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Review

Advances in Lightweight Composites and Additive Manufacturing for the Development of Service Robotic Systems

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Abstract

The widespread deployment of service robots in domestic and professional environments demands structural solutions that simultaneously achieve high stiffness, low mass, and intrinsic safety. Traditional metallic structural designs face a fundamental physical conflict: achieving high stiffness typically results in excessive mass, which compromises operational safety and battery life. To solve this, this paper presents a critical review of an integrated lightweighting strategy combining material selection, structural design, and additive manufacturing for Carbon-Fiber-Reinforced Polymer (CFRP) service robot structures. Three critical findings are presented. First, specific stiffness is established as the governing criterion for material selection, providing a unified basis to resolve the stiffness–mass conflict. Second, among current 3D printing techniques, Fused Deposition Modeling (FDM) with continuous-fiber reinforcement overcomes the geometric constraints of traditional molding, enabling the fabrication of complex, customized structures. Third, to realize the full potential of 3D-printed CFRP, we highlight the importance of integrating material properties (anisotropy), structural design (topology optimization), and manufacturing processes (path planning) into a concurrent framework. This integrated approach is validated through a collaborative robotic-arm case study, achieving a 30% reduction in structural mass.

Keywords: service robot; lightweight; 3D printing; carbon fiber composite material

1. Introduction

1.1. Social and Technological Context

With the growing severity of societal aging, significant labor shortages are emerging alongside urgent demand for social services and security. According to a United Nations report, the global population aged 65 is expected to double over the next three decades, reaching 16% by 2050 [1]. Under these trends, the traditional labor system faces increasing pressure, creating a strong demand for alternative solutions.

Service robots are expected to take over a wide array of human tasks in both production and daily life operations. Societal aging leads to a reduced labor force and increased demand for services like healthcare, personal assistance, and emotional interactions. Meanwhile, service robots have garnered widespread attention as effective alternatives to human labor, providing daily service tasks and liberating humans from heavy, tedious, or dangerous operations. Recent reports indicate significant growth in service robots across

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professional, consumer, and medical fields [2]. Driven by the demand, the global market is experiencing a rapid expansion and is predicted to reach nearly $112.4 billion by 2030 [3].

Since service robots are closely integrated into human society and frequently interact with people, safety is a primary consideration in their research and design. Lee pointed out that, unlike industrial robots operating in structured environments, service robots typically operate in dynamic and populated environments, which impose higher requirements on safety, reliability, and interaction capabilities [4]. Therefore, ensuring that humans are not physically harmed by machines during collaboration is a fundamental consideration in service robot design.

To ensure safety during human–robot interaction, the robot's moving mass and inertia must be minimized to reduce potential impact energy. However, substantial strength and payload capacity are also required for service robots to complete functional tasks. This creates a physical paradox. Traditional metallic materials, like stainless steel and aluminum, offer necessary stiffness but result in heavy systems that compromise safety and battery life [5]. Conversely, conventional polymers are lightweight but lack mechanical properties required for structural components. These conflicts cannot be fully resolved via conventional subtractive manufacturing and materials alone.

To address these challenges, a collaborative approach integrating advanced materials and manufacturing is required. Carbon-Fiber-Reinforced Polymer (CFRP) offers a specific stiffness 3–5 times higher than metals [6]. When combined with 3D printing, it becomes an ideal solution for fabricating complex, topology-optimized structures that maximize material efficiency. Meanwhile, the path-planning capabilities of 3D printing allow engineers to leverage CFRP's anisotropic nature. This integration of high-performance materials with an advanced manufacturing approach enables the creation of robot structures that are simultaneously lightweight, strong, and safe.

1.2. Scope and Methodology of the Review

With this background, this paper presents a critical review of this integrated strategy for next-generation robots. The roadmap of this review is organized as follows: Section 2 analyzes the mechanical requirements of service robots, defining the challenges of intrinsic safety, energy efficiency, and environmental adaptability. Section 3 evaluates lightweight composite materials, focusing on the mechanical advantages of CFRP for robotic applications. Section 4 reviews 3D printing technologies for CFRP, identifying the capabilities of short-fiber versus continuous-fiber reinforcement. Section 5 explores further optimization strategies, including topology optimization, path planning, and complex structure design, highlighting how to leverage material anisotropy for structural efficiency. Finally, Section 6 demonstrates this strategy through a specific case study, followed by providing a conclusion and a future outlook.

2. Service Robots

2.1. Classifications of Service Robots

Based on the classification framework established by the International Federation of Robotics (IFR), service robots can be classified into two categories: service robots for domestic or personal use and service robots for professional use [2]. Unlike industrial robots that operate in isolated structural environments, service robots are mainly deployed in dynamic, unstructured environments populated by humans [4]. Whether automating material flow in chaotic warehouses, performing delicate surgeries, or operating in dynamic farmlands, these systems are experiencing a common shift: the need to execute complex tasks while ensuring safety and adaptability [7,8]. To provide a clear overview of the current landscape, Table 1 summarizes the key application scenarios and representative systems.

Table 1. Classification and representative examples of service robots.

Category	Application Scenario	Key Function	Representative System
Personal Service Robot	Home tasks robots	Task-oriented: To complete domestic tasks such as vacuuming, floor cleaning, etc. [2].	Robotic vacuum cleaner: Standard domestic cleaning robot.
Personal Service Robot	Assistive robots	Physical assistance: To assist caregivers with physical care tasks like monitoring, lifting, feeding, and hygiene [9,10].	Stretch (Hello Robot): A lightweight arm for household tasks [11].
Personal Service Robot	Companion robots	Psychological assistance: To provide company to enhance well-being and rebuild social connections [9,10].	Lovot: A companion robot designed to improve quality of life for people with dementia [12].
Professional Service Robot	Logistics and transportation robots	Heavy-load handling: To automate the material flow in an unstructured warehouse with human workers [2].	Titan (Amazon): Capable of lifting up to 2500 lbs of heavy items [13]. Blue Jay (Amazon): Multi-arm system for picking, stowing, and packing [14].
Professional Service Robot	Medical robots	Medical support: To assist in delicate surgeries or provide physical rehabilitation support [2].	da Vinci System: Master–slave control system to ensure surgical precision [15,16]. HAL Exoskeleton: To detect bio-electric signals to assist the movement [17].
Professional Service Robot	Agricultural robots	Farming operation: To assist agricultural work without causing soil compaction and perform delicate harvesting [7,18].	Farming GT: Lightweight robot (180 kg) for precise weeding [19,20]. Dogtooth: Strawberry-picking robot using machine learning to determine fruit position and ripeness [21–23].

2.2. Structural Requirements and Challenges

In previous sections, we systematically introduced the classifications of service robots with detailed examples and highlighted the industry's critical transition in both domestic and professional categories. To enable widespread deployment in the scenarios listed in Table 1, a shift from structured industrial scenarios to unstructured, dynamic scenarios with direct interactions with human must take place. A transformation in the physical characteristics of these service robots is of great importance. Based on the application requirements analyzed above, three core challenges must be addressed: intrinsic safety, energy efficiency, and environmental adaptability.

(1) Intrinsic Safety

Intrinsic safety is the primary consideration for human–robot collaboration, particularly in medical and domestic scenarios where robots work closely with humans. While current safety control strategies often rely on sensors to monitor the workspace and stop robots upon detecting potential collisions, these active control methods have limitations. Zinn et al. demonstrate that during an impact, conventional control loops often have response delays that are longer than the duration of an impact. In practice, the contact forces are dominated by the inertial characteristics of the robot rather than control system [24]. Therefore, safety must be intrinsic to the robot's physical structure. From a mechanical perspective, the severity of collision injury is dominated by impact dynamics, specifically the kinetic energy (E_k), as shown in Equation (1):

$$E_k = \frac{1}{2}mv^2 \quad (1)$$

As indicated by the equation, potential injury energy is proportional to the moving mass (m) and the square of velocity (v^2). Since operational speed (v) determines productivity and cannot be reduced in most professional scenarios, minimizing the structural mass becomes an important factor in lowering impact energy and reducing injury risks, which is also verified by Haddadin et al. [25].

(2) Energy Efficiency

Unlike industrial robots, service robots mainly rely on onboard batteries. The fundamental inefficiency in current designs is that a significant portion of the limited energy budget is consumed to accelerate and move the robot's own heavy structure rather than the payload. Researchers have developed energy consumption models mathematically identifying that the power required for motion is dependent on the mass of the system. As shown in Equation (2), the traction force F_{tr} required to move the robot is the sum of inertial forces and resistive forces [26]:

$$F_{tr} = ma + \mu mg \cos \alpha \quad (2)$$

Here, m is robot's mass (m), a is the acceleration, μ is the coefficient of friction, g is the gravity and α is the angle of motion to the vertical [26]. Thus, reducing system mass directly decreases the power required for self-motion, directly extending battery life and operational range without increasing battery payload. This principle is equally critical in the field of wearable robotics. While the goal of the exoskeleton is to reduce the user's effort during motion, the device's own weight might create an unnecessary burden. If the robotic structure is too heavy, it might negate the mechanical assistance provided by the exoskeleton. Reducing the structural mass in this case is critical to ensure the system provides a net benefit to users [27].

(3) Environmental Adaptability

Beyond energy consumption, the structural mass of the service robot limits the dynamic performance of the manipulator in high-speed tasks and is responsible for the physical impact on the working environment. For professional service robots, productivity relies on the execution speed and working precision, yet high structural mass leads to high rotational inertia. Zinn et al. demonstrated that when a heavy robot attempts high-speed tasks, the large moving mass requires enormous torque to accelerate and decelerate. This prevents the system from achieving desired accelerations, causing slower operation and vibrations [24].

In agricultural scenarios, excessive weight causes direct physical damage to the operating field. Heavy robotic structures generate high ground pressure, leading to undesirable soil compaction. Recent studies indicate that the excess weights of current farm machines now induce mechanical stress that exceeds the safe limits for soil functioning [28]. Thus, to navigate the unstructured environment without causing ecological damage, the industry must transition gradually toward smaller and lighter units.

In summary, the physics of service robots validates that mass reduction is essential for safety, efficiency, and sustainability. However, conventional metallic materials are reaching performance limits due to their high density. They cannot achieve the necessary balance between mechanical properties and light weight. This industry faces an urgent demand for a shift toward advanced lightweight materials, which will be discussed in the later sections.

3. Lightweight Composite Materials

3.1. Material Selection Strategy

As discussed in Section 2, the conflicting requirements of intrinsic safety, energy efficiency, and environmental adaptability reflect a similar physical demand: minimizing system mass while maximizing structural stiffness. Conventional metallic materials, like stainless steels and aluminum alloys, cannot fully resolve these conflicts. While these metals have served as an industry benchmark, their high density limits their performance in service robots. To overcome the physical constraints discussed previously, a fundamental shift in material selection strategy is required, moving from a focus on absolute properties to specific properties. According to the methodology established by Ashby, the performance index of lightweight, rigid structures is defined by specific stiffness (stiffness-to-density ratio) [29]. Maximizing this index is essential for service robots, as it minimizes structural mass without compromising the superior stiffness required for precise operation.

As illustrated in the Ashby chart (Figure 1), metallic materials are clustered in the upper-right region of the chart, representing limited stiffness but high density. Fiber-reinforced composites, especially CFRP, are distributed in the central-upper region. This region represents the optimal zone for lightweight design, offering high stiffness at low density. Quantitatively, with certain types of fibers, the specific stiffness of CFRP can reach approximately 10 times higher than that of aluminum and steel [30]. In theory, this allows CFRP to achieve equivalent stiffness with a mass reduction of up to 80% [31]. This weight reduction directly lowers the kinetic energy during potential collision and reduces power consumption, effectively addressing the safety and efficiency challenges discussed in Section 2.

