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Additive manufacturing for space applications: A review of materials, methods, and future frontiers

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ABSTRACT

Additive manufacturing (AM), globally referred to as 3D printing, is a highly flexible manufacturing method that enables the design and creation of complex geometries with ease. This review article comprehensively examines the materials, methods, and applications of AM specifically for the space sector, while identifying current research gaps and proposing future directions. The primary advantages of AM over conventional subtractive manufacturing for space implementations include economic efficiency, unparalleled design freedom, high customizability, tailor-made production, and the ability to process a wide range of materials including metals, polymers, composites, and ceramics. The article focuses on space-grade materials such as high-performance alloys, polymers, and ceramics used in applications ranging from electronic equipment to propulsion systems. It provides a detailed analysis of prevalent metal AM techniques like powder bed fusion and directed energy deposition, as well as non-metal methods including used deposition modeling and selective laser sintering. Through specific case studies, it demonstrates how AM enables part consolidation, weight reduction, and the production of multifunctional components with integrated capabilities. This review will help readers comprehend current trends in space additive manufacturing and understand its future potential in next-generation space applications, from in-situ manufacturing to the realization of fully additively manufactured spacecraft.

1. Introduction

Additive manufacturing (AM) methods are widely adopted for aerospace areas like rockets, in-space electronics, aircraft, and satellites. The aerospace sector is growing day by day, and the demand for new manufacturing methods to produce more accurate machines, electronics, or machine parts is of high order [1]. Additively manufactured drones and aircraft are widely used for surveillance and military applications, driving global research efforts towards developing sustainable and cost-effective manufacturing solutions. Formerly, subtractive manufacturing methods like molding, casting, machining, and joining were widely used for aerospace fabrication processes [2]. As the name suggests, subtractive manufacturing is a time-consuming method that produces significant waste and is not economical [2]. These methods also have limitations in producing complex designs. In contrast, additive manufacturing is quite the opposite of the former method, as it can produce complex shapes with ease, requires no machining processes, and allows for easy replication of the same structure with high accuracy. Moreover, the AM method is more economical and eco-friendlier than subtractive manufacturing methods [3].

There are numerous objectives researchers must consider when implementing a manufacturing method for the aerospace industry. The product should be lightweight to reduce fuel consumption and enable the production of economic products with higher performance. The

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complexity of product design and manufacturing methods presents difficulties in conventional manufacturing, where producing complex parts requires tedious, time-consuming, and non-economical fabrication processes; these problems can be well addressed by adopting additive manufacturing methods [4]. The performance and safety of the designed product are paramount, and AM helps fabricate single units that perform multiple tasks, making safety examinations easier compared to assembled units. The ability to produce multiple replications of the same product with high precision is another significant advantage of AM, facilitating easy replacement of damaged components. Finally, once parameters and designs are fixed, the AM production process is simple and saves time by eliminating multiple fabrication processes [5]. However, all parameters must be optimized for specific aerospace applications before manufacturing. In the drive to continuously improve efficiency through cost reduction, lead time reduction, and mass reduction of flight components, the industry is increasingly using high-performance materials with complex designs, all within reasonable cost and schedule constraints to meet commercial or mission requirements. While traditional manufacturing systems have been developed over decades to accommodate these aerospace design objectives, AM will continue to profoundly impact design and manufacturing. This digital transformation, often touted as Industry 4.0, is expected to increase its market size in the aerospace sector to $3.187 billion by 2025 with an average compound annual growth rate (CAGR) of 20.24 % [6].

Unlike conventional subtractive manufacturing techniques, additive manufacturing utilizes a layer-by-layer approach based on a common feedstock, typically powder or wire, which is melted or fused by a heat source and solidifies based on a digitally defined trajectory to produce the final geometry [7,8]. The advantages of AM for aerospace components include reduced lead time and associated cost, the ability to design and manufacture complex geometries that enable lightweighting, consolidation of multiple components, and performance improvements within cost and timeline constraints, thus offering improved programmatic and technical risk management [9,10]. By utilizing the design freedom of metal AM, it is possible to optimize material distribution to reduce mass while maintaining mechanical and other performance requirements, and to combine components, reducing risk, cost, and potential failure modes across joints. Additionally, enhanced performance is possible by designing complex parts with interior features like conformal cooling channels on combustion chambers or turbine blades, which were previously impossible to manufacture [11,12]. While reduced lead times are a present main driver for AM adoption in aerospace, specific manufacturing scenarios provide distinct advantages over traditional manufacturing, as will be discussed. This article aims to review technical papers focused on the materials, methods, and applications of additive manufacturing in space, identify research gaps, and propose future scopes for AM in the space sector. The review will help readers comprehend the current trends in space additive manufacturing methods, materials, and applications, and understand its future potential in next-generation space missions.

