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4D Printing Technology and Its Application Possibilities in Unmanned Aerial Vehicles (UAVs)

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Abstract

4D printing technology is an innovative manufacturing method that adds the dimension of time to traditional 3D printing, enabling materials to respond to environmental stimuli (such as temperature, humidity, light, etc.) by changing shape, properties, or functionality. This study examines the fundamental principles of 4D printing in detail and explores its advantages and potential applications in the context of Unmanned Aerial Vehicles (UAVs). The foundation of 4D printing lies in the use of smart materials such as shape-memory polymers, self-healing composites, and hydrogels. These materials allow UAV components to dynamically adapt to flight conditions through pre-programmed responses. The study also comparatively discusses 4D printing techniques (FDM, SLA, DIW, SLM) and their suitability for UAV manufacturing. Additionally, current challenges such as material limitations, the complexity of multi-material printing, and high costs are addressed, and future research directions are highlighted. In conclusion, 4D printing technology holds revolutionary potential for improving UAV performance and durability. However, to fully realize this potential, advancements in material science, printing technologies, and design methods must continue.

Keywords: 4D printing, UAVs, smart materials, additive manufacturing.

4D Baskı Teknolojisi ve İnsansız Hava Araçlarındaki (İHA) Uygulama Olanakları

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Özet

4B baskı teknolojisi, geleneksel 3B baskıya zaman boyutunu ekleyerek malzemelerin çevresel uyaranlara (sıcaklık, nem, ışık vb.) tepki vererek şekil, özellik veya işlev değiştirmesine olanak tanıyan yenilikçi bir üretim yöntemidir. Bu çalışma, 4B baskının temel ilkelerini detaylı bir şekilde inceleyerek, İnsansız Hava Araçları (İHA'lar) bağlamında sunduğu avantajları ve uygulama potansiyellerini araştırmaktadır. 4B baskının temelini, şekil hafızalı polimerler, kendini onaran kompozitler ve hidrojeller gibi akıllı malzemelerin kullanımı oluşturur. Bu malzemeler, önceden programlanmış tepkiler sayesinde İHA bileşenlerinin uçuş koşullarına dinamik olarak uyum sağlamasını mümkün kılar. Çalışmada, 4B baskı teknikleri (FDM, SLA, DIW, SLM) ve bu tekniklerin İHA üretimindeki uygunlukları karşılaştırmalı olarak ele alınmıştır. Bunun yanı sıra, malzeme sınırlamaları, çoklu malzeme baskısının karmaşıklığı ve yüksek maliyet gibi mevcut zorluklar tartışılarak, gelecekteki araştırma yönleri vurgulanmıştır. Sonuç olarak, 4B baskı teknolojisi, İHA'ların performansını ve dayanıklılığını artırmada devrim niteliğinde bir potansiyele sahiptir. Ancak bu potansiyelin tam olarak gerçekleştirilebilmesi için malzeme bilimi, baskı teknolojileri ve tasarım yöntemlerindeki gelişmelerin sürdürülmesi gerekmektedir.

Anahtar Kelimeler: 4D baskı, İHA'lar, akıllı malzemeler, katmanlı üretim.

1. Fundamental Principles of 4D Printing

4D printing represents an innovative evolution in additive manufacturing by incorporating the dimension of time into the fabrication process, allowing printed objects to change their shape, properties, or functionality in response to external stimuli. This technology builds upon the principles of 3D printing by incorporating smart materials, such as shape-memory polymers, hydrogels, or responsive composites, which are programmed to react to environmental triggers like temperature, light, or humidity (Ryan et al., 2021). The fundamental principle of 4D printing lies in the precise design and programming of these materials to achieve predictable, controlled transformations over time, distinguishing it from static 3D-printed objects (Mitchell et al., 2018). This dynamic capability opens new possibilities for applications requiring adaptability, such as self-assembling structures, biomedical devices, and aerospace components. In this section, we provide a detailed overview of 4D printing, its core principles, and its significance in advancing manufacturing technologies.