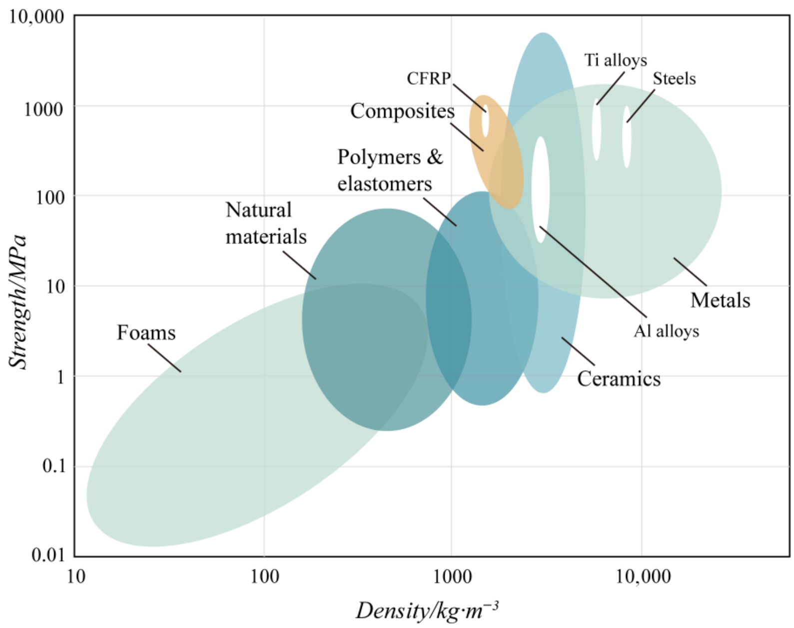

Figure 1. Ashby diagram: Young's modulus E vs. density. Objective: maximize stiffness at minimum mass [32].

Beyond superior specific properties, another dominant advantage of composite materials is anisotropy. Unlike isotropic metals, which exhibit uniform mechanical properties in all directions, composites are multiphase systems that allow for property customization. In robotic manipulators, loads are directional bending forces and torsional moments. Using isotropic metals to meet these stiffness requirements leads to material waste in low-stress directions. In contrast, by tailoring the fiber alignment along specific load directions, CFRP enables an optimized material distribution [33]. This assists in achieving an optimal balance between stiffness and mass, meeting the precise demands of service robots.

3.2. Classification of Fiber-Reinforced Polymers

3.2.1. Glass-Fiber-Reinforced Polymer (GFRP)

Glass-Fiber-Reinforced Polymer (GFRP) represents the most mature and cost-effective category within the lightweight composite family. Defined as a polymer matrix reinforced by fine glass fibers (mostly E-glass), GFRP offers an excellent balance of low density, high tensile strength, and manufacturability. Although its specific strength is lower than that of carbon fiber, these characteristics enable widespread applications in aerospace, automotive, and construction areas to achieve weight reduction at an affordable price [34].

A key advantage of GFRP is that its mechanical properties can be tailored by adjusting the fiber volume fraction. El-Wazery et al. investigated polyester matrix composite with varying fiber weight fraction (15–60 wt%). Their results indicated that the performance peaks are at 60%, achieving 78.83 MPa of tensile strength and 119.23 MPa of flexural strength. Additionally, surface hardness and impact energy were enhanced [35]. Similarly, Srinivasa et al. demonstrated that the glass fibers mitigate failure under diverse stress conditions. The paper revealed an increase of 20–25% in compressive strength and 15–20% in both flexural and split tensile strengths [36]. For service robots operating in an unstructured environment, a defining advantage of GFRP is its impact resistance rather than static stiffness. Unlike stiffer materials, GFRP has good energy absorption ability. Asmare et al. confirmed that by optimizing fiber content up to 65%, the maximum impact strength of GFRP can reach 12.6 Joule with 52.46 MPa stress concentration at 1.4 mm deformation [37].

To further leverage these properties while mitigating the lower modulus, engineers are now working on hybrid composites. By combining glass fiber with high-strength materials, the overall yield strength can be improved while maintaining low manufacturing costs [38]. This hybrid approach has been realized in the automotive industry, where structural components like bumper beams are fabricated from 40% long-glass-fiber hybrid polymer. The bumper beams exhibit a significantly higher specific-energy absorption ratio and reduced weight at a comparable price [39]. Similarly, hybrid CFRP can also work as an ideal material for protective shells and skins of service robots, protecting the sensors and electronics during collisions or falls.

3.2.2. Natural-Fiber-Reinforced Polymer (NFRP)

Driven by growing demand for environmental sustainability, Natural-Fiber-Reinforced Polymer (NFRP) has emerged as an alternative composite. Processed from bio-based resources like flax, hemp, and jute, these materials offer a significant reduction in carbon footprint during manufacturing. Yan et al. highlighted that while natural fibers possess comparably lower strength compared to carbon fiber, their low density allows them to achieve specific mechanical properties comparable to those of GFRP [40].

Sayeed et al. investigated various natural fibers, including jute, kenaf, and PALF, reinforced polypropylene composites. Their findings indicated that with fiber volume fractions from 30% to 40%, the composite can achieve tensile strength up to 58 MPa and impact strength of 46 kJ/m^2, significantly higher than the pure matrix [41]. However, for service robots operating in a dynamic environment, the most critical advantage of NFRP is its vibration-damping capacity. In high precision tasks, operating accuracy is constrained by structural vibration. Prabhakaran et al. validated that flax-fiber-reinforced polymers possess a vibration-damping capacity 51.03% higher than traditional GFRP.

Furthermore, flax composites exhibited a sound coefficient 21–25% higher across both low and high frequency ranges [42]. These findings suggest that NFRP is suitable for applications requiring noise reduction and vibration isolation, which are essential for ensuring precise manipulation.

Despite these advantages, the lower stiffness of natural fibers limits their application in heavy-load structural components. To leverage the superior damping capability of NFRP without compromising stiffness, hybrid composites are adopted. Fairlie and Njuguna demonstrated that by interlacing carbon fiber with flax fiber, the dynamic performance of a structure can be significantly optimized. While the addition of flax layers might slightly reduce the overall stiffness compared to pure CFRP, it enhances the material's ability to absorb vibration energy [43]. Thus, balancing these characteristics enables the design of robot links that are lightweight, stiff, and dynamically stable.

3.2.3. Carbon-Fiber-Reinforced Polymer (CFRP)

Carbon-Fiber-Reinforced Polymer (CFRP) is regarded as a typical representative of modern lightweight composites, serving as the primary choice for high-end applications requiring maximized performance. CFRP consists of reinforcing carbon fiber embedded in a polymer matrix [44]. In this composite system, the fibers bear the mechanical loads while the matrix ensures proper orientation and uniform load transfer [45]. Through this combination, CFRP exhibits superior mechanical properties, including high strength, corrosion resistance, fatigue resistance and light weight [44]. Figure 2 provides an overview of typical categories of carbon fiber composites [46].

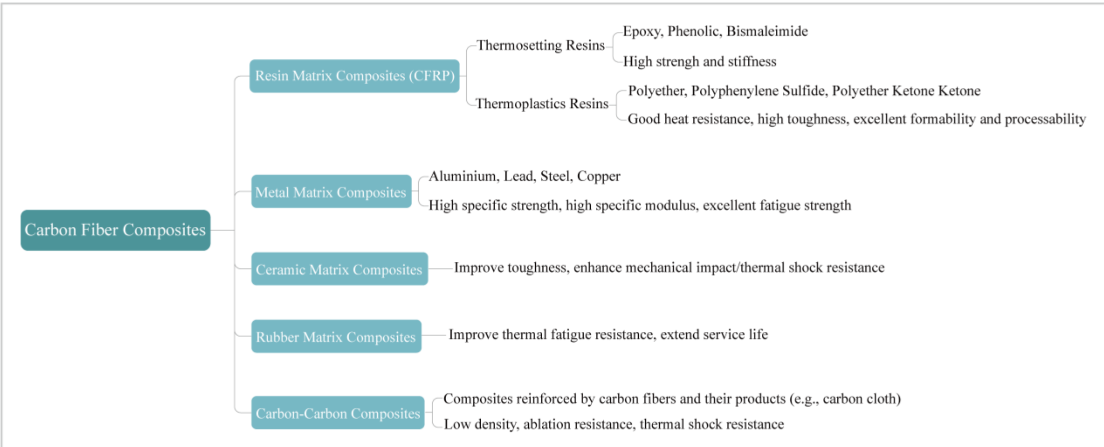

Figure 2. Overview of typical categories of carbon fiber composites [46].

Pierson et al. demonstrated the reinforcing efficiency of carbon fiber. They reported that adding only 5.5 vol% carbon fiber to neat epoxy doubled both strength and stiffness. For ABS thermoplastic matrices, the mechanical properties were even tripled [47]. These advantages translate directly to robotic applications. Khozeimeh et al. replaced the aluminum alloy parts in a robotic manipulator with CFRP. Their study observed that CFRP hollow square-section beams exhibited 1.17 times greater stiffness and 1.20 times higher load capacity compared to I-section beams. Furthermore, the CFRP design resulted in a significant increase in natural frequencies and a reduction in tip deflection, improving operating accuracy [48].

Based on the type of matrix, CFRP is divided into thermoset and thermoplastic composites. Thermoset matrix currently dominates the market (~66.7%) due to its overall structural rigidity and thermal stability [49,50]. However, the main disadvantage of thermoset is obvious: once cured, the resin cannot be remelted or reshaped, making the recycling process

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significantly challenging and costly [51,52]. In contrast, thermoplastics are malleable and can be reshaped. This feature allows recyclability [49], which is regarded as an essential advantage in modern industry due to sustainability requirements. Furthermore, many thermoplastics composites show significantly higher impact resistance, sometimes even 10 times than that of thermoplastic [52]. Due to these advantages, research into Carbon-Fiber-Reinforced Thermoplastics (CFRTPs), especially with matrices like Polypropylene or PEEK, has emerged as critical focus for the medical service robot industry.

3.2.4. Critical Analysis: The Selection of Lightweight Materials in Service Robots

According to Section 3.1, an alternative strategy for material selection in service robots becomes evident. While each fiber-reinforced-polymer category offers distinct advantages, their application is strictly constrained by physical limitations. GFRP exhibits high impact resistance and cost-efficiency, making it ideal for external protective shells, similar to its applications in the automotive industry [53,54]. Similarly, NFRP offers superior vibration damping, allowing it to serve in dynamic but non-structural component [55].

However, the limitations of these two materials in service robots for structural components are revealed by quantitative analysis. As discussed in Section 3.1, specific stiffness is one essential selection criterion. While the densities of these composites are comparable—1.50–2.10 g/cm^3 for CFRP, 1.25–2.50 g/cm^3 for GFRP, and 1.2–1.6 g/cm^3 for typical NFRP [55–57]—an obvious difference exists in stiffness; the elastic modulus of CFRP is 120–580 Gpa, far exceeding that of GFRP (35–51 Gpa) and NFRP (2.5–96 GPa) [58,59]. Based on calculations, the specific stiffness of CFRP is 57–387 $GPa/(g/cm^3)$, while GFRP is limited to 14–41 $GPa/(g/cm^3)$, and NFRP is limited to 1.6–80 $GPa/(g/cm^3)$. This calculation indicates that the specific stiffness of CFRP is at least 3 times higher than that of the other two types. To achieve the same structural rigidity using GFRP or NFRP, a much thicker cross-section would be required. Thus, to simultaneously meet the requirements for light weight and structural rigidity, CFRP remains the competitive option for main structural parts of service robots. Consequently, the subsequent section will focus mainly on CFRP and its processing strategies.

3.3. Carbon-Fiber-Reinforced Polymers (CFRPs): Properties and Anisotropy

As discussed, CFRP has various advantages, such as high specific strength, a low coefficient of thermal expansion, superior fatigue resistance, and good thermal conductivity. These properties allow CFRP to be widely applied in high-performance fields like aerospace, automotive, machinery, electronics, and medical devices [60]. According to Zheng et al., the fundamental mechanical properties are defined by fiber type, while volume fraction and orientation of the fiber affect strength and stiffness. Optimization of post-processing and manufacturing parameters can enhance the overall performance of the final component [61].

Unlike isotropic metals, which exhibit uniform properties in all directions, the mechanical performance of FRPs is governed by the orientation of the fibers related to the load direction. Mortazavian et al. validated that the mechanical properties, such as tensile strength and elastic modulus, are highly direction-dependent. Their research observed a significant reduction in mechanical properties when the load angle shifts away from the fiber direction [62]. This property can be applied to maximize the structural rigidity. Jiang and Smith quantified this effect in 3D-printed composites, demonstrating that when fibers are aligned with 0° (along load direction), the material exhibits a 312% improvement in elastic modulus and 48.2% increase in tensile strength [63]. Furthermore, Zhang et al. introduced a strategy integrating fiber alignment with topology optimization. Compared to the original design, the optimized sample achieved a 305% improvement in strength and

256% in stiffness, primarily due to reduced porosity and customized fiber paths matching stress directions [64].

