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Polymers and Composites in the Design and Construction of Unmanned Aerial Vehicles: A Comprehensive Technical Review

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Abstract

The emergence of Unmanned Aerial Vehicles (UAVs) over the last few years has mostly been made possible by breakthroughs in material science. This review is concerned with an overview of some of the polymers and composites that are being commonly used in drone manufacturing in recent times, especially in relation to the influence of material choice on drone performance and capability. It sheds light on the drastic change in the material composition of UAVs, where there has been an observable shift from aluminum to FRP (Fiber-Reinforced Polymers), specifically CFRP (Carbon Fiber Reinforced Polymer) and GFRP (Glass Fiber Reinforced Polymers). These materials exhibit much better mechanical and fatigue properties than conventional metals such as aluminum. Properties like specific strength and specific modulus, among others, were investigated by the authors due to their relevance to structural endurance and handling. Beyond these performance attributes, the review highlights the importance of factors involving thermal management, electromagnetic interference, and environmental integrity as material selection factors. The review also covers different classes of UAVs, design considerations, and few major material fabrication methods used, namely: Wet lay-up, prepreg/autoclave, resin transfer molding, injection molding, and additive manufacturing. A decision model based on tradeoff between enhanced performance characteristics from high performance composite materials versus relatively low price for traditional engineering polymers is also offered. The article also includes future outlooks for new materials, like multi-functional nano composites, graphene filled polymers, self-healing matrix materials, and biopolymers.

Keyword: Unmanned aerial vehicles, nano composites, biopolymers, CFRP, electromagnetic interference

INTRODUCTION

We are witnessing massive transformation within aerospace [1]. Unmanned Aerial Vehicles (UAVs) are transitioning from prototypes to being utilized in practically every market. This can be observed throughout military, commercial and consumer applications [1]. The new types of materials along with how they are integrated have played an important part in this growth alongside enhanced avionics, battery systems, and autopilot systems. With increasing variety of materials, designs followed and there can be observed a shift from heavy metal frames to either plastic or composite frame components which can significantly increase the flight time, carry diverse payload and can be constructed to a range of missions [2]. Initially UAV designs utilized aluminum alloys for structural elements of nearly every UAV [2].

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The 6061 and 7075 grades were utilized almost exclusively as safe and reliable choices. This was because engineers had established knowledge and understanding of the properties of the material and the strength-to-weight characteristics compared to steel were vastly superior and were relatively easy to work with [2]. To be able to achieve a required payload capacity or flight range it became imperative to find other alternatives.

It was when fiber-reinforced polymer (FRP) composite material became viable for widespread use that the breakthrough occurred [3]. Composites provide much superior strength and stiffness to weight, so designers were able to substantially reduce the mass of the structure. Comparing designs using metal versus composites can result in significant weight reduction of 15 to 45 percent which translates into extended flight times or increase payload capability [3]. Materials like aluminum and titanium are still utilized for heavy duty components in UAVs, like the landing gear or motor mounts [4].

The availability of materials with enhanced specific properties enabled designs for wide variety of drones ranging from nano-quadcopters of under 200 grams up to 600+ kilogram takeoff weight cargo UAVs [5]. The choice of materials used are one of the most critical initial design decisions as they directly impact the cost and performance. In addition, the unique molding properties of composites and three-dimensional printing capabilities of polymer materials have facilitated and accelerated a burst of novel drone design forms, including the use of box-wing and Prandtl-wing configurations [6, 7].

LITERATURE REVIEW

Design Considerations of UAV Materials

There are numerous practical requirements when selecting materials for UAV: they have to be sufficiently strong, light, and temperature tolerant and, in some cases, not to block electromagnetic signals. Usually, in practice, design decisions is to meet those requirements with constraints of mission, size, budget.

Specific Strength and Specific Modulus

We always use "specific" properties, i.e., a property normalized by mass, in aerospace research. Among the specific properties, Specific Strength and Specific Modulus are two of the most important [8]:

Specific Strength (/): the ratio of the material strength to its density. Higher Specific Strength normally implies the structure weight can be reduced for same load capacity, which improve flight time and range, and allow higher payload [8].

Specific Modulus (E/): the ratio of Young's Modulus to density. Stiffness (E/) is also a critical parameter, as it governs the tendency of a structure component to deform under a load or vibrate during flight. It ensures structural integrity under loads, aerodynamic accuracy and sensor accuracy during flight [8].