Technological advancements in additive manufacturing have led to significant innovations in various fields, including aerospace, medicine, and robotics. Among these advancements, 4D printing technology has emerged as a revolutionary production method that builds upon the foundation of 3D printing by incorporating the time dimension. Unlike conventional 3D-printed objects, which remain static after fabrication, 4D-printed objects have the ability to change their shape, properties, or functionality in response to external stimuli such as temperature, light, magnetic fields, humidity, pH levels, or electrical signals (Bodaghi, Mahdi et al., 2024; Khan et al., 2022; Raina et al., 2021). This transformation is enabled by integrating smart materials with 3D printing techniques, allowing the production of adaptive and reconfigurable structures (Bai & Bu, 2022; Mallakpour et al., 2021; Momeni et al., 2017; Shinde et al., 2023). For instance, a study by Bodaghi et al. demonstrated the use of shape memory polymers in 4D printing to create self-folding structures that activate under thermal stimuli, showcasing the technology's potential for programmable transformations (Bodaghi et al., 2016).

The concept of 4D printing was first introduced by Skylar Tibbits in a TED talk in 2013, where he emphasized its potential to revolutionize manufacturing by enabling dynamic structures that evolve over time (Patil & Sarje, 2021). Since then, this technology has attracted widespread attention from academic researchers and industrial sectors. The primary motivation behind 4D printing is to overcome the limitations of 3D printing in producing static, rigid objects. By utilizing smart materials that respond to environmental stimuli, 4D printing enables objects to undergo programmed transformations, thus simplifying design, production, and assembly processes (Subeshan et al., 2021; Wang et al., 2023). A notable example is the work of Gladman et al., who developed hydrogel-based 4D-printed structures mimicking plant-inspired architectures that bend and twist in response to humidity changes, highlighting the precision of stimulus-responsive designs (Gladman et al., 2017).

UAV design faces persistent engineering constraints, including rigid structural configurations that hinder aerodynamic adaptability, weight limitations that affect flight efficiency and payload capacity, and vulnerability to damage in complex environments. Traditional materials and design strategies often require complex mechanical systems to achieve reconfigurability, which add to the overall weight and energy consumption. Additionally, operational environments such as high turbulence, extreme temperatures, or physical impacts necessitate materials that can dynamically respond or self-recover to maintain performance. These challenges highlight the need for smart materials capable of adaptive behaviour, which can be realized through 4D printing technologies.

UAVs, commonly known as drones, have witnessed remarkable advancements in recent years. These autonomous systems are widely used in military, commercial, and research applications, ranging from surveillance and reconnaissance to disaster response and cargo delivery. However, UAVs face several challenges, such as structural adaptability, weight optimization, and durability in dynamic environments. Conventional UAV structures rely on fixed materials that limit their ability to adapt to changing conditions, thereby restricting their efficiency and operational lifespan (Leist & Zhou, 2016; Li, S., 2023).

The integration of 4D printing technology into UAV design and manufacturing presents a promising solution to these challenges. By leveraging smart materials capable of self-adjustment, UAV components can be designed to morph, self-heal, and enhance aerodynamic performance based on environmental factors. For example, wings fabricated using 4D printing could adjust their shape in response to airflow changes, optimizing lift and manoeuvrability without the need for additional mechanical components

(Antezana et al., 2023; Sahafnejad-Mohammadi et al., 2022). Similarly, 4D-printed self-healing materials could enhance UAV durability by repairing minor damages autonomously, thus reducing maintenance costs and extending operational longevity (Saritha & Boyina, 2021).

Various additive manufacturing techniques, such as Fused Deposition Modelling (FDM), Stereolithography (SLA), Direct Ink Writing (DIW), and Selective Laser Melting (SLM), have been explored for 4D printing applications (Ryan et al., 2021). Each of these methods offers distinct advantages depending on the material properties and functional requirements of UAV components. Furthermore, advancements in computational design tools and simulation software, such as Autodesk Project Cyborg, facilitate the modelling and optimization of 4D-printed UAV structures, enabling engineers to predict and refine their behaviour before fabrication (Zhao et al., 2023).