2. Design imperatives and opportunities for AM in space

2.1. Topology optimization for mass reduction and high packing ratios

A primary consideration when selecting components for the space sector is achieving a high strength-to-weight ratio to enhance fuel efficiency and reduce emissions. This necessitates that a part must be lightweight, satisfy all reliability and safety measures, and simultaneously be strong enough to withstand extreme space pressures. Additive manufacturing fulfills this imperative through its freeform fabrication ability, enabling the production of complex, lightweight structures that meet these stringent requirements [13]. A prime example is the magneto-optical trap chamber prototype, shown in Fig. 1 [14], which is designed for use in spacecraft. Developed by Added Scientific in collaboration with quantum physicists at the Universities of Nottingham and Sussex, UK, this robust ultrahigh-vacuum device has a mass of just 245 g, demonstrating the significant mass savings achievable with AM [15].

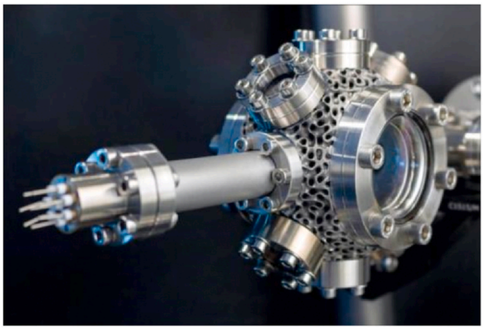

Fig. 1. Magneto-optical trap chamber prototype. Adapted with permission from Ref. [14]. Copyright 2021 Cooper et al.

Fig. 2. Light weight lattice structure. Adapted from Ref. [14]. Copyright 2021 Cooper et al.

A key strategy for achieving such weight reduction is the use of intricate internal lattice structures. These lattices, often based on matrix-based gyroid designs, are incorporated into the core of components to drastically reduce their overall mass while crucially maintaining structural stiffness and performance [16]. An example of such a lightweight lattice used in a vacuum chamber's internal core is presented in Fig. 2 [14]. In conventional subtractive manufacturing processes, designing complex structures was constrained by the need to divide a large assembly into smaller, manufacturable parts. Each unit would be manufactured separately and assembled using fasteners or welding [17]. AM methods overcome this limitation by enabling the fabrication of complex structures as consolidated single parts. For space-related frame structures, a key design objective is to maximize the packing ratio, or the efficient use of internal space. To achieve this, topology optimization is widely adopted [18]. This algorithmic approach allows for the design of highly efficient structures that meet performance requirements with minimal material usage. Using advanced software, optimized lattice materials and lightweight structures can be designed and their production costs, mechanical performance, and lifespan can be predicted for space applications [19,20].

The process of topology optimization is illustrated in the redesign of a spacecraft bracket. Fig. 3 shows the original bracket design [21], which must bear mechanical forces and thermal stress loads from temperature fields.

The optimization process begins by defining the design space and identifying non-designable areas, as shown in the geometric model in Fig. 4. The topology optimization algorithm then generates an optimal material layout within these constraints, resulting in a design that is both lighter and stronger than the original [22].