Compare to steel or aluminum, CFRP show much higher specific strength and modulus. This is one of the primary reasons of their wide applications in high performance airframes [8].

Comparative studies indicate that carbon fiber composite's tensile strength typically ranges from 3000 to 6000MPa which is far higher than titanium alloys (600-900 MPa), aluminum alloys (200-400MPa) and most steels suitable for UAV design [9].

Durability, Fatigue, Vibration Resistance and Environmental Resistance

The material needs to be able to survive its service life as well as withstanding impacts, repetitive loading and environments where the drone will operate [10].

Durability and impact resistance: There is a trade-off between stiffness and toughness; CFRP is very stiff but prone to failure from impact whereas engineering plastics such as polycarbonate (PC), ABS and nylon are more tough and suitable where impacts are possible [9].

Environmental stability: UAVs are often subject to salt atmosphere, wet environment, strong UV radiation. Polymers and composites have better corrosion resistance compared with metals; specific composites may also offer excellent resistance to UV radiation, moisture, and thermal cycles [10].

Fatigue resistance: UAVs are subject to dynamic loading due to motors and air pressure. Fiber composite, especially CFRP, can have better resistance to repeated loading compared with other metals [10].

Vibration resistance: In the context of an increasing use of health monitoring and visual based inspections from UAV platform, structural stability of air frame is very important in order to increase reliability of measurement data. Similarly with visual vibration SHM by stationary camera, the UAV camera should be stable and UAV body should not move with drift when observing the tests. Otherwise, data would be incorrect [11].

Experimental testing of an 8-arm CFRP drone airframe has shown that progressive stiffness reduction and localized buckling can occur under increasing static loads, with assembly-sensitive joint behavior influencing residual deformation highlighting the importance of detailed fatigue and dynamic testing beyond basic material property evaluation [12].

- *Thermal conductivity and stability:* Motors and electronics can generate a lot of heat. Materials like aluminum and magnesium, which can conduct heat away from hot sources, are suitable for motor mounts and heat sinks, whereas near thermal sources, materials which have a higher thermal stability should be used, (e.g. CFRP with high-temperature resins) [13, 14].
- *EMI and signal effects:* For radios and GPS the electrical properties of a material are important. Polymer matrices are insulators, however the carbon fiber itself is conductive. The conductive nature is useful for EMI shielding, but it may also cause interference issues if not properly addressed in the design. Insulators like glass-fiber composites (GFRP) are therefore generally favored for radomes and sensor enclosures [15].

Some recent work using carbon-fiber based composites has shown that hybrid filler systems with tailored architectures and layer stacking are capable of substantially improving EMI shielding performance whilst maintaining structural capability [16]. While these efforts have produced a situation where structural components of the UAV are potentially able to perform both a structural load-bearing function, and an electromagnetic shielding one, design carefulness is required in terms of the anisotropic electrical conductivity and the added weight of the composite structure.

- *Advanced fiber reinforced polymer (FRP) composites:* The combination of strong fibers with light matrix material provides FRP composites. For high performance UAVs this type of material composite system is ideal. The benefit of using a composite material in aeronautical design has shown great advantage in terms of saving mass-commonly in the 20–50% range [17].
- *Carbon fiber reinforced polymer (CFRP):* When a performance over weight balance is needed, CFRP is selected. CFRP is typically found in professional, military and long-endurance UAVs. They are composed of carbon filaments in a matrix system, which is generally an epoxy or high performance thermoplastics like PEEK9. CFRP provides a very high specific strength, specific stiffness and a long fatigue life along with low thermal expansion characteristics. However CFRP does exhibit lower toughness and a relatively high cost. Using thermoplastic matrices have gained popularity as they often show better impact toughness and have increased production rate with an element of recyclability [18]. A superior balance has reportedly been demonstrated in CF reinforced polymer composite when compared to

- *Aramid and hybrid composites:* Aramid fibers (like Kevlar®) bring excellent toughness and energy absorption, so they are useful in military settings or where impact protection is needed. Hybrid laminates for example, outer aramid layers for toughness combined with CFRP cores for stiffness let designers tune strength, stiffness, and damage resistance in one part [21].

Engineering Polymers in Drone Components

For mass-market parts, engineering thermoplastics are common because they are tough, easy to make, and relatively cheap.