As 4D printing technology continues to evolve, its potential to transform UAV manufacturing becomes increasingly evident. By enabling dynamic, adaptive, and multifunctional structures, this technology paves the way for next-generation UAVs that are lighter, more efficient, and capable of operating in complex environments. This paper explores the fundamental principles of 4D printing, its underlying smart materials, and its application possibilities in UAVs. Additionally, the challenges and prospects of integrating 4D printing in UAV design will be discussed, highlighting its potential to revolutionize the aerospace industry.

2. 4D Printing Techniques

4D printing refers to additive manufacturing processes that enable smart materials to change their shape or properties over time, with various 3D printing techniques such as FDM, DIW, SLA, and SLM being of critical importance in this field (Figure 1). FDM falls under the category of material extrusion and operates on the principle of heating and depositing thermoplastic or thermoset polymer filaments layer by layer. Commonly used thermoplastics such as PLA, and particularly Shape Memory Polymers (SMPs), are frequently employed for 4D printing applications (Fu et al., 2022; Joharji et al., 2022). Composites such as CNT/PLA filaments have been printed using FDM for electro-active shape recovery through Joule heating. Various SMP materials, including PLA/PCL and TPU/PLA/CNT, have also been utilized. The advantages of FDM include ease of processing, cost-effectiveness, recyclability of products, and a wide range of material options (Fu et al., 2022). Its disadvantages include low resolution (~100 μm), poor surface quality, the need for post-processing, and inferior mechanical properties; print resolution can be influenced by parameters such as raster angle and build orientation (Joharji et al., 2022; Khorsandi et al., 2021). It has been utilized in various applications, including prosthetics, implants, and automotive components (Megdich et al., 2023). Additionally, it is also suitable for producing bone scaffolds using porous PLA structures formed with chemical foaming agents or by combining PLA with alginate hydrogel (Khalid et al., 2022). DIW is a material extrusion technique that typically involves by depositing liquid or paste-like inks (photo- or thermo-curable) under pressure. It is a highly sought-after method, particularly for 4D printing of Liquid Crystal Elastomers (LCEs), and can be used with various inks containing polymer, ceramic, or metal particles (Fu et al., 2022). Azobenzene-functionalized LCEs are light-sensitive and undergo shape transformation upon exposure to light. Disk and log-pile structures printed via DIW can exhibit shrinkage with increasing temperature. The flexibility in material selection and the capability to print multiple materials are among the key advantages of this method (Joharji et al., 2022). The disadvantages of DIW include low print quality, reduced resolution, and difficulties in printing complex 3D geometries. Its potential has been highlighted in the fields of biomimetic components, robotics, electronics, and biomedical engineering. DIW has also been employed to fabricate shape-shifting structures using biodegradable shape memory polymers (Fu et al., 2022). Porous magnetic structures composed of TPU and NdFeB composite powders have been designed using DIW for self-powered electromagnetic devices. SLA falls under the category of vat photopolymerization and offers high resolution and good print quality by polymerizing liquid photocurable resins layer by layer using UV lasers or light. It is one of the most popular 4D printing techniques after material extrusion. It is suitable for 4D printing of SMPs, hydrogels, and biodegradable smart polymers. SLA-based technology has been reported for the fabrication of biodegradable smart polymer materials in disposable UAV systems. DLP (Digital Light Processing), a technique like SLA, cures an entire layer simultaneously, which results in faster printing and higher throughput; DLP has been used for SMPs and hydrogels. The high-resolution Projection Micro Stereolithography technique is also derived from SLA and is used for printing SMP-based microstructures. The disadvantages of SLA include resin waste, higher cost compared to other methods, and the need for careful handling due to photosensitive monomers. However, methods such as FDM, which do not use resin, are suggested to potentially be safer with respect to residual monomers that may cause irritation (Khalid et al., 2022; Khorsandi et al., 2021). SLA and related techniques are also widely used in various biomedical and dental applications, such as dental ceramics, dental scaffolds, surgical guides, and prosthetics (Hada et al., 2020; Kruth et al., 2005). SLM (Selective Laser Melting) is one of the powder bed fusion techniques and forms layers by melting metal powders with a laser. It is particularly used for the fabrication of metal components. The advantages of SLM include its suitability for powder processing and high mechanical strength. However, its disadvantages are low dimensional accuracy and longer printing times. It has been employed in the 4D printing of shape memory alloys such as TiNi (Speirs et al., 2017). Additionally, it has also been used in biomedical applications—alongside Selective Laser Sintering (SLS)—for metal dental prostheses such as Co-Cr alloys, porous tantalum and titanium implants, and customized dental implants (Kruth et al., 2005). In general, each of these techniques has distinct material compatibilities, advantages, and disadvantages, and the selection of a particular method for a 4D printing application depends on factors such as the desired shape-morphing behavior, functionality, and material characteristics. For instance, the use of SLA-based technology in the fabrication of biodegradable smart polymer materials for disposable UAV wings can simplify production by enabling automated manufacturing, enhanced accuracy, minimal waste, and optimized cost/customization/structural integrity. Table 2 provides a comparative overview of these techniques, offering guidance to UAV designers on which method is suitable for specific applications.