Finally, achieving these theoretical mechanical properties relies on the quality of the interfacial bonding between the fiber and the matrix. Zheng et al. highlight that the inertness of fiber surfaces limits the bonding adhesion. Strategies include chemical treatment, plasma treatment, and sizing modification, which are employed to enhance chemical compatibility and wettability between matrix and fiber [65]. Thus, modified composites exhibit superior mechanical properties, ensuring structural rigidity under dynamic loads [66].

3.4. Conventional Manufacturing Technologies of Carbon-Fiber-Reinforced Polymer

3.4.1. Key Techniques

The manufacturing technologies for CFRP are diverse, depending mainly on the reinforcement type and the actual application of the final product [67]. Generally, the fabrication process consists of two main stages: the creation of fiber preforms and the curing with matrix [50]. Despite the emergence of advanced technologies, the industry still relies heavily on conventional mold-based technologies. Among these, pultrusion, filament winding, and compression molding are the most dominant processes relevant to structural components.

Pultrusion is an automated manufacturing process designed to create components with constant cross-sections (Figure 3). In this method, the fiber bundles are impregnated with resin and then pulled through a heated die for curing. This technology is mature and widely applied for mass production due to its high automation level [68,69]. However, its geometric capability is limited to linear profiles, making it unsuitable for complex shapes [70]. Meanwhile, the high initial capital investment for die fabrication makes it economically unavailable for low-volume batch production or rapid prototyping [71,72].

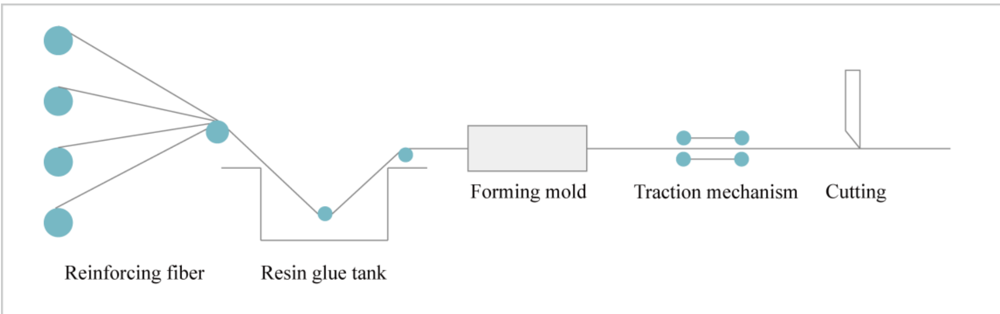

Figure 3. Illustration of pultrusion technique for fiber-reinforced resin matrix composite [73].

Filament winding involves pulling continuous carbon fiber through a resin bath and winding it onto a rotating mandrel, which serves as a mold (Figure 4). This technique is widely applied for symmetric structures, such as pressure vessels and shafts, as it allows fibers to be aligned along the load direction [50,68]. The primary advantage of this method is its ability to produce high-stiffness products by utilizing continuous fibers with optimized direction [70,72]. However, the geometry is limited to convex-shaped composites defined by the mandrel, and the rough outer surface often requires post-processing. Similarly to pultrusion, high setup costs limit its application to mass production [68].

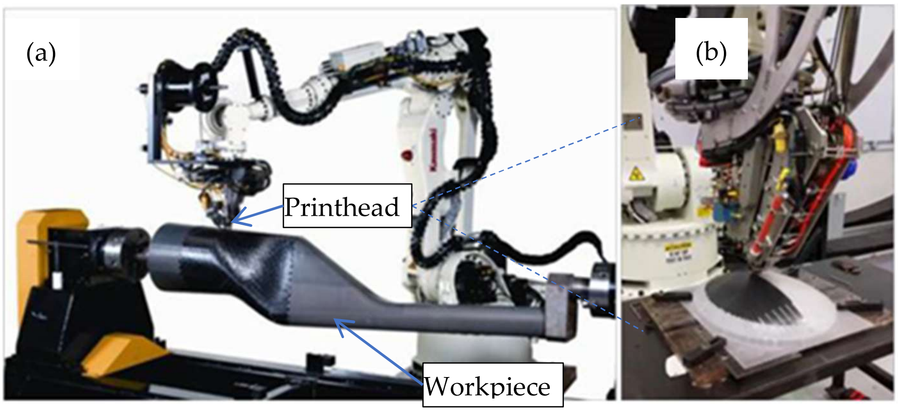

Figure 4. Representative equipment for thermoplastic wire laying: (**a**) overview, (**b**) printhead [74].

Compression molding is a close-mold process where prepregs are placed into preheated molds. By applying heat and pressure, the material is cured in desired shapes [70,72]. This method is recognized for its precision and ability to produce components with excellent surface finishes and complex features, such as integrated strengthening ribs [75]. Among conventional techniques, it is often the most cost-effective for high-volume production as it minimizes the material waste [68]. However, the limitations remain obvious: the tooling costs for die fabrications are expensive, energy consumption is high, and precise thickness control can be challenging [50,76].

3.4.2. Limitations of Conventional Manufacturing for Service Robots

While conventional techniques like pultrusion and compress molding are mature and widely adopted in mass production in aerospace and automotive industries, their direct application to service robotics faces significant economic and geometric limitations.

(1) Economic Constraints: Traditional CFRP manufacturing heavily relies on specialized toolings and molds. Processes like compression molding require expensive metal dies that demand high initial investment and a long setup period [50,71,72]. While cost-effective for standardized mass production, the service robot industry currently involves low-volume production and rapid iterative cycles. For customized robotic parts, like rehabilitation exoskeletons for patients, the cost and time required for mold fabrication are unacceptable.

(2) Geometric Constraints: Traditional techniques are limited to simple profiles or convex shapes, such as plates, tubes, or shells [68,70]. They struggle to create extremely complex, hollow, or topologically optimized structures required for lightweight robotic parts. To achieve such complexity via traditional means, multiple simple parts are fabricated independently and assembled. This introduces joints and fasteners that not only add weight but also create potential failure points.

(3) Challenges in Anisotropy Control: Most critically, conventional methods fail to fully leverage CFRP's anisotropic properties in complex geometries. Service robot components often operate under complex stress states, requiring continuous reinforcement along load directions. Traditional winding or laying processes generally lack the capability to fabricate fibers continuously along these complex stress vectors.

In summary, a shift from conventional manufacturing processes to a more flexible and rapid manufacturing process is required. 3D printing techniques can eliminate tooling constraints for customization, and more importantly, enable the rapid fabrication of complex geometries. Meanwhile, the precise control of path planning in 3D printing allows for the full utilization of CFRP anisotropy, aligning fibers precisely with complex stress directions. This ability to simultaneously meet the demands of geometric complexity and material performance makes 3D printing key to unlock CFRP's full potential in service robots. Thus, Section 4 will present a comprehensive discussion of 3D printing technologies, especially analyzing how digital freedom enhances the composites' performance.

4. 3D Printing Technology

4.1. Overview of 3D Printing

3D printing, academically referred to as additive manufacturing (AM), is widely regarded as a transformative advanced manufacturing technique. The fundamental principle involves creating solid objects layer by layer based on the three-dimensional model data [77]. Objects are constructed directly from Computer-Aided Design (CAD) drawings, utilizing diverse materials from conventional thermoplastic to advanced graphene-based composites [78,79]. As illustrated in Figure 5, the process consists of three stages: (1) gaining geometric data via scanning or direct digital modeling; (2) slicing the digital model into layers, followed by a physical deposition process; (3) finishing treatment, such as support removal and surface polishing, to achieve final specifications [80]. This direct digital-to-physical process eliminates the need for specialized tooling and machining. It serves as an ideal technique for low-volume production, prototyping, and mass customization across diverse sectors including research, medical, and automotive industries [78,80].

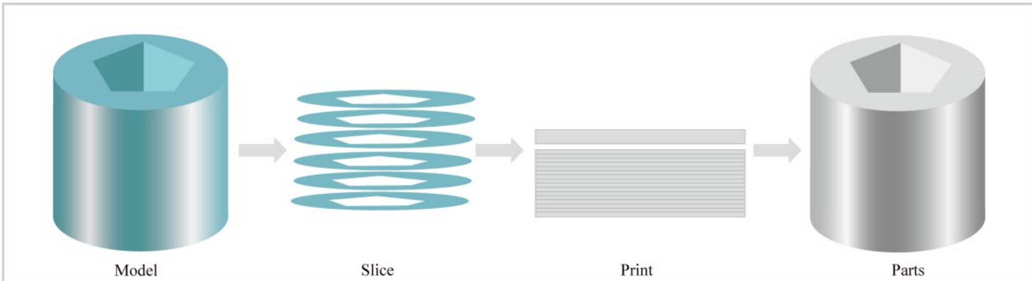

Figure 5. Illustration of the discrete layer-based 3D printing process [81].

The adoption of 3D printing in service robotics industry is driven by following advantages:

(1) Geometry Complexity and Lightweighting: In high-performance applications such as aerospace and robotics, lightweighting is a critical priority. 3D printing pushes the limits of design freedom, allowing for the fabrication of complex, topology-optimized structures that are impossible to produce via conventional injection molding or machining. Consequently, this technology enables the creation of mechanically efficient structures with minimized mass [79,80].

(2) Mass Customization: 3D printing enables fully customized designs to fit specific needs without initial tooling cost [80]. This is the particular evident in medical robotics, where 3D printing is used for personalized surgical implants or rehabilitation exoskeletons [82]. Currently, a wide range of medical-grade implants created with 3D printing have been adopted clinically [83]. Since manufacturing facilities can be located closer to consumers than conventional factories, the process is more flexible and responsive [78].

(3) Rapid Prototyping: 3D printing significantly shortens product development cycles. Unlike conventional manufacturing that requires expensive models, this technique allows for immediate creation and iteration of components. This ensures a faster time to market, allowing companies to test and presell products. Also, rapid prototyping permits verification of design before mass production [80].

(4) Material and Energy Efficiency: As an additive process, material waste can be minimized. Furthermore, by simplifying the supply chain and enabling localized manufacturing, the carbon footprint associated with transportation and logistics is substantially decreased, aligning with global sustainability goals [78]. Additionally, the technology offers potential for using recycled materials and reducing overall emissions [84].

While various 3D printing technologies exist, they are broadly categorized based on the state of the raw materials (solid filament, liquid resin, or powder). For CFRP, the most related techniques are Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), Stereolithography (SLA), and Selective Laser Sintering (SLS). Table 2 presents the comparison of these technologies synthesized from recent reviews [80,85–89]. Among them, FDM has emerged as the dominant method for manufacturing CFRP. This is because FDM is capable of printing both continuous and short fibers, ensuring superior mechanical properties, multi-material capability, and low cost [90]. Although SLA has demonstrated the ability to print continuous fibers via specialized mechanisms, it is mostly applied for short-fiber composites and lacks the maturity for continuous integration [91]. Similarly, while SLS offers excellent surface resolution and accuracy for complex geometries, its material compatibility is largely restricted to short-fiber powders, limiting the mechanical reinforcement potential compared to FDM [92].

Table 2. Comparison of key 3D printing technologies for composites [80,85–89].

3D Printing Technology	Conventional Forming	Materials	Advantages	Disadvantages	Accuracy
Fused Deposition Modeling (FDM)	Extrusion	Thermoplastics (PLA, ABS, PEEK, Nylon)	Mature technology; continuous-fiber capability; low cost; multi-material.	Anisotropy (weak Z-axis strength); stair-step effect; lower accuracy.	0.1–0.2 mm
Stereolithography (SLA)	Photopolymerization	Photocurable resins	High accuracy; excellent surface finish; detailed features.	Limited material options (mostly short fibers); resin shrinkage; brittle.	<0.1 mm
Selective Laser Sintering (SLS)	Powder sintering	Thermoplastics (Nylon), metal/ceramic powder	No support structures needed; complex geometries; fast speed.	Limited to short fibers; porous surface; poor mechanical properties vs. continuous.	0.2 mm

Driven by CFRP's remarkable chemical stability and exceptional mechanical, electrical, and thermal properties, the integration of 3D printing with CFRP represents a significant advancement in modern industry. 3D printing unlocks the full potential of composites by enabling complex geometries and precise fiber path control, delivering extreme lightweight designs that traditional manufacturing cannot achieve [92]. To fully understand this potential, the next section will discuss the two main two categories of CFRP 3D printing, short-fiber printing and continuous-fiber printing.