2.2. Part consolidation for enhanced reliability and efficiency

Part consolidation (PC) represents one of the most significant

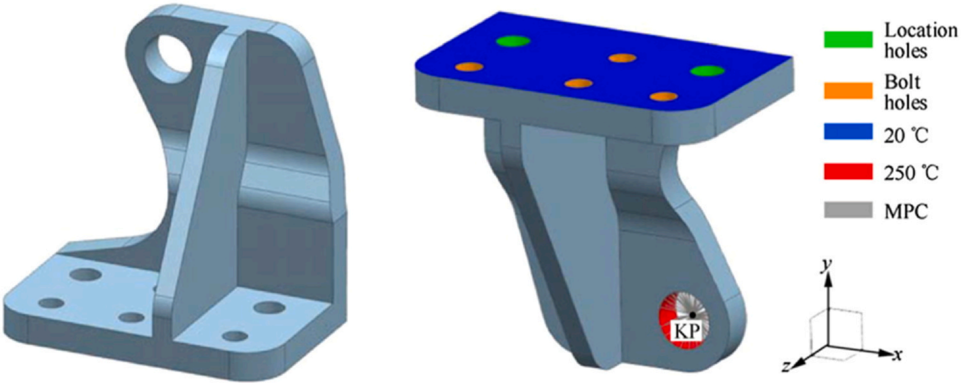

Fig. 3. Original spacecraft bracket design. Adapted from Ref. [21]. Copyright 2019 Chinese Society of Aeronautics and Astronautics.

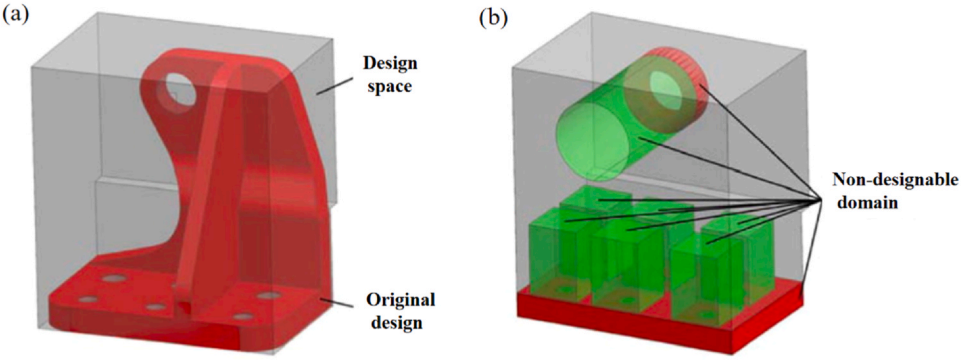

Fig. 4. Topology optimization geometric model: (a) Design space by extending original design, (b) Design domain with non-designable areas. Adapted from Ref. [21]. Copyright 2019 Chinese Society of Aeronautics and Astronautics.

advantages of additive manufacturing for the space sector. Conventional modular design strategies involve organizing various elements into separate parts to boost production efficiency in subtractive manufacturing [23]. However, by transitioning to an additive manufacturing framework, multiple parts within an assembly become prime candidates for consolidation into a single, monolithic component [24]. In contrast to subtractive techniques, AM facilitates the fabrication of parts with complicated geometries and the consolidation of what were previously multiple components, maximizing productivity while consuming minimal material and energy [25]. Traditionally, intricate aerospace components are composed of numerous simple parts that are attached together with various fasteners such as welds, bolts, and brazes [26]. Such assemblies typically deliver inferior reliability and demand additional inspection, tooling, and sustainment costs compared to a single, unified part [27]. Furthermore, geometric defects and unintended misalignments or distortions in these multi-part assemblies can exceed acceptable tolerances in critical aerospace applications [28].

The benefits of design for part consolidation through AM are substantial. The PC design methodology has gained significant attention from designers seeking to enhance performance through production redesign [29,30]. The main advantages include a reduction in the complexity of production management and part assembly, the elimination of tedious assembly operations that hinder production efficiency, and the removal of the need for assembly tools such as fixtures and fasteners, which collectively contribute to lower production costs [31]. This approach also reduces part inventory and diminishes the economies of scale typically associated with large centralized factories, as complex parts can be fabricated on a single AM machine [32]. Decreasing the number of parts in an assembly consequently reduces the number of tools held in inventory, the costs associated with documentation, inspection, and production, the assembly line footprint, and the overall manufacturing costs [33,34]. The summary of key aerospace components where additive manufacturing has enabled significant part consolidation, resulting in reduced assembly complexity, enhanced performance, and weight savings is shown in Table 1.

Industrial applications demonstrate the profound impact of PC. General Electric (GE) consolidated 900 parts of a helicopter engine, including fasteners, into just 14 parts, resulting in a design approximately 40 % lighter and 60 % cheaper [35]. A well-documented early case involved the redesign of an aircraft duct, which was consolidated from 16 parts into a single AM part as shown in Fig. 5(a) [36]. Similarly, Airbus successfully reduced a 126 part hydraulic housing to a single AM component, as shown in the Fig. 5(b) [37].