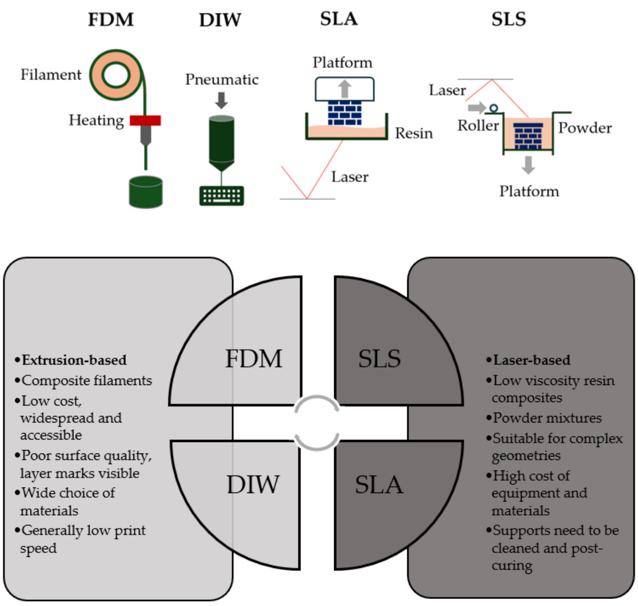

Figure 1. FDM, DIW, SLA and SLS printing techniques (Wu et al., 2025).

Table 2. Analysis of 4D Printing Techniques used in UAV Manufacturing (Frazier, 2014; Khoo et al., 2015; Lewis, 2006; Melchels et al., 2010).

Technique	Compatible Materials	Printing Speed	Suitability for UAV Components
FDM	SMPs, Thermoplastics	20–50 mm/s	- Suitable for adaptive wings and lightweight components -Low-cost prototyping
SLA	Photopolymers, Hydrogels	50–100 mm/s	- High precision for small components (e.g., sensor covers) - Smooth surfaces for aerodynamic parts
DIW	Self-Healing Composites, Hydrogels	5–20 mm/s	- Ideal for self-healing panels - Flexible and complex structures
SLM	SMAs, Metal Powders	10–40 mm/s	- Suitable for durable actuators and supports - High mechanical strength