High-impact and structural thermoplastics

- *Polycarbonate (PC) and PC/ABS blends:* PC is tough, resists UV, and is optically clear, so it is good for camera covers and protective domes.
- *ABS:* A good all-around material for molded shells because it balances stiffness, toughness, and ease of processing. Nylon (PA): Known for toughness and fatigue resistance; used for landing gear, guards, and flexible parts.

Thermoplastic composites such as PEEK, PEI, and PPS are gaining increased attention in aerospace structures due to their superior impact resistance, weldability, and shorter processing cycles compared to conventional thermoset systems. Recent technical assessments highlight their potential for automated manufacturing and improved recyclability, positioning thermoplastics as strong candidates for medium-volume UAV production and lifecycle cost reduction.

- *Additive manufacturing (3D printing) polymers:* 3D printing is enabling design iteration and small-batch parts to be fabricated quickly. One of the most interesting research projects in this area is the world's first 3D-printed jet powered UAV (Aurora Flight Science, Stratasys [22]).
- *PLA:* Generally easy to print but Brittle and weak at high temperatures, making them unsuitable for load bearing components.
- *PETG:* Is much stronger than PLA and suitable for parts for smaller light weight drones.
- *Fiber reinforced polymers:* Can print with chopped Carbon Fiber or Glass Fiber filaments that increases tensile strength sufficiently to allow printing frames and motor mounts [23]. Studies show tensile strength and Young's Modulus of a short carbon-fiber reinforced PLA, made using FDM, are strongly dependent on nozzle temperature and raster orientation, showing higher values at 230 C and for raster angles aligned to the loading direction. The addition of post-print annealing greatly improves crystallinity and stiffness [24]. The tensile strength of PLA was increased by up to 18.2% at 1 wt% loading of nano-cellulose, although, higher filler percentages may result in reduced tensile strength [25].

Manufacturing and Fabrication Technologies

A part's properties and cost can be influenced by how it is made as much as by the material selection.

- *Composite fabrication:* Wet lay-up is the most straight forward technique used for prototyping but it is difficult to gain control over fiber alignment. High performance parts require curing using prepregs and autoclaves, or use automated RTM methods for high volume production.
- *High-volume polymer processing:* Injection moulding is cost effective for mass produced plastic parts such as propellers and drone body shells.
- *Digital & custom manufacture:* CNC machining is suitable for precise metal or composite parts, such as motor mounts. 3D printing is efficient for rapid prototyping and low-volume bespoke parts.

The Future: Nanocomposites and Graphene Reinforced Polymers

Incorporating carbon nanotubes or graphene can improve mechanical strength, electrical conductivity and thermal performance enabling multifunctional part applications, where components act as both structural elements and conductors or have embedded sensors or use their increased thermal conductivity for heat management or de-icing [26]. Research reviews confirm graphene polymer nanocomposites significantly enhance mechanical properties (strength, fracture toughness), thermal conductivity and EMI shielding effectiveness, provided dispersion and interface bonding are optimized [27]. Functionalisized graphene nanoplatelets can be dispersed within polymer matrices (thermoset or thermoplastic) increasing multifunctionality without significantly adding weight [28]. The benefits of using such hybrid filler composites, due to the exceptional properties of graphene, are accessible with both conventional and novel manufacturing processes, with notable improvements reported in strength, thermal stability and conductivity [28]. Increasing the toughness and durability of UAV composite structures, beyond weight-saving, becomes increasingly important to prolong service life and minimize maintenance. The term "self-healing polymer matrix composites" denotes materials that, upon the application of an external stimulus such as a crack, can autonomously repair themselves and recover their properties and integrity, similar to processes in biological systems [29].

Bio-based & Biodegradable Polymers: Increasing awareness of the environmental impact of UAVs means there is great interest in the use of natural fiber composites (e.g. Hemp, flax) and bio-degradable polymers (PLA or PCL1). This could be a viable alternative to the use of conventional plastics for components in missions where it is undesirable for components to persist in the environment after completion [30]. Comprehensive reviews have identified the growing suitability of biodegradable & bio-based polymers (PLA and PHAs), for low- to moderate-load applications where short-life or single-use scenarios could be addressed [31]. Improvements in the fabrication of biopolymers using 3D printing technology are making these materials more suitable for a range of UAV applications, however, thermal performance, durability and UV resistance remain challenges [31]. Biodegradable polymer candidates from plant sources (corn, soya bean or algae) have gained prominence as attractive lightweight materials for Aerospace, leading to lighter and environmentally benign UAVs with the potential to print complex shapes [32]. The weight-savings achieved using these polymers could benefit components from housings for electronics to interior panels and could further extend to the airframes of UAVs, but without significantly compromising on performance [33].