2.3. *Designing for multifunctionality*

A prime consideration when designing for space is the multifunctionality of a unit. AM technology provides unparalleled capability to address this need by integrating multiple functions into a single, consolidated component [38]. This multifunctionality in space systems encompasses integrated heat dissipation, structural flexibility, and embedded electrical or hydraulic circuits [39]. In conventional machining processes, achieving multifunctionality requires the use of multiple components. Each part must be manufactured individually and assembled, which is not a cost-effective production method and generates significant material waste [40]. AM enables these functionalities to be produced as a single, integrated unit. A pertinent example is the swirler in spacecraft engines, which recirculates injected fuel in the combustion chamber to create a high turbulence flow for pressure reduction. Attaining the required pressure demands a highly complex swirler design, a challenge readily met by AM methods [41]. This design freedom is further illustrated by two advanced components. Fig. 6a shows the prototype of an aerospike engine, developed and tested by TU Dresden's Institute of Aerospace Engineering. Fig. 6b shows 3D printed heat exchangers coated with zeolites. Both designs are not only

Table 1
Notable examples of part consolidation in aerospace applications.

Company	Component	Traditional part count	Consolidated part count	Key benefits	Citation
General Electric (GE)	Helicopter Engine	900 parts	14 parts	40 % lighter, 60 % cheaper	[35]
GE Aviation	Engine Components	855 parts	Dozen parts	20 % improved fuel efficiency, 10 % more power	[35]
GE Aviation	Bearing Support & Sump	80 parts	1 part	Significant weight and cost reduction	[35]
GE Aviation	Nozzle	20 parts	1 part	25 % weight reduction	[36]
Airbus	Hydraulic Housing Tank	126 parts	1 part	Improved reliability, reduced weight	[37]

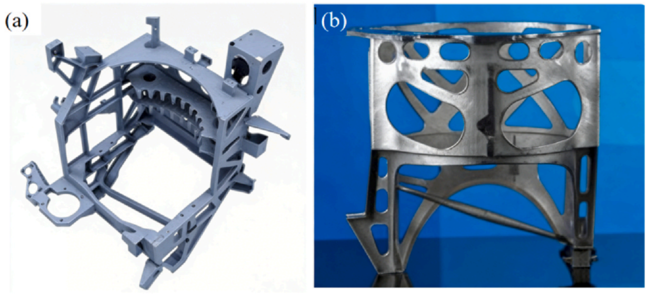

Fig. 5. Additively manufactured hydraulic reservoir (consolidated part): (a) Additively manufactured hydraulic reservoir rack in Airbus, consolidating 126 components, (b) The consolidated design as a single part. Adapted from Ref. [35]. Copyright Airbus - Hermann Jansen.

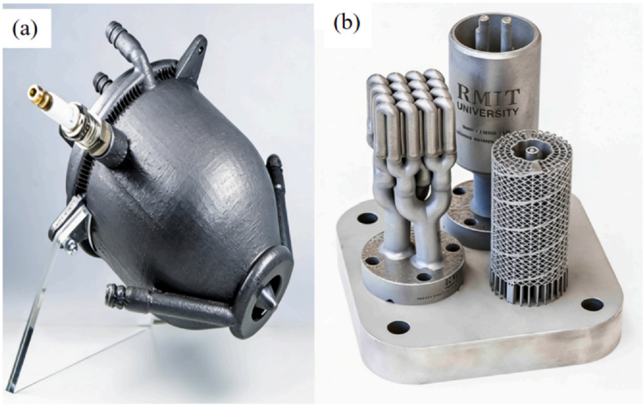

Fig. 6. Additively manufactured multifunctional components: (a) Prototype of the aerospike engine. Adapted from Ref. [42]. Copyright 2024 Selbmann et al. (b) 3D printed heat exchangers. Adapted from Ref. [43]. Copyright 2021 Hubesch et al.

highly complex and functional but also cost-effective to print and easy to scale for various mission requirements, showcasing how AM enables multifunctional designs that were previously impractical or impossible to manufacture.

3. Additive manufacturing technologies for space applications

Additive manufacturing, as delineated by the international standard ISO/ASTM 52900, is categorized by the American Society for Testing and Materials International Committee F42 into seven distinct methods [44]. For the demanding requirements of the space sector, these technologies are most effectively classified into two primary categories based on the materials used: metal additive manufacturing (MAM) and non-metal additive manufacturing (NAM) [45]. This section will review the principal MAM methods, while NAM will be addressed in the subsequent section.