3. Advanced Materials, Structural Adaptability, and Performance Innovations

The integration of 4D printing technology into UAVs opens new horizons in aerospace engineering, offering advancements in material selection, structural adaptability, aerodynamics, energy efficiency, and modularity. One of the fundamental aspects of 4D printing is the use of smart materials such as shape-memory polymers, self-healing composites, hydrogels, and SMAs. Schematic representation of the shape-memory effect is shown in Figure 2. However, not all 3D printing methods are equally suited for 4D printing, as the technology demands compatibility with stimuli-responsive materials and dynamic structural capabilities (Tibbits, 2014). For instance, while FDM is widely accessible, its reliance on thermoplastics like PLA or ABS limits its ability to process shape-memory polymers or hydrogels, which are critical for 4D-printed UAV components (Ge et al., 2013). Similarly, SLA excels in precision but struggles with flexible or biocompatible photopolymers, restricting its use in morphing wing applications (Zarek et al., 2015) These materials contribute to improved structural resilience, reducing maintenance requirements and enhancing UAV longevity by autonomously repairing minor damages (Ebeid & James, 2023; Lin et al., 2024). For example, Zang and colleagues developed a self-healing double-network shape memory polymer system suitable for high-resolution 4D printing. By incorporating linear polycaprolactone polymer into a methacrylate-based rigid SMP structure, they demonstrated that more than 90% of structural damage could be repaired (Zhang et al., 2019). The schematic representation of the self-healing mechanism is provided in Figure 3. The success of such applications hinges on selecting printing methods that preserve the stimuli-responsive properties of these materials, as traditional SLS—despite its durability—often produces static structures incompatible with dynamic 4D behaviours (Momeni et al., 2017).

Additionally, aerodynamic optimization plays a crucial role in UAV efficiency, where shape-morphing wings and airframes can reduce drag, improve lift, and optimize manoeuvrability in changing flight conditions. Additionally, aerodynamic optimization plays a crucial role in UAV efficiency, where shape-morphing wings and airframes can reduce drag, improve lift, and optimize manoeuvrability in changing flight conditions (Hoa et al., 2022). A notable study by Han et al. developed a shape-memory alloy-based morphing wing for UAVs to address aerodynamic inefficiencies during variable flight speeds. As a result, they achieved a 5.8% increase in lift-to-drag ratio at angles of attack above 5°, improving flight performance (Han et al., 2016).

Beyond aerodynamic benefits, 4D-printed UAVs can adapt their mission capabilities, enabling real-time shape transformation to accommodate different payloads and operational needs. This adaptability is particularly advantageous in military, search and rescue, and commercial applications where modular designs allow drones to switch functionalities seamlessly (Goh et al., 2017; Zaharia et al., 2023).

Furthermore, energy efficiency is significantly improved through innovations like adaptive solar panels, which optimize sunlight absorption based on UAV orientation, and morphing rotor blades that enhance propulsion efficiency (Chen et al., 2024).

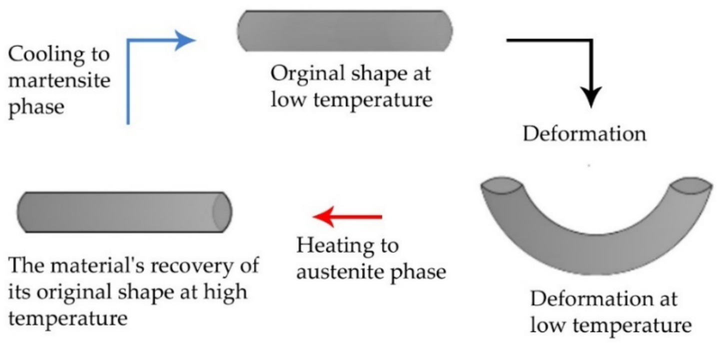

Figure 2. Macroscopic illustration of the phase transformation process in shape memory alloys.

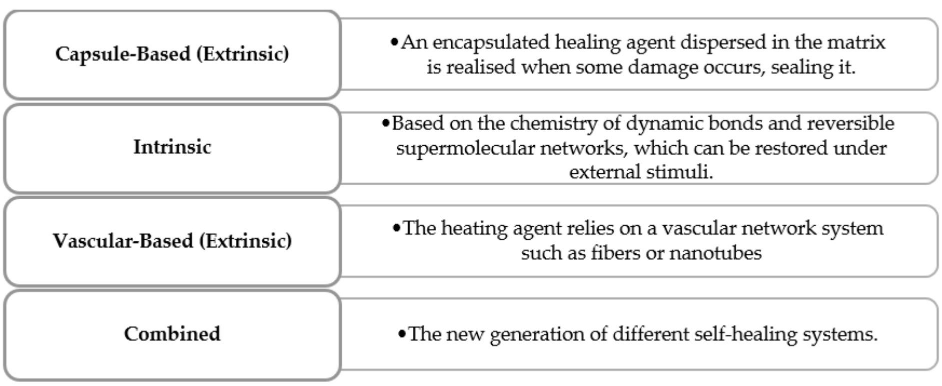

Figure 3. Self-healing mechanism.