4.2. Short- vs. Continuous-Fiber Printing

Generally, CFRP utilized in 3D printing is categorized into two types: Short-Fiber-Reinforced Polymer (SFRP) and Continuous-Fiber-Reinforced Polymer Composite (CFRPC) [93,94]. The fundamental difference lies in the load transfer capability between the matrix and the reinforcement. While continuous fibers can be precisely aligned with the direction of force to maximize strength, short fibers (typically 0.2–0.4 mm) are oriented randomly or partially aligned along the extrusion path [93,95] (Figure 6). As discussed before, the degree of alignment and fiber length significantly affect the mechanical properties.

Consequently, short fibers exhibit lower reinforcement efficiency compared to continuous fibers [96]. This section analyzes the processing mechanics, mechanical properties, and limitations, as well as applications for both categories.

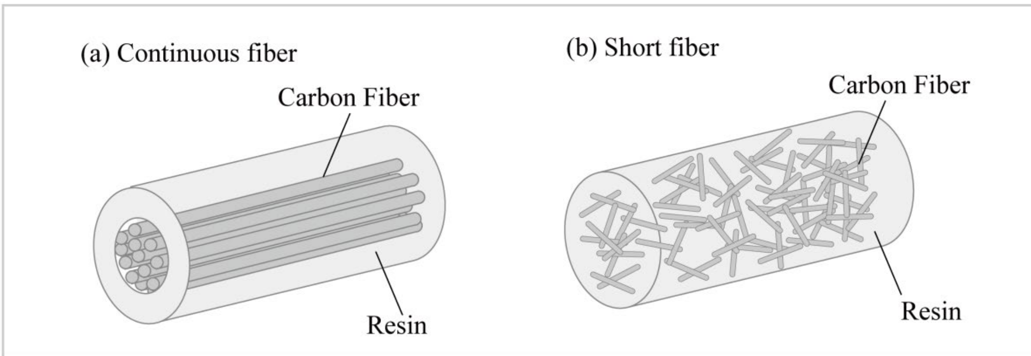

Figure 6. The fiber orientation in (**a**) Continuous-Fiber-Reinforced Polymer vs. (**b**) Short-Fiber-Reinforced Polymer [93].

4.2.1. Short-Fiber-Reinforced Polymer (SFRP)

Material extrusion technologies, such as FDM, have been widely applied for short-fiber reinforcement [97]. In this process, the filament consists of thermoplastic matrix blended with chopped fibers. The composite is heated to working temperature and extruded through a nozzle to fabricate the component layer by layer [98]. The simplicity of this process is similar to standard polymer printing, requiring no specialized hardware modifications.

Studies have proven that SFRP significantly enhances stiffness compared to pure polymer. Ivey et al. demonstrated that the addition of short fibers into PLA filaments improves the elastic modulus of printed samples [97]. Toth et al. also revealed that short-fiber reinforcement increased the overall tensile modulus by an average of 2.22 times and flexural modulus by 2.69 times compared to the original matrix [99]. Liao et al. similarly reported a 102.2% increase in tensile strength and a 265.9% increase in Young's modulus by adding 10 wt% short carbon fiber to PA12 [100]. Zhang et al. achieved a 141.3% increase in modulus with 15 wt% short fiber in ABS matrix [101]. Overall, these findings indicate that while the extent of reinforcement varies, it is strongly related to manufacturing parameters, matrix type, and fiber volume fraction [102]. Table 3 presents the mechanical performance of commercial short-fiber composites fabricated by FDM.

Table 3. Summary of mechanical performance of commercial short-carbon-fiber composites fabricated by FDM [103].

Supplier	Material	Tensile Strength in x-Direction (MPa)	Tensile Modulus in x-Direction (GPa)
Stratasys	PA12/CF	75.6	7.5
	ABS/CF	44	4.0
	PLA/CF	47.9	4.8
3Dxtech	PETG/CF	55.5	4.9
	PA/CF	63.9	4.4
Lehvoss	PEEK/CF	176	14.5
Colorfabb	PETG/CF	76	—

Despite these enhancements, the strengthening potential of SFRP is limited. The effectiveness of reinforcement is constrained by the critical fiber length and the largely random fiber distribution, which can induce anisotropic properties and localized stress concentrations [104]. Although recent research has focused on optimizing nozzle designs to improve flow-induced alignment, SFRP cannot match the load-bearing capacity of continuous fibers [105]. The advantages of SFRP lie in its processability and cost-efficiency. Due to its high compatibility with conventional extrusion-based 3D printing, it offers a simplified manufacturing route [106]. Consequently, short-fiber reinforcement is ideal for semi-structural components such as robotic castings, sensor housings, and grippers, where geometric complexity and dimensional accuracy are more critical than load capacity.

4.2.2. Continuous-Fiber-Reinforced Polymer Composites (CFRPCs)

Continuous fiber refers to reinforcing fiber that exceeds the critical length, ensuring continuous load transfer along the fiber axis and maximizing mechanical efficiency [107]. In the context of FDM/FFF, the incorporation of continuous fibers typically occurs via three distinct strategies [108]: (1) using pre-impregnated composite filaments where the fiber and matrix are bonded prior to printing; (2) co-extrusion, where dry fibers and thermoplastic matrix are combined within a single heated nozzle; and (3) dual-nozzle deposition, where the matrix and fiber are deposited separately on the component. Through these processes, continuous carbon fibers and polymer matrix are consolidated to form high-performance quality structures [109].

The addition of continuous carbon fiber significantly increases overall mechanical properties. Isobe et al. demonstrated that with continuous fiber reinforcement, the final tensile strength is approximately 7 times higher and the elastic modulus is around 5 times higher than that of short fiber or pure matrix [110]. To fully exploit this potential, advanced processing strategies have been developed. Uşun et al. achieved a high fiber fraction up to 50%, with layers preheated by an infrared heater. Interlayer adhesion was enhanced, possessing a flexural strength of 1304 MPa and a tensile strength of 995 MPa [111]. Furthermore, to overcome the defects of FDM like weak interlayer bondings and high porosity, Parandoush et al. introduced a novel laminated-object manufacturing approach. With precise control of fiber alignment, they achieved a tensile strength of 668.3 MPa and flexural strength of 591.16 MPa, significantly mitigating the weakness of interlayer bonding [112].

By running reinforcement through the full length of the printed part, CFRC offers superior stiffness, fatigue resistance, and load-bearing capacity [94,113]. Precise control over fiber orientation enables the tailoring of anisotropic mechanical properties, making it perfect for load-bearing structural applications in high-performance industries such as aerospace and automative [94]. However, several drawbacks in manufacturing process and performance gaps still exist. Current continuous-fiber printing is constrained by low print speeds, higher costs, and complexities in fabricating large or curved structures [94,114]. A critical limitation is the fiber volume fraction: while traditional manufacturing methods can achieve up to 50–60% fiber content, mainstream 3D printing systems are typically limited to under 30% [104]. Additionally, fibers often cannot be fully impregnated due to low forming pressure, causing poor interfacial interaction. These drawbacks affect the accuracy and mechanical consistency of fabricated components, requiring further optimization to increase the fiber content and consolidation quality [114,115].

5. 3D Printing of Lightweight Materials

While 3D printing provides the capability to create complex geometries, and CFRP provides the material potential for high specific stiffness, structural optimization is the bridge to translate these capabilities into physical performance. In conventional manufacturing, the realization of complex optimization is hard to realize, but 3D printing allows the accurate deposition of materials in the desired position, as well as the precise control of fiber orientation [116]. This section will review three critical optimization strategies enabled by 3D printing: topology optimization, path planning, and the fabrication of special structures.

5.1. Integrated Topology Optimization of CFRP with Path Planning

5.1.1. Definition and Necessity

Topology optimization (TO) refers to a class of computational tools applied to optimize the material layout within a given design, maximizing the objective function subject to specific constraints (Figure 7) [117]. Currently, TO is widely adopted for weight reduction in aerospace and automotive applications [118]. Although various approaches exist, the Solid Isotropic Microstructure with Penalization for intermediate densities (SIMP) method, established by Bendsoe decades ago, remains the most generally adopted approach [119]. However, traditional SIMP assumes isotropic material properties (like metals), which are fundamentally incompatible with the anisotropic nature of composites [120,121].

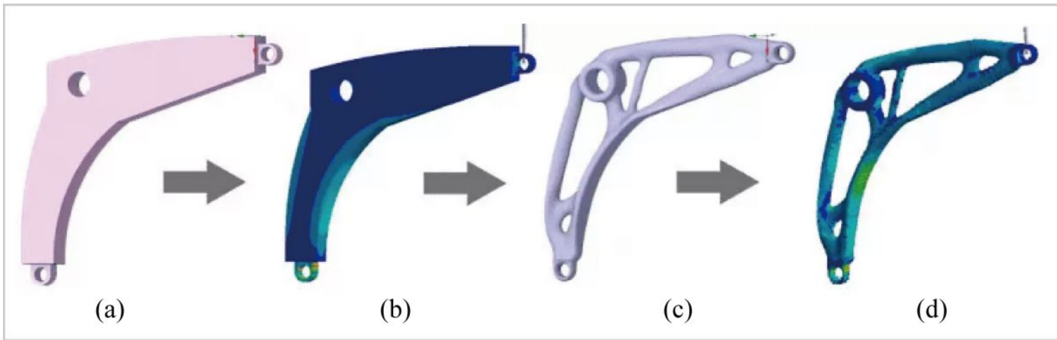

Figure 7. Illustration of topology optimization (from left to right): (**a**) the original model, (**b**) stress profile, (**c**) topology-optimized structure, and (**d**) the final stress profile [122].

A significant risk in applying isotropic TO to composites is structural instability. In TO, slender members are frequently generated to achieve maximum weight reduction. While high-strength fibers can theoretically support these loads, extremely slender composite members are likely to buckle under compression. Current research often ignores this anisotropy [123]. The full potential and mechanical properties of these high-performance materials cannot be fully leveraged. Thus, anisotropic topology optimization that simultaneously considers material layout and fiber orientation is a crucial strategy to maximize mechanical properties while minimizing weight.

The primary value of TO for service robots is the extreme removal of non-load-bearing mass. By eliminating redundant material, the robotic part's moment of inertia is minimized without compromising its payload capacity. This direct reduction in moving mass fundamentally addresses the kinetic energy (E_k) challenge defined in Section 2, ensuring intrinsic safety during high-speed human–robot collaboration.

5.1.2. Methodologies: From Short to Continuous Fibers

To align TO with the anisotropic nature of CFRP, researchers have developed various systems. These methods range from optimizing short-fiber alignment to generating complex path planning for continuous fiber composites, and recently, they include the AI-driven path-planning method.

For SFRP, mechanical properties highly depend on bead orientation defined by printing parameters. Jiang et al. presented a fiber angle optimization method for SFRP produced using FFF. This method focuses on both the structural optimization and the fiber orientation (defined by print parameter). By aligning print paths with force directions significantly, mechanical stiffness is improved [124]. Similarly, Almeida Jr. et al. presented a concurrent framework to optimize both structure and orientation of chopped Carbon-Fiber-Reinforced Thermoplastics (e.g., Onyx). Confirmed via FFF, their study indicated that by simultaneously addressing material layout with fiber angles, the stiffness and strength of printed parts are enhanced compared to isotropic designs [121].

For CFRPCs, the challenge lies in maintaining fiber continuity along complex shapes. Fernandes et al. successfully integrated TO with fiber path planning for continuous carbon fiber composites. Although some post-processing was required, a 100% improvement of specific stiffness and a 50% weight reduction were observed compared to conventional directional laminates [116]. To bridge the gap between theoretical vector fields and the actual fiber printing path, Zhang et al. introduced a parallel topology optimization system. This system simultaneously optimizes topology, fiber volume fraction, and orientation under strength constraints, utilizing a non-equidistant fiber-path-planning method to generate printable toolpaths for beam structures [125].