3.1. *Metal additive manufacturing (MAM)*

Among the various AM techniques, powder bed fusion (PBF) and directed energy deposition (DED) are the most widely adopted and mature MAM processes for space applications, while other methods generally remain at lower technology readiness levels for critical space components [46]. The different manufacturing methods adopted by MAM for space sectors are summarized in Table 2.

3.1.1. *Powder bed fusion (PBF)*

In the powder bed fusion method, a bed of metal powder is spread over a substrate and a heat source is used to selectively melt the powder locally, fusing it to form a solid layer [47]. After each layer is created, the build platform moves downward, a new layer of powder is spread, and the process is repeated. A schematic representation of the PBF working principle is given in Fig. 7.

A critical advantage of this method is that the surrounding unsintered powder provides inherent support for the successive layers and the overhanging structures, eliminating the need for dedicated support structures in many cases [49]. This unused metal powder is also typically reusable, significantly improving material economy. PBF processes are generally performed in an inert gas chamber to prevent oxidation, with the exception of electron beam powder bed fusion, which is conducted in a vacuum chamber [50]. This requirement for a controlled atmosphere makes PBF particularly

Table 2
Metal additive manufacturing (MAM) methods for space applications.

Powder bed fusion (PBF)	Directed energy deposition (DED)
Laser powder bed fusion (LPBF)	Laser metal deposition (LMD)
Selective laser melting (SLM)	Electron beam free-form fabrication (EBF^3)
Electron beam powder bed fusion (EBPBF)	Wire arc additive manufacturing (WAAM)

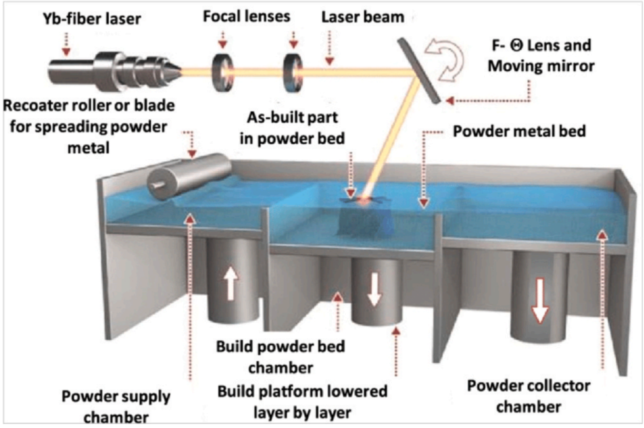

Fig. 7. Schematic of PBF working principle. Adapted from Ref. [48]. Copyright 2024 Bruggeman et al.

suitable for the high-performance alloys required in space. Components manufactured via PBF, especially using electron beam melting with high-strength alloys like titanium and chromium, exhibit high fidelity build qualities and can incorporate complex internal passages [51]. The final grain structure and mechanical properties of the product are highly dependent on process parameters such as layer thickness and energy input [52].

3.1.2. Laser powder bed fusion (LPBF)

In the laser powder bed fusion method, a high-power laser beam is used to selectively melt metal powder within a sealed chamber [53]. The entire manufacturing process is governed by the provided 3D design data. To achieve a high-quality output, parameters such as gas flow, layer thickness, powder feed rate, and laser scanning strategy must be meticulously optimized [54]. Due to its superior resolution and quality, the LPBF method has been successfully adopted for a wide range of metals, from soft aluminum alloys to advanced high-entropy alloys [55]. The production time for this process is significantly less than traditional methods, and a high surface finish can be achieved. Although LPBF is relatively expensive compared to other AM methods, its precision makes it indispensable for industrial sectors requiring high-performance machines and structures [56]. It is particularly suited for space sectors where performance and safety are paramount. The LPBF method can produce parts with features ranging from 0.20 mm to 400 mm with a maximum build height of 850 mm [57].