METHODOLOGY

This paper employs a comparison methodology in order to determine the most suitable polymers and composites for building UAVs. Initially, a review of material properties, common manufacturing processes and a few real world examples were examined. The results of this analysis enabled the authors to derive a basic decision-making framework, which captures the trade-offs between key considerations. In order to validate the decision-making framework the authors analyzed a few examples of high-profile commercial and military systems, which show the material choices made and relate them to mission demands.

Case Studies of Commercial and Military Drones

- *Consumer drones (DJI, Parrot, Skydio):* Typically rely on material mixes to provide a balance of performance and price. In these platforms, Mg alloys may be used for structural components and heat sinks, which are often covered by an injection-molded PC/ABS shell. Propellers are frequently molded from a polyamide reinforced with carbon fibers. In some unusual cases, material blends have been developed. An example is the Parrot Anafi, utilizing carbon fiber composites filled with hollow glass microbeads for reduced weight.
- *Military platforms (MQ-9 Reaper, RQ-4 Global Hawk):* Since these platforms require a focus on high performance and mission endurance, high-performance composites are used extensively. MALE and HALE aircraft generally rely on autoclave-cured CFRP construction for wings and major structures, achieving high strength while minimizing weight. While the Global Hawk uses an aluminum semi-monocoque fuselage structure, wings are constructed of very large CFRP elements to allow high-altitude performance. Smaller tactical UAVs (e.g., the RQ-11 Raven) generally utilize mixtures of GFRP and aluminum, which ensures robustness and ease of field repair.

Table 1. Weighted material selection scoring matrix for UAV airframe design.

Selection criterion	Weighting factor (Example: military HALE)	CFRP score (1–5)	GFRP score (1–5)	Engineering polymer (PC/Nylon) score (1–5)
Performance-to-Weight Ratio	0.4	5	3	1
Impact Resistance/Toughness	0.1	2	4	5
Manufacturing Cost (per part at scale)	0.1	1	3	5
Manufacturing Complexity/Cycle Time	0.1	2	3	5
Production Scalability	0.05	2	3	5
Repairability/Serviceability	0.1	2	3	4
Environmental Resistance	0.15	5	4	3
Weighted Score (HALE Example)	-	3.25	3.35	2.95
Weighting Factor (Example: Toy Drone)	-	-	-	-
Performance-to-Weight Ratio	0.05	5	3	1
Impact Resistance/Toughness	0.3	2	4	5
Manufacturing Cost (per part at scale)	0.4	1	3	5
Manufacturing Complexity/Cycle Time	0.05	2	3	5
Production Scalability	0.1	2	3	5
Repairability/Serviceability	0.05	2	3	4
Environmental Resistance	0.05	5	4	3
Weighted Score (Toy Drone Example)	-	1.95	3.35	4.35

Decision Framework for Material Selection

The selection of materials predominantly hinges on the effective management of trade-offs. To represent this, the authors constructed a scoring matrix where different mission-critical parameters (mechanical performance, weight, cost, manufacturability, repairability, etc.) are weighted according to mission demands (as demonstrated in Table 1).

Each material is scored from 1 (poor) to 5 (best), and the weighted sum offers a rough ranking of the material choice. This will facilitate comparisons with dramatically different priorities - the strength, stiffness and flight duration of a HALE drone would likely score higher in a weighted sum than the cost and manufacturability for an toy drone.

The most obvious trade-off that shows up repeatedly is performance for cost. CFRPs offer high strength-to-weight and stiffness-to-weight but are expensive to acquire and manufacture. The engineering polymers offer lower cost and are highly manufacturable at large scales using injection molding but do not possess the mechanical properties of composites. Ease of repair also presents an interesting challenge; it is typically expensive and difficult to repair thermoset CFRP structures, whereas many thermoplastic parts can be easily replaced. New thermoplastic composites show potential to increase repairability (e.g., via fusion bonding) while maintaining a degree of the high performance characteristics of the matrix.