Recent advancements also incorporate Artificial Intelligence to handle complex manufacturing constraints. Liu et al. proposed a co-optimization framework inspired by neural network, which simultaneously optimizes structural topology, curve layers, and path orientations. Physical experiments demonstrated that this integrated approach improved failure loads by up to 33.1% compared to conventional ones [126]. Similarly, Shahzad and Baur presented a topology and fiber orientation optimization framework tailored for the ADRRIFT 3D printing process. Manufacturing constraints were addressed, and the optimized design achieved a 50% fiber volume fraction, resulting in a 85% increase in stiffness, validating the numerical predictions [127].

5.1.3. Manufacturing Constraints and Limitations

Despite the advancements and current optimization with fiber print path planning, the transition from digital design to physical fabrication is hindered by strict characteristics. The main challenge is that the theoretical fiber paths often exceed the bending limits of carbon fiber. Zhang et al. found that if the turning angle is larger than 120° or the curvature radii smaller than 5 mm, it causes fiber breakage, misalignment, and twisting due to the excessive nozzle forces [128].

Similarly, even if the path is theoretically printable, the actual deposition process is affected by material behavior. Matsuzaki et al. analyzed the relationship between the designed and actual print radii. They demonstrated that larger fiber bundle size and tighter curvatures cause shrinking in actual printing due to fiber twisting. According to their work, 75% of the radius represents a critical failure where printing becomes impossible [129].

Beyond this, maintaining the global consistency of the fiber path still remains a challenge. Pan et al. mentioned that although streamlining strategies improve stiffness, they still tend to generate sharp angles and discontinuous regions with rapidly varying stress directions. The application of topology optimization often introduces excessive geometric changes that disrupt consistency [130]. Future algorithms combining paths must prioritize generating real continuous paths that avoid disrupting stress transmission, strictly eliminating high-curvature corners to prevent fiber breakage [131].

5.2. Special Structures

In addition to macro-scale topology optimization, the design of meso-scale structures plays a critical role in achieving functional goals for service robots. This section focuses on two architectural strategies enabled by 3D printing: thin-walled sandwich structures and lattice structures.

5.2.1. Thin-Walled and Sandwich Structures

Hollow sandwich and thin-walled rib structures (like honeycomb) typically consist of relatively thin face sheets separated by a thicker, lightweight core. Mechanically, the face sheets primarily carry tensile and compressive stresses, while the core resists shear stress. These structures offer high bending stiffness and strong resistance to buckling while minimizing overall mass [132]. In the context of 3D printing, the performance of these structures is determined by geometric parameters and path planning. Britto et al. determined that optimizing geometric parameters, especially increasing the wall thickness to only 1.6 mm, can significantly enhance the integrity of the structure. In this case, a peak compressive strength of 2122 MPa is achieved [133]. However, fabricating complex sandwich cores with continuous fibers remains challenging due to the need for continuous extrusion paths. To address this, Sugiyama et al. developed a support-free printing method for continuous-carbon-fiber sandwich structures. By applying a path-planning strategy based on fiber tension, they successfully printed complex core geometries continuously without support. Tests confirmed that the mechanical properties could be effectively adjusted by manipulating the core topology [134].

Beyond basic mechanics, complex structures can offer multiple functions. Li et al. fabricated novel thin-walled honeycomb hollow-pyramid sandwich structures using PLA filaments. This design achieved significant improvements in compressive strength (up to 12.5 MPa) with mechanical energy absorption, alongside effective microwave absorption [135]. Raghava and Chandra Reddy investigated hybrid structures combining 3D-printed carbon fiber filament cores with carbon- and glass-fiber-reinforced skins. By optimizing the filling patterns, these hybrid structures reached a maximum stress of 68 MPa [136].

For robotic applications, the superior bending stiffness of sandwich structures makes them highly suitable for powered exoskeletons and wearable systems. Thin-wall CFRP shells are capable of supporting the patient's weight and resisting actuator torques without adding burden mass, thereby directly extending battery life. Additionally, the multi-functionality of these structures, like microwave absorption, makes them ideal for delivery robots and inspection drones. In these scenarios, the shell can work as an electromagnetic shield to protect sensitive internal processors from external interference and physical impact.

5.2.2. Lattice and Cellular Structures

Lattice and cellular structures are widely adopted structures in engineering designs, offering numerous benefits like superior specific strength, high rigidity, and energy absorption. Widely applied in aerospace engineering, these structures are confirmed to bear load while minimizing weight [137]. The efficiency of these structures was investigated by Perween et al., who evaluated the function-based lattices. Cylindrical components containing cellular lattices with only 70% infill density exhibited outstanding strength and specific strength than fully printed ones. This demonstrates the potential of engineered cellular geometries to achieve lightweight, high-performance structures [138].

Gorguluarslan et al. introduced a framework for the design and non-linear analysis of lattice-based cellular structures. Confirmed via physical tests, the octet-frame unit was found to be the most effective structure for maximizing yield strength and energy absorption [139]. Singh et al. compared mechanical properties and vibrational properties of diamond, kelvin, and octa topologies. They revealed that while high-density octa lattice achieved the highest stiffness (174.95 MPa), the medium-density diamond topology offered the highest compression and vibration isolation [140]. These findings highlight that the selection of shapes should be tailored to the specific operational environment of the robots.

Recent research also integrated continuous carbon fiber into lattice cores to push performance limits. Türkoğlu et al. investigated the dynamic performance of sandwich panels featuring prismatic lattice cores made of continuous-fiber-reinforced polypropylene. They produced fully recyclable, ultra-lightweight structures, which present superior mechanical capacity, bearing ~270 kN in compression and ~240 kN in three-point bending. Notably, under dynamic loading, the peak force capability doubled to 450 kN [141]. Furthermore, Jin et al. investigated hybrid topological designs via FFF, achieving a 12.7-fold increase in elastic modulus compared to conventional lattices [142].

For robotics systems, lattice structures offer critical advantages in intrinsic safety and operational stability. In collaborative robots, the energy absorption of these structures enables structural links to eliminate impact energy, thereby mitigating injury risks during human–robot interactions. Simultaneously, for mobile platforms, the damping characteristics of specific structures isolate motor vibrations. This ensures stable operation and control accuracy while achieving significant weight reduction.

6. Applications in Service Robots: Case Study

To validate the materials and manufacturing strategies discussed in the previous section, the team from the Tsinghua University Future Laboratory designed and developed the "Tianhe" mobile catering service robot platform and the "Tianzuo" collaborative robotic arm (Figure 8). These systems represent the next generation of service robots designed for intelligent, emotional, and bionic interaction scenarios, mainly used in the catering service industry. Capable of providing contactless delivery of food and beverages (e.g., coffee, juice, meals) 24/7, these robots exemplify the strict requirements for intrinsic safety and energy efficiency outlined in Section 2 [85].

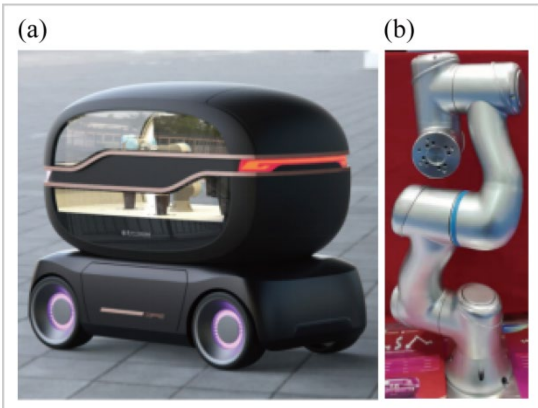

Figure 8. Service robot systems developed by the research team: (**a**) "Tianhe" mobile catering service robot platform; (**b**) "Tianzuo" collaborative manipulator [85].

6.1. Manufacturing Strategy

Consistent with the specific-stiffness criteria discussed in Section 3, the team adopted a hybrid manufacturing approach, selecting specific 3D printing technologies tailored to the functional requirements of different parts.

The curved shell of the mobile platform requires high dimensional accuracy and a smooth surface finish to ensure safe and comfortable human interaction. Consequently, it was printed using a large-scale 3D printing device SLA2400-DLC (Vistar (Xiamen) Industries Co., Xiamen, China) with ABS-like photosensitive resin. As mentioned in Section 4.1, SLA is capable of creating complex, organic curves with superior surface resolution, eliminating the need for expensive molds.

The six-axis robotic arm serves as the main moving component, where mass reduction is crucial to minimize the inertia. In this case, its shell was printed using the industrial-grade 3D printing device Stratasys Fortus 380mc with Nylon 12 Carbon-Fiber-Reinforced Thermoplastic material. As mentioned in Section 4.2, SFRP provides a superior specific stiffness, while maintaining flexibility to print complex, topology-optimized parts.

6.2. Structural Optimization and Performance

With the design freedom of 3D printing, the shell of the robotic arm was topology-optimized before fabrication, as discussed in Section 5.1, creating a highly integrated lightweight structure. The implementation of these advanced manufacturing technologies brings significant advantages. Firstly, the overall mass of the robotic arm structure was reduced by 30%. According to the dynamic principles in Section 2, this mass reduction directly lowers the kinetic energy during operation, significantly enhancing the intrinsic safety during potential collisions. Secondly, the reduced structural mass decreased the torque requirements for the motors. This directly lowered energy consumption and extended the operating period, meeting the efficiency goals of mobile service robots. Thirdly, by applying 3D printing, the number of shell components requiring assembly was reduced [85]. Thus, the R&D cycle was shortened and production cost was lowered, demonstrating that 3D-printed CFRP is a solution for small-batch production typical for the service robot industry.

7. Challenges

Driven by the global trend of population aging and increasing demand for automation, the widespread deployment of service robots has become a critical industry focus. This review identifies intrinsic safety, energy efficiency, and environmental adaptability as the three fundamental challenges hindering the deployment. These requirements create a physical conflict between high stiffness and lightweight design that conventional metallic materials cannot meet. Through quantitative analysis, Carbon-Fiber-Reinforced Polymer has been identified as a competitive solution, offering specific stiffness up to 10 times higher than metals. However, the application of CFRP has long been constrained by the geometric limitations and economic costs of traditional molding processes. 3D printing emerges as the critical solution, removing these barriers in traditional manufacturing. It fully leverages CFRP's potential by manufacturing complex, topology-optimized structures with paths tailored to the material's anisotropic nature.

8. Conclusions and Perspective

This review establishes a systematic, integrated framework for the lightweight design of CFRP service robot structures using additive manufacturing. By addressing the physical conflict between high stiffness and low mass, the following conclusions are drawn:

1. Specific stiffness is confirmed as the most appropriate performance criterion for robotic structural design. Unlike conventional metallic materials, CFRP offers a specific stiffness up to 10 times higher, fulfilling the intrinsic safety, energy efficiency, and environmental adaptability requirements of service robots collaborating with humans.
2. Among current 3D printing technologies, Fused Deposition Modeling (FDM) emerges as the most competitive manufacturing technique. By eliminating the geometric limitations and economic costs associated with conventional molds, it enables the rapid fabrication of complex service robot structures.
3. To leverage the full potential of 3D-printed CFRP, a concurrent design approach must be adopted. We highlight the importance of integrating material selection, structural design (topology optimization), and manufacturing (printing path) into an integrated optimization framework, moving away from a traditional sequential

engineering workflow. As demonstrated by the "Tianhe" and "Tianzuo" case studies, this concurrent approach achieved a 30% reduction in structural mass, validating the framework's effectiveness in ensuring reliability and intrinsic safety.

Furthermore, to promote the industrialization and capabilities of service robots, two primary challenges must be addressed. First, the industry may move toward multi-material 3D printing to integrate rigid CFRP load-bearing skeletons with compliant polymer skins. Mimicking biological bone-and-flesh structures, this approach combines high load capacity with safe human interaction. Second, attention must be paid to real-time processing quality. Future systems should integrate AI and ML to detect manufacturing defects in real time. Addressing these challenges is crucial for accelerating the large-scale industrialization of 3D-printed service robots.