3.1.3. Electron beam powder bed fusion (EBPBF)

In the electron beam powder bed fusion method, localized melting of the metal powder is achieved using a high-energy electron beam [58]. A key differentiator from LPBF is that EBPBF requires a vacuum chamber, as the electron beam can only function effectively in a vacuum; this environment also helps to reduce oxidation and porosity within the final part [59]. The mechanical properties of materials manufactured by EBPBF are often comparable to those produced by vacuum die casting methods. A trade-off, however, is that parts produced by EBPBF typically exhibit higher surface roughness due to the larger powder grain size used in the feedstock and the nature of the process [60]. Nevertheless, EBPBF benefits from rapid electron beam scanning and high-power input, resulting in faster production times. The typical build volume for EBPBF systems can produce parts from 0.4 mm to 350 mm in size, with a maximum height of approximately 380 mm [61]. Table 3 presents a detailed comparison between laser powder bed fusion (LPBF) and electron beam powder bed fusion (EBPBF) technologies.

3.1.4. Directed energy deposition (DED)

In the directed energy deposition (DED) method, material layers are created by feeding stock material, typically in the form of wire or powder, directly into a localized melt pool generated by a focused heat source [62]. The energy sources employed for melting the feedstock include lasers, electron beams, or electric arcs. While DED can process polymers and ceramics, its primary application in the space sector is with metals and metal alloys [63]. A significant advantage of DED over powder bed fusion methods is its greater geometric freedom and ability to fabricate much larger components, making it the preferred technology for large-area additive manufacturing (BAAM) of substantial structures [64].

The process schematics for the two primary DED variants are illustrated in Fig. 8 [65]. In most cases, DED does not require dedicated support structures for printing. However, when used for very large area manufacturing (BAAM), some supports may be necessary to prevent bridge defects and ensure geometric accuracy [66]. A notable limitation of DED is its relatively low print resolution compared to PBF, which often necessitates subsequent post-processing, such as machining, to achieve final dimensional tolerances and surface finish [67]. Conversely, its enhanced flexibility in deposition orientation and ability to add material to existing components significantly advance its use for repair and refurbishment applications for valuable spacecraft components [68]. DED is widely employed to repair engine parts, air foils, turbine blades, and compressors. For instance, a turbine blade has been repaired with a remarkable accuracy of 0.03 mm using DED, a process that also provided a 36% total energy saving compared to manufacturing a new part [69].

The mechanical and metallurgical properties of the final AM product are highly dependent on the process parameters; therefore, parameter optimization plays a vital role in determining the output quality [70]. Based on the feedstock material used, DED is commonly classified into two main types: laser powder DED and laser wire DED. The fundamental difference is that laser powder DED feeds metallic powder into the melt pool to create layers, while laser wire DED uses metal wire as the feedstock [71]. These two methods produce different outcomes in terms of print resolution, cooling rates, and post-processing requirements, making them suitable for different applications within the space industry [72].

The unique capabilities of DED make it particularly suited for three key application areas in the space sector. First, its ability to deposit material at high rates makes it ideal for manufacturing large-scale structures, such as primary rocket engine components and large structural brackets, that would be impractical or time-consuming to build using PBF [73]. Second, its precision in adding material to existing parts makes it an invaluable technology for the repair and refurbishment of high-value components, extending their service life and reducing replacement costs [74]. Finally, DED is often integrated with subtractive machining tools in hybrid manufacturing systems. This combination allows for a component to be additively manufactured to a near-net shape and then precisely finished with subtractive processes in a single setup, streamlining production and ensuring high dimensional accuracy for critical space applications [75].

3.2. Non-metal additive manufacturing (NAM)

Complementing metal-based processes, non-metal additive manufacturing offers unique advantages for the space sector, particularly for weight reduction, rapid prototyping, and the production of non-structural yet mission-critical components [76]. The most common NAM methods applicable to space, along with their respective materials and applications, are summarized in Table 4.

Table 3
Comparison of LPBF and EBPBF characteristics.

