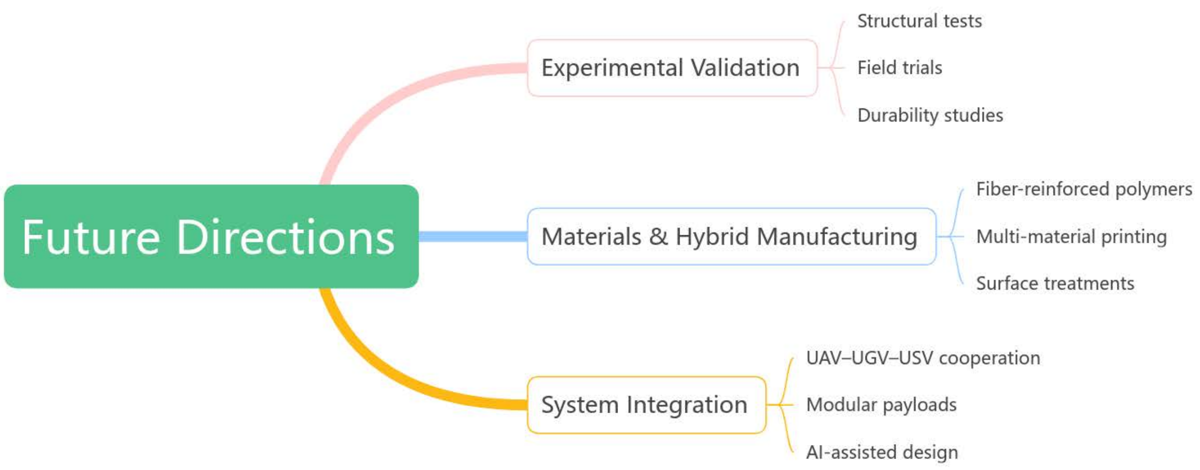

Fig. 10 Future Directions for Disaster-Relief UAVs

In conclusion, while current limitations highlight the need for further investigation, the results of this thesis confirm that additive manufacturing holds strong potential for advancing UAV design in disaster relief. Continued efforts in material testing, optimization, and system integration will be essential to realize this potential in practice.

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