Overall, this review provides both a critical synthesis of the current stage of the field and a forward-looking manufacturing roadmap, offering a practical guide for researchers and engineers working toward the next generation of reliable, safe, and efficient service robots.

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References

1. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Ageing 2020 Highlights*; United Nations: New York, NY, USA, 2020.
2. International Federation of Robotics (IFR). *World Robotics 2025—Service Robots*; IFR Statistical Department: Frankfurt, Germany, 2025.
3. Strategic Market Research. *Service Robotics Market Size Report 2024–2030*; Strategic Market Research: Sambalpur, India, 2025.
4. Lee, I. Service Robots: A Systematic Literature Review. *Electronics* **2021**, *10*, 2658. [CrossRef]
5. Mott, N.F. The Mechanical Properties of Metals. *Proc. Phys. Soc. Sect. B* **1951**, *64*, 729. [CrossRef]
6. Gibson, R.F. *Principles of Composite Material Mechanics*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2016.
7. Bechar, A.; Vigneault, C. Agricultural Robots for Field Operations: Concepts and Components. *Biosyst. Eng.* **2016**, *149*, 94–111. [CrossRef]
8. Dupont, P.E.; Nelson, B.J.; Goldfarb, M.; Hannaford, B.; Menciassi, A.; O'Malley, M.K.; Simaan, N.; Valdastri, P.; Yang, G.Z. A Decade Retrospective of Medical Robotics Research from 2010 to 2020. *Sci. Robot.* **2021**, *6*, eabi8017. [CrossRef] [PubMed]

9. Cifuentes, C.A.; Pinto, M.J.; Céspedes, N.; Múnera, M. Social Robots in Therapy and Care. *Curr. Robot. Rep.* **2020**, *1*, 59–74. [CrossRef]
10. Abdi, J.; Al-Hindawi, A.; Ng, T.; Vizcaychipi, M.P. Scoping Review on the Use of Socially Assistive Robot Technology in Elderly Care. *BMJ Open* **2018**, *8*, e018815. [CrossRef] [PubMed]
11. Kemp, C.C.; Edsinger, A.; Clever, H.M.; Matulevich, B. The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments. In Proceedings of the 2022 International Conference on Robotics and Automation, Philadelphia, PA, USA, 23–27 May 2022; pp. 3156–3163.
12. Dinesen, B.; Hansen, H.K.; Grønborg, G.B.; Dyrvig, A.K.; Leisted, S.D.; Stenstrup, H.; Schacksen, C.S.; Oestergaard, C. Use of a Social Robot (LOVOT) for Persons with Dementia: Exploratory Study. *JMIR Rehabil. Assist. Technol.* **2022**, *9*, e36505. [CrossRef]
13. Amazon Robotics. Amazon Unveils Titan, New Fulfillment Center Robot. Amazon News: Operations. 2023. Available online: https://www.aboutamazon.com/news/operations/amazon-unveils-titan-fulfillment-center-robot (accessed on 27 January 2026).
14. Amazon Robotics. Introducing Blue Jay and Project Eluna: Amazon's Latest Robotics and AI Technology. Amazon News: Operations. 2025. Available online: https://www.aboutamazon.com/news/operations/new-robots-amazon-fulfillment-agentic-ai (accessed on 27 January 2026).
15. Rivero-Moreno, Y.; Echevarria, S.; Vidal-Valderrama, C.; Pianetti, L.; Cordova-Guilarte, J.; Navarro-Gonzalez, J.; Acevedo-Rodríguez, J.; Dorado-Avila, G.; Osorio-Romero, L.; Carmen Chavez-Campos, C.; et al. Robotic Surgery: A Comprehensive Review of the Literature and Current Trends. *Cureus* **2023**, *15*, e42370. [CrossRef]
16. Intuitive Surgical. da Vinci Systems: Products and Services. Available online: https://www.intuitive.com/en-us/products-and-services/da-vinci (accessed on 27 January 2026).
17. Sankai, Y. HAL: Hybrid Assistive Limb Based on Cybernics. In *Robotics Research*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 25–34.
18. Zhao, C.; Fan, B.; Li, J.; Feng, Q. Agricultural Robots: Technology Progress, Challenges and Trends. *Smart Agric.* **2023**, *5*, 1–20. (In Chinese)
19. Carbon Robotics. LaserWeeder: Autonomous Laserweeding Robot. Available online: https://farming-revolution.com/ (accessed on 27 January 2026).
20. Gerhards, R.; Risser, P.; Spaeth, M.; Saile, M.; Peteinatos, G. A Comparison of Seven Innovative Robotic Weeding Systems and Reference Herbicide Strategies in Sugar Beet and Rapeseed. *Weed Res.* **2024**, *64*, 42–53. [CrossRef]
21. Dogtooth Technologies. Autonomous Fruit Picking Robots. Available online: https://dogtooth.tech/robots/ (accessed on 27 January 2026).
22. Tan, Y.; Liu, X.; Zhang, J.; Wang, Y.; Hu, Y. A Review of Research on Fruit and Vegetable Picking Robots Based on Deep Learning. *Sensors* **2025**, *25*, 3677. [CrossRef] [PubMed]
23. Xiong, Y.; Ge, Y.; Grimstad, L.; From, P.J. An Autonomous Strawberry-Harvesting Robot: Design, Development, Field Tests, and Ablation Analysis. *J. Field Robot.* **2020**, *37*, 202–224. [CrossRef]
24. Zinn, M.; Khatib, O.; Roth, B.; Salisbury, J.K. A New Actuation Approach for Human-Friendly Robot Design. *Int. J. Robot. Res.* **2004**, *23*, 379–398. [CrossRef]
25. Haddadin, S.; Albu-Schäffer, A.; Hirzinger, G. Safety Evaluation of Physical Human-Robot Interaction via Crash-Testing. *Robot. Sci. Syst.* **2009**, *3*, 217–224.
26. Gürgöze, G.; Türkoğlu, İ. A Novel Energy Consumption Model for Autonomous Mobile Robot. *Turk. J. Electr. Eng. Comput. Sci.* **2022**, *30*, 216–232. [CrossRef]
27. Hybart, R.; Villancio-Wolter, K.S.; Ferris, D.P. Metabolic Cost of Walking with Electromechanical Ankle Exoskeletons Under Proportional Myoelectric Control on a Treadmill and Outdoors. *PeerJ* **2023**, *11*, e15775. [CrossRef]
28. Keller, T.; Or, D. Farm Vehicles Approaching Weights of Sauropods Exceed Safe Mechanical Limits for Soil Functioning. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2117699119. [CrossRef]
29. Ashby, M.F. *Materials Selection in Mechanical Design*, 4th ed.; Butterworth-Heinemann: Oxford, UK, 2011.
30. Zhang, J.; Lin, G.; Vaidya, U.; Wang, H. Past, Present and Future Prospective of Global Carbon Fibre Composite Developments and Applications. *Compos. Part B Eng.* **2023**, *250*, 110463. [CrossRef]
31. Polygerinos, P.; Correll, N.; Morin, S.A.; Mosadegh, B.; Onal, C.D.; Petersen, K.; Cianchetti, M.; Tolley, M.T.; Shepherd, R.F. Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot Interaction. *Adv. Eng. Mater.* **2017**, *19*, 1700016. [CrossRef]
32. ResearchGate. Ashby Plot of Strength vs. Density for Engineering Materials. Available online: https://www.researchgate.net/figure/Ashby-plot-of-strength-vs-density-for-engineering-materials-Yield-strength-for-metals_fig4_269466137 (accessed on 9 March 2026).
33. Kaw, A.K. *Mechanics of Composite Materials*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2005.
34. Singh, J.; Kumar, M.; Kumar, S.; Mohapatra, S.K. Properties of Glass Fiber Hybrid Composites: A Review. *Mater. Today Proc.* **2017**, *4*, 9. [CrossRef]

35. El-Wazery, M.S.; El-Elamy, M.I.; Zoalfakar, S.H. Mechanical Properties of Glass Fiber Reinforced Polyester Composites. *Int. J. Appl. Sci. Eng.* **2017**, *14*, 121–131.
36. Srinivasa, P.R.; Pannirselvam, N.; Sekhar, T. Strength Properties of Glass Fibre Concrete. *ARPN J.* **2010**, *5*, 4.
37. Asmare, S.; Yoseph, B.; Jamir, T.M. Investigating the Impact Resistance of E-glass/Polyester Composite Materials in Variable Fiber-to-Matrix Weight Ratio Composition. *Cogent Eng.* **2023**, *10*, 2178110. [CrossRef]
38. Sajan, S.; Philip Selvaraj, D. A Review on Polymer Matrix Composite Materials and Their Applications. *Mater. Today Proc.* **2021**, *47*, 5493–5498. [CrossRef]
39. Du, B.; Li, Z.; Bai, H.; Li, Q.; Zheng, C.; Liu, J.; Qiu, F.; Fan, Z.; Hu, H.; Chen, L. Mechanical Property of Long Glass Fiber Reinforced Polypropylene Composite: From Material to Car Seat Frame and Bumper Beam. *Polymers* **2022**, *14*, 1814. [CrossRef]
40. Yan, L.; Chouw, N.; Jayaraman, K. Flax Fibre and Its Composites—A Review. *Compos. Part B Eng.* **2014**, *56*, 296–317. [CrossRef]
41. Sayeed, M.; Sayem, A.; Haider, J.; Akter, S.; Habib, M.; Rahman, H.; Shahinur, S. Assessing Mechanical Properties of Jute, Kenaf, and Pineapple Leaf Fiber-Reinforced Polypropylene Composites: Experiment and Modelling. *Polymers* **2023**, *15*, 830. [CrossRef]
42. Prabhakaran, S.; Krishnaraj, V.; Zitoune, R. Sound and Vibration Damping Properties of Flax Fiber Reinforced Composites. *Procedia Eng.* **2014**, *97*, 573–581. [CrossRef]
43. Fairlie, G.; Njuguna, J. Damping Properties of Flax/Carbon Hybrid Epoxy/Fibre-Reinforced Composites for Automotive Semi-structural Applications. *Fibers* **2020**, *8*, 64. [CrossRef]
44. Hegde, S.; Shenoy, B.S.; Chethan, K.N. Review on Carbon Fiber Reinforced Polymer (CFRP) and Their Mechanical Performance. *Mater. Today Proc.* **2019**, *19*, 658–662. [CrossRef]
45. Yanagimoto, J.; Ikeuchi, K. Sheet Forming Process of Carbon Fiber Reinforced Plastics for Lightweight Parts. *CIRP Ann.-Manuf. Technol.* **2012**, *61*, 247–250. [CrossRef]
46. Fan, X. Application Status and Development Trend of Carbon Fiber Composites. *Chem. Ind.* **2019**, *37*, 12–16. (In Chinese)
47. Pierson, H.A.; Celik, E.; Abbott, A.; Jarnette, H.D.; Gutierrez, L.S.; Johnson, K.; Koerner, H.; Baur, J.W. Mechanical Properties of Printed Epoxy-Carbon Fiber Composites. *Exp. Mech.* **2019**, *59*, 843–857. [CrossRef]
48. Khozeimeh, M.A.; Fotouhi, R.; Moazed, R. Static and Vibration Analyses of a Composite CFRP Robot Manipulator. *J. Compos. Sci.* **2022**, *6*, 196. [CrossRef]
49. Karim, M.A.; Abdullah, M.Z.; Deifalla, A.F.; Azab, M.; Waqar, A. An Assessment of the Processing Parameters and Application of Fibre-Reinforced Polymers (FRPs) in the Petroleum and Natural Gas Industries: A Review. *Results Eng.* **2023**, *18*, 101091. [CrossRef]
50. Diniță, A.; Ripeanu, R.G.; Ilincă, C.N.; Cursaru, D.; Matei, D.; Naim, R.I.; Tănase, M.; Portoacă, A.I. Advancements in Fiber-Reinforced Polymer Composites: A Comprehensive Analysis. *Polymers* **2024**, *16*, 2.
51. Bîrcă, A.; Gherasim, O.; Grumezescu, V.; Grumezescu, A.M. Introduction in Thermoplastic and Thermosetting Polymers. In *Materials for Biomedical Engineering*; Elsevier: Amsterdam, The Netherlands, 2019. [CrossRef]
52. AddComposites. Fiber-Reinforced Plastics Composites—Thermoplastic and Thermoset Resins. Available online: https://www.addcomposites.com/post/thermoplastic-thermoset-resins-frp-composites (accessed on 29 January 2026).
53. Mohammadi, H.; Ahmad, Z.; Mazlan, S.A.; Johari, M.A.F.; Siebert, G.; Petrů, M.; Koloor, S.S.R. Lightweight Glass Fiber-Reinforced Polymer Composite for Automotive Bumper Applications: A Review. *Polymers* **2023**, *15*, 193.
54. Belingardi, G.; Koricho, E.G.; Martorana, B. Implementation of composite and recyclable thermoplastic materials for automotive bumper subsystem. *Int. J. Automot. Compos.* **2014**, *1*, 67–89. [CrossRef]
55. Abbood, I.S.; Odaa, S.A.; Hasan, K.F.; Jasim, M.A. Properties Evaluation of Fiber Reinforced Polymers and Their Constituent Materials Used in Structures—A Review. *Mater. Today Proc.* **2021**, *43*, 1003–1008.
56. Ahmed, A.; Guo, S.; Zhang, Z.; Shi, C.; Zhu, D. A Review on Durability of Fiber Reinforced Polymer (FRP) Bars Reinforced Seawater Sea Sand Concrete. *Constr. Build. Mater.* **2020**, *256*, 119484. [CrossRef]
57. Vigneshwaran, S.; Sundarakannan, R.; John, K.M.; Johnson, R.D.J.; Prasath, K.A.; Ajith, S.; Arumugaprabu, V.; Uthayakumar, M. Recent Advancement in the Natural Fiber Polymer Composites: A Comprehensive Review. *J. Clean. Prod.* **2020**, *277*, 124109. [CrossRef]
58. Mugahed Amran, Y.H.; Alyousef, R.; Rashid, R.S.M.; Alabduljabbar, H.; Hung, C.-C. Properties and Applications of FRP in Strengthening RC Structures: A Review. *Structures* **2018**, *16*, 208–238. [CrossRef]
59. Srinivas, K.; Lakshumu Naidu, A.; Raju Bahubalendruni, M.V.A. A Review on Chemical and Mechanical Properties of Natural Fiber Reinforced Polymer Composites. *Int. J. Perform. Eng.* **2017**, *13*, 189–200. [CrossRef]
60. Ozkan, D.; Gok, M.S.; Karaoglanli, A.C. Carbon Fiber Reinforced Polymer (CFRP) Composite Materials, Their Characteristic Properties, Industrial Application Areas and Their Machinability. In *Structured/Sandwich Composites*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 235–253.
61. Zheng, H.; Zhu, S.; Chen, L.; Wang, L.; Zhang, H.; Wang, P.; Sun, K.; Wang, H.; Liu, C. 3D Printing Continuous Fiber Reinforced Polymers: A Review of Material Selection, Process, and Mechanics-Function Integration for Targeted Applications. *Polymers* **2025**, *17*, 1601. [CrossRef]