Table 1. Properties of smart materials for 4D printing in UAV applications.

Material Type	Stimulus	Mechanical Strength	Density	Advantages in UAV Applications	Disadvantages in UAV Applications
Shape Memory Polymers (SMPs)	Heat, Light	10–100 MPa (Liu et al., 2007)	~1.2 g/cm^3 (Huang et al., 2012)	- Shape morphing for adaptive wing structures -Aerodynamic optimization -Lightweight (Yan et al., 2023)	-Low environmental durability - Susceptible to repeated cyclic deformation (Yan et al., 2023)
Self-Healing Composites	Heat, Mechanical Stress	50–200 MPa (Heo et al., 2016; Norris et al., 2011)	~1.1 g/cm^3 (Li, G., 2014)	- Autonomous crack repair - Extended lifespan - Reduced maintenance costs (Sabet, 2024; Tan et al., 2021)	- Long repair times (hours) - High production costs (Sabet, 2024)
Hydrogels	Moisture, pH	<1 MPa (Yin et al., 2013)	~1.3 g/cm^3 (Cates, 2010)	- Lightweight and flexible -Biocompatibility -Environmental sensor integration (Chen et al., 2024)	- Low mechanical strength - Limited use in structural applications (Chen et al., 2024)
SMAs	Heat, Electrical	500–1000 MPa (Yi & Kim, 2021)	~6.5 g/cm^3 (Chu et al., 2004)	- High strength/weight ratio - Fast response time - Actuator applications (Yi & Kim, 2021)	- High weight - Complex manufacturing process - High cost (Yi & Kim, 2021)

Another transformative aspect of 4D printing is the development of collapsible and self-assembling UAVs, which are highly beneficial for compact transportation and rapid deployment in inaccessible areas (Yi & Kim, 2021). These UAVs can be stored in minimal space and autonomously expand into their operational configurations when required. Moreover, in manufacturing, 4D printing revolutionizes UAV production by enabling rapid prototyping, cost-effective customization, and on-demand production of specialized UAV components (Ebeid & James, 2023). This innovation accelerates development cycles and reduces dependency on traditional manufacturing constraints.

Despite its immense potential, integrating 4D printing into UAV development still faces technological and material challenges. However, as research progresses, the refinement of printing techniques, enhanced computational modelling, and the discovery of new responsive materials will continue to push the boundaries of UAV innovation.

Overall, 4D printing has the potential to revolutionize UAV technology by enabling autonomous adaptation, enhanced durability, optimized flight performance, and mission-specific configurability. As highlighted by Gladman et al., the future of 4D-printed UAVs lies in merging advanced materials with scalable, high-precision printing methods to overcome current limitations (Sydney Gladman et al., 2016). The aerospace industry is poised to witness the emergence of next-generation UAVs that are lighter, smarter, and more efficient than ever before (Yan et al., 2023).

4. Challenges and Limitations in UAV Applications

The development of 4D printing technology is closely linked to advancements in smart materials. However, the variety of smart materials suitable for 4D printing is still limited. In UAV applications, there is a strong demand for lightweight, biocompatible, biodegradable, and durable smart materials. These materials must be capable of providing fast, consistent, and predictable responses to environmental stimuli while maintaining high mechanical strength. For instance, biocompatible and biodegradable materials are critical for UAVs used in ecological research, such as monitoring protected natural reserves, where components must degrade without leaving harmful residues to avoid disrupting delicate ecosystems. A concrete example is the work of Rajendran et al., who developed a biodegradable shape-memory polymer for 4D-printed UAV wing components for disposable UAV systems in environmental monitoring. Their material, a PLA-based composite, achieved complete biodegradation within approximately 1 year under natural conditions while enabling thermally triggered shape morphing for adaptive flight, thus ensuring minimal environmental impact (Ebeid & James, 2023). Some smart materials currently struggle to meet these requirements, leading to concerns about their long-term stability and durability (Khare et al., 2017; Pei & Loh, 2018; Ryan et al., 2021)