RESULTS

Here are three key points regarding how UAVs are made:

First, there's a significant divide in material performance. Fiber-reinforced composites-especially CFRP-generally provide the best strength/weight and stiffness/weight ratios, making them the primary choice for long-duration, heavy-payload UAVs. Engineering polymers-ABS, PC, Nylon, etc.-offer superior impact toughness, but fall short of composites in terms of stiffness and strength per unit mass. This distinction reflects the split we see in the marketplace: high-end military and industrial UAVs like the MQ-9 Reaper and RQ-4 Global Hawk are mostly CFRP-based; many consumer drones like the DJI Mavic series and Parrot Anafi utilize molded polymers for shells and metals for their critical components to find a balance of cost and durability.

Second, manufacturing considerations greatly influence the viability of certain materials. High-performance thermoset composites require long, labor-intensive process steps such as autoclave curing-a model that is well-suited for low-volume, high-cost military aircraft, but poorly suited for consumer products. Engineering polymers can effectively be utilized within the rapid, low-cost processes like injection molding-thus leading to their prevalence in mass-market UAVs. Additive manufacturing (including fiber-filled filaments) also plays a significant role by providing a method for prototyping quickly and for low-volume production runs, serving as an intermediary step between hobbyist and commercial ventures.

Third, our decision framework, the weighted scoring matrix, validates these trends quantitatively. The matrix indicates that when the highest weight is assigned to performance/weight (like for a high-altitude long endurance military drone), composites emerge as the winner. When cost and impact resistance become the most important considerations (like for a toy drone), engineering plastics receive the highest scores. It is important to recognize that there isn't one "best" material-each is chosen based on the intended application, production scale, and cost constraints.

CONCLUSION

The construction of Unmanned Aerial Vehicles is inherently dependent upon the performance of the materials from which they are constructed. This review has tracked the historical development of the materials used-from traditional metals, to the current paradigm where polymers and composites dominate. This has been directly responsible for the rapid advancement of drone technology in all areas: performance, variety, and applications. Several important trends emerge from this study, and they will undoubtedly continue to mold the industry for years to come. Three primary conclusions can be drawn:

First, the highest priority given to specific strength and specific modulus definitively designates fiber-reinforced composites, particularly CFRP, as the preferred materials for high-performance UAVs. The ability to create exceptionally lightweight yet incredibly stiff structures directly influences extended flight times, the capacity for greater payloads, and stability for precise flight control.

Second, a clear trade-off between maximum performance delivered by advanced composites and the scalable economic benefits provided by engineering polymers characterizes the primary segmentation of the drone market. High-end military, industrial, and professional drones can justify the elevated costs and sophisticated manufacturing requirements of CFRP to achieve mission-critical levels of performance, whereas the consumer and prosumer segments of the market benefit from the low cost per unit and mass producibility that characterize injection-molded thermoplastics.

Third, a strong dependency exists between manufacturing methods and material choice, both of which contribute to the overall capability of the UAV. Composites typically rely on high-value process steps like autoclave curing in order to fully realize their potential performance. The advantages of polymers are largely centered around cost-since injection molding can produce them economically and in high volumes. Consequently, an optimally designed UAV is likely to be a hybrid construct; individual components should be manufactured using a method tailored to the particular material and required function.

UAV materials science will see the development of components that are ever more integrated, functionally robust, and sustainable. The addition of novel materials like graphene into structural parts that can simultaneously act as sensors or heat shields will reduce the number of components, hence decreasing weight and enhancing reliability. The development of thermoplastic composites will continue to supplant thermosets due to their increased toughness, easier recycling and quicker manufacturing speeds. There is also growing interest in biodegradable drones to perform single-use missions in environments where environmental impact is of utmost concern.

Further integration of multifunctional attributes into advanced composites such as embedded sensing capabilities, superior thermal management, and the ability to self-heal, signifies an important research area in the field of aerospace materials. The creation of novel nanofiller architectures and integrated structural sensor laminates hold the promise of fewer required components, improved structural health monitoring (SHM), and increased overall reliability for state-of-the-art UAV systems.

Ultimately, the next significant advancement in the functionality of Unmanned Aerial Vehicles will be driven not solely by improvements in software or avionics, but rather by a new era of lighter, stronger, more intelligent, and sustainable materials than those currently available, perpetuating the symbiotic evolution between materials science and unmanned flight.

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