62. Mortazavian, S.; Fatemi, A. Effects of Fiber Orientation and Anisotropy on Tensile Strength and Elastic Modulus of Short Fiber Reinforced Polymer Composites. *Compos. Part B Eng.* **2015**, *72*, 116–129. [CrossRef]
63. Jiang, D.; Smith, D.E. Anisotropic Mechanical Properties of Oriented Carbon Fiber Filled Polymer Composites Produced with Fused Filament Fabrication. *Addit. Manuf.* **2017**, *18*, 84–94. [CrossRef]
64. Zhang, H.; Wang, S.; Zhang, K.; Wu., J.; Li, A.; Liu, J.; Yang, D. 3D Printing of Continuous Carbon Fibre Reinforced Polymer Composites with Optimised Structural Topology and Fibre Orientation. *Compos. Struct.* **2023**, *313*, 116914. [CrossRef]
65. Zheng, H.; Zhang, W.; Li, B.; Zhu, J.; Wang, C.; Song, G.; Wu, G.; Yang, X.; Huang, Y.; Ma, L. Recent Advances of Interphases in Carbon Fiber-reinforced Polymer Composites: A Review. *Compos. Part B Eng.* **2022**, *233*, 109639.
66. Alshammari, B.A.; Alsuhybani, M.S.; Almushaikeh, A.M.; Alotaibi, B.M.; Alenad, A.M.; Alqahtani, N.B.; Alharbi, A.G. Comprehensive Review of the Properties and Modifications of Carbon Fiber-Reinforced Thermoplastic Composites. *Polymers* **2021**, *13*, 2474. [CrossRef]
67. Bhatt, A.T.; Gohil, P.P.; Chaudhary, V. Primary Manufacturing Processes for Fiber Reinforced Composites: History, Development & Future Research Trends. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *330*, 012107.
68. Rajak, D.K.; Wagh, P.H.; Linul, E. Manufacturing Technologies of Carbon/Glass Fiber-Reinforced Polymer Composites and Their Properties: A Review. *Polymers* **2021**, *13*, 3721. [CrossRef] [PubMed]
69. Sandberg, M.; Yuksel, O.; Comminal, R.B.; Sonne, M.R.; Jabbari, M.; Larsen, M.; Salling, F.B.; Baran, I.; Spangenberg, J.; Hattel, J.H. Numerical Modeling of the Mechanics of Pultrusion. In *Mechanics of Materials in Modern Manufacturing Methods and Processing Techniques*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 173–195.
70. Ashrith, H.S.; Jeevan, T.P.; Xu, J. A Review on the Fabrication and Mechanical Characterization of Fibrous Composites for Engineering Applications. *J. Compos. Sci.* **2023**, *7*, 252. [CrossRef]
71. European Pultrusion Technology Association (EPTA). Pultrusion. Available online: https://pultruders.dev.neomesh.de/pultrusion/2-technical-principles/ (accessed on 9 March 2026).
72. Starr, T. *Pultrusion for Engineers*; Taylor & Francis: Abingdon, UK, 2000.
73. Li, X. Development and Application of Fiber Reinforced Ceramic Matrix Composites. *Silicon Val.* **2010**, *3*, 116. (In Chinese)
74. Chen, J.; Li, Y.; Liu, W.; Song, Q.; Yang, Y.; Lin, Z. Aviation Development Status of In-Situ Forming Technology for Continuous Fiber Reinforced Thermoplastic Resin Matrix Composites via Automated Placement. *Acta Mater. Compos. Sin.* **2019**, *36*, 784–794. (In Chinese)
75. Rajak, D.K.; Pagar, D.D.; Kumar, R.; Pruncu, C.I. Recent Progress of Reinforcement Materials: A Comprehensive Overview of Composite Materials. *J. Mater. Res. Technol.* **2019**, *8*, 6354–6374. [CrossRef]
76. Howell, D.; Fukumoto, S. *Compression Molding of Long Chopped Fiber Thermoplastic Composites*; Society of Plastics Engineers: Danbury, CT, USA, 2014.
77. *ISO/PRF 17296-1*; Additive Manufacturing—General Principles—Part 1: Terminology. International Organization for Standardization: Geneva, Switzerland, 2015.
78. Tofail, S.A.M.; Koumoulos, E.P.; Bandyopadhyay, A.; Bose, S.; O'Donoghue, L.; Charitidis, C. Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities. *Mater. Today* **2018**, *21*, 22–37. [CrossRef]
79. Low, Z.X.; Chua, Y.T.; Ray, B.M.; Mattia, D.; Metcalfe, I.S.; Patterson, D.A. Perspective on 3D Printing of Separation Membranes and Comparison to Related Unconventional Fabrication Techniques. *J. Membr. Sci.* **2016**, *523*, 596–613. [CrossRef]
80. Gokhare, V.G.; Raut, D.N.; Shinde, D.K. A Review Paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing. *Int. J. Eng. Res. Technol.* **2017**, *6*, 953–958.
81. Bai, S.; Zhang, S.; Zhong, S.; Fang, M.; Zhao, R. 3D Printing and Its Application in Stomatology (Part 1): The Working Principle of 3D Printing Technology. *J. Pract. Stomatol.* **2022**, *38*, 136–140. (In Chinese)
82. Aimar, A.; Palermo, A.; Innocenti, B. The Role of 3D Printing in Medical Applications: A State of the Art. *J. Healthc. Eng.* **2019**, *2019*, 5340616. [CrossRef]
83. Di Prima, M.; Coburn, J.; Hwang, D.; Kelly, J.; Khairuzzaman, A.; Ricles, L. Additively Manufactured Medical Products—The FDA Perspective. *3D Print. Med.* **2016**, *2*, 1. [CrossRef]
84. Shahrubudin, N.; Lee, T.C.; Ramlan, R. An Overview on 3D Printing Technology: Technological, Materials, and Applications. *Procedia Manuf.* **2019**, *35*, 1286–1296. [CrossRef]
85. Chen, H.; Liu, G.; Wang, X.; Le, H. Application and Prospect of Lightweight Composite Materials and 3D Printing Technology in Service Robots. *J. Eng. Stud.* **2022**, *14*, 30–39. (In Chinese) [CrossRef]
86. Zong, R.; Li, H.; Ge, G.; Wang, J.; Zhang, N.; Xu, Z. Application of 3D Printing Technology in the Automotive Industry. *Automob. Appl. Technol.* **2022**, *47*, 195–199. (In Chinese)
87. Zhao, Y.; Liu, C.; Xu, C.; Li, W. Development Status of 3D Printing Technology and Equipment. *Mech. Res. Appl.* **2021**, *34*, 224–227. (In Chinese)
88. Cheng, J.; Zhang, Y.; Lu, J. Brief Discussion on the Application and Development of 3D Printing Technology. *Mech. Electr. Inf.* **2018**, *27*, 96–99. (In Chinese)