Furthermore, the integration of multiple materials in a single 4D-printed UAV component introduces additional challenges. Combining different materials in the same printing process can lead to compatibility issues, adhesion problems, and difficulties in controlling material reactions. This complexity requires further research into multi-material 4D printing techniques and the development of new material combinations specifically designed for UAV applications (Khare et al., 2017; Pei & Loh, 2018; Ryan et al., 2021).

Despite the broad application potential offered by 4D printing technology in UAVs, it faces certain challenges and limitations. These challenges range from technological constraints to material limitations and barriers in manufacturing processes. Addressing these issues is crucial for the successful integration of 4D printing into UAV development and production.

The effectiveness of 4D printing techniques in UAV manufacturing depends on factors such as material compatibility, speed, and cost of the selected method. 4D printing requires precise control of the shape-changing processes of printed objects. This control is achieved by accurately adjusting the material properties, environmental stimuli, and printing parameters. Therefore, 4D printing systems need more complex and sophisticated control mechanisms. Although existing 4D printing technologies are generally suitable for small-scale prototypes and specialized applications, they still face challenges in large-scale production. In the UAV industry, scalability issues must be resolved to enable the widespread adoption of 4D-printed components in commercial and military drones (Pei & Loh, 2018).

Another major technological limitation is the need for advanced software tools to accurately simulate the behaviour of 4D-printed objects and optimize designs. Existing software often struggles to model complex geometries and multi-material interactions, making it difficult to predict how 4D-printed UAV components will behave under different conditions. More sophisticated and user-friendly simulation tools must be developed to improve design precision and efficiency (Pei & Loh, 2018).

Not all existing 3D printing methods are suitable for 4D printing. Some conventional printing techniques are unable to process certain types of smart materials or support shape-changing processes that require precise control. As a result, new printing methods specifically designed for 4D printing applications must be developed. For UAV manufacturing, this includes optimizing printing techniques to produce aerodynamically efficient, lightweight, and structurally resilient components. Additionally, 4D printing processes can be time-consuming, particularly for complex geometries and multi-material applications. This can significantly increase production costs and limit industrial-scale applicability. Improving printing speeds and enhancing manufacturing efficiency are critical for making 4D printing a viable solution for UAV production. Moreover, errors that occur during the printing process can negatively impact the shape-changing performance and durability of UAV components. To address this, advanced control systems and real-time process monitoring techniques must be implemented to improve print quality and reliability (Bodaghi, et al., 2024; Pei & Loh, 2018; Ryan et al., 2021).

5. Application Areas and Potential Usage Scenarios in UAVs

One of the most promising applications of 4D printing in UAVs is the development of adaptive wing structures. Traditional UAV wings are static and designed for specific flight conditions. However, with 4D printing, wings can be engineered to change shape in response to environmental factors such as wind speed, temperature, or altitude. This adaptability can improve aerodynamic efficiency, reduce energy consumption, and extend the flight range of UAVs. For instance, wings that adapt their shape mid-flight to improve lift and reduce drag can greatly boost the efficiency of long-endurance drones deployed for surveillance or delivery tasks (Bai & Bu, 2022; Li, S., 2023).

Another significant advantage of 4D printing is its ability to enable the production of self-assembling UAVs, which can be particularly useful in military applications or disaster response scenarios. These UAVs can be compactly stored and transported, and upon deployment, they can automatically assemble into their operational form. This capability is crucial for rapid deployment in remote or inaccessible areas where traditional assembly methods are impractical, offering a practical solution for time-sensitive missions (Li, 2023; Wang et al., 2023).