89. Zhang, W. Research and Application of 3D Printing Materials. *Met. World* **2021**, *1*, 12–19. (In Chinese)
90. Adil, S.; Lazoglu, I. A Review on Additive Manufacturing of Carbon Fiber-reinforced Polymers: Current Methods, Materials, Mechanical Properties, Applications and Challenges. *J. Appl. Polym. Sci.* **2022**, *139*, 52026.
91. Goh, G.D.; Yap, Y.L.; Agarwala, S.; Yeong, W.Y. Recent Progress in Additive Manufacturing of Fiber Reinforced Polymer Composites. *Adv. Mater. Technol.* **2019**, *4*, 1800271.
92. Ning, F.; Cong, W.; Qiu, J.; Wei, J.; Wang, S. Additive Manufacturing of Carbon Fiber Reinforced Thermoplastic Composites Using Fused Deposition Modeling. *Compos. Part B Eng.* **2015**, *80*, 369–378.
93. Carbon Elie. Short vs. Long Carbon Fiber Reinforced Thermoplastics. Available online: https://www.carbonele.com/news/short-vs-long-carbon-fiber-reinforced-thermoplastics/ (accessed on 27 January 2026).
94. Kumar, S.; Yoo, D.H.; Song, J.S.; Kim, H.S. A Critical Review of the Past, Present, and Future of 3D Printing for Continuous and Short Fiber Composites. *Compos. Struct.* **2026**, *376*, 119819. [CrossRef]
95. Nur, S.; Ramli, R.; Teknikal, U. The Effect of Alkaline Treatment and Fiber Length on Pineapple Leaf Fiber Reinforced Poly Lactic Acid Biocomposite. *J. Teknol.* **2017**, *79*, 111–115. [CrossRef]
96. Chung, D.D.L. *Carbon Composites*, 2nd ed.; Butterworth-Heinemann: Oxford, UK, 2017.
97. Ivey, M.; Melenka, G.W.; Carey, J.P.; Ayranci, C. Characterizing Short-fiber-reinforced Composites Produced Using Additive Manufacturing. *Adv. Manuf. Polym. Compos. Sci.* **2017**, *3*, 81–91. [CrossRef]
98. Tolcha, D.A.; Woldemichael, D.E. Development and Characterization of Short Glass Fiber Reinforced-waste Plastic Composite Filaments for 3D Printing Applications. *Heliyon* **2023**, *9*, e22333. [CrossRef] [PubMed]
99. Toth, C.; Molnar, K.; Virág, A. Short Fiber Reinforcement in Material Extrusion 3D Printing: A Meta-analysis Review with Insights into Sustainable Alternatives. *Polym. Compos.* **2025**, *46*, S9–S47. [CrossRef]
100. Liao, G.; Li, Z.; Cheng, Y.; Xu, D.; Zhu, D.; Jiang, S.; Guo, J.; Chen, X.; Xu, G.; Zhu, Y. Proerties of Oriented Carbon Fiber/Polyamide 12 Composite Parts Fabricated by Fused Deposition Modeling. *J. Alloys Compd.* **2018**, *739*, 222–229.
101. Zhang, W.; Cotton, C.; Sun, J.; Heider, D.; Gu, B.; Sun, B.; Chou, T.W. Interfacial Bonding Strength of Short Carbon Fiber/Acrylonitrile-butadiene-styrene Composites Fabricated by Fused Deposition Modeling. *Compos. Part B Eng.* **2018**, *137*, 51–59. [CrossRef]
102. Yang, Z.; Yang, Z.; Chen, H.; Yan, W. 3D Printing of Short Fiber Reinforced Composites via Material Extrusion: Fiber Breakage. *Addit. Manuf.* **2022**, *58*, 103067. [CrossRef]
103. 3D Printing and Application of Carbon Fiber Reinforced Polymer Composites. Available online: https://zhuanlan.zhihu.com/p/48343671 (accessed on 14 December 2021). (In Chinese)
104. Wang, H.; Han, Y.; Lu, J.; Tang, S.; Fan, H.; Xia, Y.; Xiang, Z.; Gong, C.; Wang, R.; Chen, S.; et al. Additive Manufacturing of Continuous Fiber Reinforced Composites with Variable Volume Fractions. *Compos. Part A Appl. Sci. Manuf.* **2024**, *187*, 108504. [CrossRef]
105. Zhang, C.; Fu, K. Additively Manufactured 3D Short Carbon Fiber Scaffold for Thermoset Composites. *MRS Commun.* **2024**, *14*, 520–526. [CrossRef]
106. Ramsteiner, F.; Theysohn, R. The Influence of Fibre Diameter on the Tensile Behaviour of Short-glass-fibre Reinforced Polymers. *Compos. Sci. Technol.* **1985**, *24*, 231–240. [CrossRef]
107. Kurtz, S.M. Continuous CFR PEEK. In *PEEK Biomaterials Handbook*, 2nd ed.; William Andrew: Norwich, NY, USA, 2019.
108. Abualbandora, T.A.; Alshneeqat, M.G.; Mourad, A.I. Impact of 3D Printing Parameters of Short Carbon Fiber Reinforced Polymer CFRP on the Mechanical and Failure Performance: Review and Future Perspective. *Next Mater.* **2025**, *8*, 100645. [CrossRef]
109. Naranjo-Lozada, J.; Ahuett-Garza, H.; Orta-Castañón, P.; Verbeeten, W.M.H.; Sáiz-Rodríguez, D. Tensile Properties and Failure Behavior of Chopped and Continuous Carbon Fiber Composites Produced by Additive Manufacturing. *Addit. Manuf.* **2019**, *26*, 227–241. [CrossRef]
110. Isobe, T.; Tanaka, T.; Nomura, T.; Yuasa, R. Comparison of Strength of 3D Printing Objects Using Short Fiber and Continuous Long Fiber. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *406*, 012042. [CrossRef]
111. Uşun, A.; Vatandaş, B.B.; Gümrük, R. Enhanced Mechanical Properties of Continuous Carbon Fiber Reinforced Polyether-ether-ketone Composites via Infrared Preheating and High Fiber Volume Fraction. *Addit. Manuf.* **2024**, *89*, 104289. [CrossRef]
112. Parandoush, P.; Zhou, C.; Lin, D. 3D Printing of Ultrahigh Strength Continuous Carbon Fiber Composites. *Adv. Eng. Mater.* **2019**, *21*, 1800622. [CrossRef]
113. Kabir, S.M.F.; Mathur, K.; Seyam, A.F.M. A Critical Review on 3D Printed Continuous Fiber-reinforced Composites: History, Mechanism, Materials and Properties. *Compos. Struct.* **2020**, *232*, 111476. [CrossRef]
114. Zhang, Y.; Qiao, J.; Zhang, G.; Li, Y.; Li, L. Prediction of Deformation and Failure Behavior of Continuous Fiber Reinforced Composite Fabricated by Additive Manufacturing. *Compos. Struct.* **2021**, *265*, 113738. [CrossRef]
115. Cheng, P.; Peng, Y.; Li, S.; Rao, Y.; Le Duigou, A.; Wang, K.; Ahzi, S. 3D Printed Continuous Fiber Reinforced Composite Lightweight Structures: A Review and Outlook. *Compos. Part B Eng.* **2023**, *250*, 110450. [CrossRef]

116. Fernandes, R.R.; van de Werken, N.; Koirala, P.; Yap, T.; Tamijani, A.Y.; Tehrani, M. Experimental Investigation of Additively Manufactured Continuous Fiber Reinforced Composite Parts with Optimized Topology and Fiber Paths. *Addit. Manuf.* **2021**, *45*, 102056. [CrossRef]
117. Vantyghem, G.; De Corte, W.; Shakour, E.; Amir, O. 3D Printing of a Post-tensioned Concrete Girder Designed by Topology Optimization. *Autom. Constr.* **2020**, *112*, 103084. [CrossRef]
118. Zhu, J.H.; Zhang, W.H.; Xia, L. Topology Optimization in Aircraft and Aerospace Structures Design. *Arch. Comput. Methods Eng.* **2015**, *23*, 595–622. [CrossRef]
119. Rozvany, G. The SIMP Method in Topology Optimization-theoretical Background, Advantages and New Applications. In Proceedings of the 8th Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, USA, 6–8 September 2000.
120. Sigmund, O. A 99 Line Topology Optimization Code Written in Matlab. *Struct. Multidiscip. Optim.* **2001**, *21*, 120–127. [CrossRef]
121. Almeida, J.H.S., Jr.; Christoff, B.G.; Tita, V.; St-Pierre, L. A Concurrent Fibre Orientation and Topology Optimisation Framework for 3D-printed Fibre-reinforced Composites. *Compos. Part B Eng.* **2021**, *222*, 109052. [CrossRef]
122. Ansys. What Is Topology Optimization? Available online: https://www.ansys.com/simulation-topics/what-is-topology-optimization (accessed on 2 February 2026).
123. Luo, Y.; Hewson, R.; Santer, M. Topology Optimisation of Fibre-reinforced Composites Accounting for Buckling Resistance and Manufacturability. *Struct. Multidiscip. Optim.* **2024**, *67*, 145. [CrossRef]
124. Jiang, D.; Hoglund, R.; Smith, D.E. Continuous Fiber Angle Topology Optimization for Polymer Composite Deposition Additive Manufacturing Applications. *Fibers* **2019**, *7*, 14. [CrossRef]
125. Zhang, F.; Li, B.; Wo, W.; Hu, X.; Chang, M.; Jin, P. Topology Design of 3D Printing Continuous Fiber-Reinforced Structure Considering Strength and Non-Equidistant Fiber. *Adv. Eng. Mater.* **2023**, *26*, 2301340. [CrossRef]
126. Liu, T.; Zhang, T.; Chen, Y.; Wang, W.; Jiang, Y.; Huang, Y.; Wang, C.C.L. Neural Co-Optimization of Structural Topology, Manufacturable Layers, and Path Orientations for Fiber-Reinforced Composites. *ACM Trans. Graph.* **2025**, *44*, 128. [CrossRef]
127. Shahzad, A.; Baur, J. Additive Manufacturing and Mechanical Testing of Topology-Optimized Continuous Carbon Fiber Reinforced Thermosetting Composites. In Proceedings of the SAMPE 2025 Conference and Exhibition, Indianapolis, IN, USA, 19–22 May 2025. [CrossRef]
128. Zhang, H.; Chen, J.; Yang, D. Fibre Misalignment and Breakage in 3D Printing of Continuous Carbon Fibre Reinforced Thermoplastic Composites. *Addit. Manuf.* **2021**, *38*, 101775. [CrossRef]
129. Matsuzaki, R.; Nakamura, T.; Sugiyama, K.; Ueda, M.; Todoroki, A.; Hirano, Y.; Yamagata, Y. Effects of Set Curvature and Fiber Bundle Size on the Printed Radius of Curvature by a Continuous Carbon Fiber Composite 3D Printer. *Addit. Manuf.* **2018**, *24*, 93–102. [CrossRef]
130. Pan, J.; Liu, F.; Wang, D.; Ye, M. Reinforcement Learning-Based Path Planning Method for 3D Printing of Continuous Fiber Reinforced Thermoplastic Composites. *SSRN Electron. J.* **2024**, 5935215.
131. Wang, T.; Li, N.; Link, G.; Jelonnek, J.; Fleischer, J.; Dittus, J.; Kupzik, D. Load-dependent Path Planning Method for 3D Printing of Continuous Fiber Reinforced Plastics. *Compos. Part A Appl. Sci. Manuf.* **2021**, *140*, 106181.
132. 3D Science Valley. Four Approaches to Achieving Lightweighting via 3D Printing. Available online: http://www.3dsciencevalley.com/?p=7187 (accessed on 14 January 2026). (In Chinese)
133. Britto, J.J.J.; Vasanthanathan, A.; Krishnasamy, S.; Amudhan, K. Mechanical Property Study of 3D Printed Honeycomb Structures with Carbon Fiber Reinforcement: A Finite Element Analysis and Experimental Approach. *Discov. Mater.* **2025**, *5*, 104. [CrossRef]
134. Sugiyama, K.; Matsuzaki, R.; Ueda, M.; Todoroki, A.; Hirano, Y. 3D Printing of Composite Sandwich Structures Using Continuous Carbon Fiber and Fiber Tension. *Compos. Part A Appl. Sci. Manuf.* **2018**, *113*, 114–121. [CrossRef]
135. Li, Q.; Wang, Z.; Wang, X.; Wang, Y.; Yang, J. The 3D Printing of Novel Honeycomb–Hollow Pyramid Sandwich Structures for Microwave and Mechanical Energy Absorption. *Polymers* **2023**, *15*, 4719. [CrossRef]
136. Raghava, P.M.; Chandra Reddy, G.J. 3D-Printed Lightweight Sandwich Structures with Carbon-fibre-reinforced Polymer Skins and Building-fibre-reinforced Polymer Core: A Comparative Study. *Smart Mater. Methods* **2025**, *2*, 20–38.
137. Reddy, A.H.; Davuluri, S.; Boyina, D. 3D Printed Lattice Structures: A Brief Review. In Proceedings of the 2020 IEEE 10th International Conference Nanomaterials: Applications & Properties (NAP), Virtual, 9–13 November 2020.
138. Perween, S.; Fahad, M.; Khan, M.A. Systematic Experimental Evaluation of Function Based Cellular Lattice Structure Manufactured by 3D Printing. *Appl. Sci.* **2021**, *11*, 10489. [CrossRef]
139. Gorguluarslan, R.M.; Gandhi, U.N.; Mandapati, R.; Choi, S.K. Design and Fabrication of Periodic Lattice-based Cellular Structures. *Comput. Aided Des. Appl.* **2016**, *13*, 50–62.
140. Singh, G.; Singh, J.; Singh, N.; Ilenia, F.; Francesco, C.; Pulak, P. Effect of Unit Cell Shape and Structure Volume Fraction on the Mechanical and Vibration Properties of 3D Printed Lattice Structures. *J. Thermoplast. Compos. Mater.* **2023**, *37*, 1841–1858. [CrossRef]

141. Türkoğlu, İ.K.; Bayram, T.; Yazıcı, M. Mechanical Properties of 3D Printed Continuous Carbon Fiber/Polypropylene Lattice Core Composite Sandwich Structure. *Uludağ Univ. J. Fac. Eng.* **2024**, *29*, 863–880.
142. Jin, L.; Shi, J.; Chen, Z.; Wang, Z.; Zhi, Y.; Yang, L.; Xiao, X. In-Plane Compression Properties of Continuous Carbon-Fiber-Reinforced Composite Hybrid Lattice Structures by Additive Manufacturing. *Polymers* **2024**, *16*, 1882. [CrossRef]