In addition to structural adaptability, 4D printing facilitates the use of lightweight yet durable materials, which are essential for maximizing UAV payload capacity and flight efficiency. Smart materials produced through 4D printing can be both lightweight and capable of self-healing or adapting to stress. For instance, a UAV frame made from self-healing materials can repair minor damage incurred during flight, thereby increasing the lifespan and reliability of the drone and reducing maintenance needs (Momeni et al., 2017; Raina et al., 2021; Sahafnejad-Mohammadi et al., 2022).

Energy efficiency is another area where 4D printing can make a substantial impact on UAV performance. This technology can be used to create energy-efficient components, such as adaptable solar panels, which can change their shape and orientation to maximize sunlight absorption. Such panels can extend the flight time of solar-powered drones, making them particularly beneficial for long-duration missions like environmental monitoring or border surveillance (Li, S., 2023; Sahafnejad-Mohammadi et al., 2022).

Furthermore, 4D printing enables the production of customizable payload systems, addressing the diverse needs of UAV missions. UAVs often need to carry different types of payloads depending on their objectives, and 4D printing allows for payload systems that can adapt to various shapes and sizes. For example, a UAV designed for agricultural monitoring can have a payload system that adjusts to carry different sensors or cameras, depending on the specific requirements of the mission, enhancing operational flexibility (Aldawood, 2023; Sahafnejad-Mohammadi et al., 2022; Saritha & Boyina, 2021).

As 4D printing technology continues to evolve, its potential to transform UAV manufacturing becomes increasingly evident. By enabling dynamic, adaptive, and multifunctional structures, this technology paves the way for next-generation UAVs that are lighter, more efficient, and capable of operating in complex environments. This paper further explores the fundamental principles of 4D printing, its underlying smart materials, and its application possibilities in UAVs, while also discussing the challenges and prospects of integrating 4D printing into UAV design, highlighting its potential to revolutionize the aerospace industry.

The high cost of 4D printing technology currently limits its commercial applicability in UAV manufacturing. Smart material costs, specialized printing equipment, and the development of advanced software tools contribute to the overall expense of the technology. To facilitate broader adoption, research is needed to make 4D printing more cost-effective by optimizing material production, reducing waste, and improving printing efficiency. Finally, 4D printing requires a different set of knowledge and skills compared to traditional design and engineering approaches. UAV designers must have a deep understanding of smart materials, environmental interactions, and 4D printing processes. Therefore, specialized training programs and interdisciplinary research efforts are essential to build expertise in 4D printing applications for UAVs. Developing a workforce proficient in this technology will be key to overcoming current challenges and unlocking its full potential in UAV development (Bodaghi, Mahdi et al., 2024; Pei & Loh, 2018; Ryan et al., 2021).

6. Conclusion

4D printing represents a groundbreaking advancement in additive manufacturing, offering unparalleled opportunities for creating adaptive and multifunctional UAV structures through the integration of smart materials. This study underscores the technology’s potential to revolutionize aerospace engineering by enabling UAVs with adaptive aerodynamics, self-assembling capabilities, self-healing components, and energy-efficient designs, thereby enhancing operational efficiency and longevity. However, significant challenges, including the limited availability of lightweight and durable smart materials, complexities in multi-material printing processes, and high production costs, currently impede its widespread adoption. Overcoming these barriers requires sustained advancements in material science, printing technologies, and computational modelling, coupled with investment in interdisciplinary education to develop a skilled workforce. By fostering collaboration among material scientists, engineers, and industry stakeholders, 4D printing can unlock the full potential of next-generation UAVs, paving the way for smarter, more resilient, and sustainable autonomous flight solutions in both commercial and defense applications. In the future, the integration of AI-driven design algorithms into 4D printing processes may enable more precise prediction of material behaviors, opening new research avenues for the development of UAV systems that can intelligently respond to environmental stimuli.

Authors' Contribution

The authors declare that they have contributed equally to the article.

Conflict of Interest Statement

There is no conflict of interest among the authors.

Research and Publication Ethics Statement

The study has been conducted in accordance with research and publication ethics

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