Parameters	Laser powder bed fusion (LPBF)	Electron beam powder bed fusion (EBPBF)
Energy source	High-power laser	High-energy electron beam
Build environment	Inert gas (e.g., Argon)	High vacuum
Typical build volume	Up to 400 mm × 400 mm × 850 mm	Up to 350 mm × 350 mm × 380 mm
Surface finish	Superior, smoother	Higher roughness
Typical production speed	Slower scan speeds	Faster due to high-speed electron beam
Key advantage	High resolution, detail	Excellent for reactive materials (Ti, Cr)

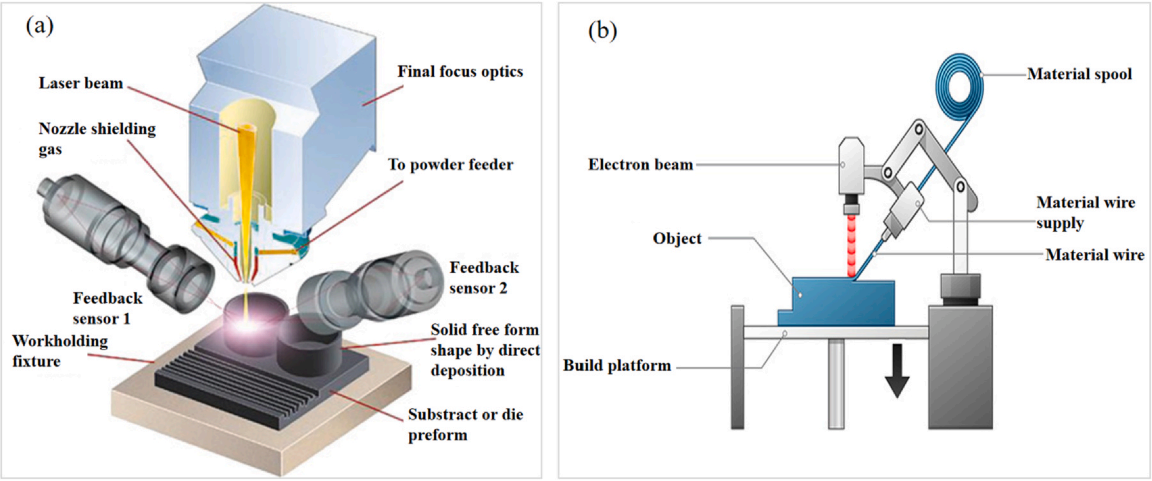

Fig. 8. Schematic diagram: (a) DED with a powder feeder. Adapted from Ref. [65]. Copyright 2010 Springer Nature. (b) DED with a wire feeder.

Table 4
Non-metal additive manufacturing methods, materials, and their space applications.

NAM method	Materials	Space applications
Fused deposition modeling (FDM)	Polycarbonate, ABS, ULTEM™	Tools and prototypes, cabin accessories, antenna arrays
Selective laser sintering (SLS)	Nylon 12, Nylon 11 FR, Glass-filled nylons	Airflow ducts, engine compartment parts, functional brackets
Stereolithography (SLA)	Standard, castable, clear, high-temp resins	Panels, brackets, cabin accessories, mold patterns
Material jetting (PolyJet)	Various photopolymers	Bezels, lights prototypes, intricate wing design prototypes

3.2.1. *Fused deposition modeling (FDM)*

To reduce weight, space sectors are increasingly replacing conventional metal parts with high-performance polymer components produced via fused deposition modeling (FDM) [77]. This process creates parts by extruding thermoplastic material layer-by-layer according to a 3D model. A key example is shown in Fig. 9 [78], which depicts satellite antenna arrays manufactured using the FDM method. The main advantage of FDM is that it does not require chemical post-processing. High-strength thermoplastics like polycarbonate, acrylonitrile butadiene styrene (ABS), and polyetherimide (e.g., ULTEM™) are commonly used in FDM for space applications [72,79]. This method is relatively inexpensive and highly versatile, suitable for both end-use parts and prototyping. NASA's Mars rover, for instance, incorporated 70 production-grade thermoplastic parts made via FDM to reduce weight and increase durability [80]. Furthermore, many unmanned aerial vehicles are now manufactured using FDM due to its high printing speed and low production costs [81,82].

3.2.2. *Selective laser sintering (SLS)*

Selective laser sintering is one of the most effective and comparatively low-cost methods for fabricating polymer parts with good mechanical properties [83,84]. SLS uses a laser heat source to selectively sinter polymer powder particles, fusing them together to create solid layers. In space sectors, SLS is adopted for making both functional and non-functional parts like airflow ducts and engine compartment parts [85]. To achieve specific material properties, Nylon 12 is widely used for its flexibility, while nylons reinforced with short glass fibers are employed to produce parts requiring high thermal resistance and reduced thermal conductivity [86]. This property makes SLS ideal for fabricating heat-resistant and small-volume components for space applications. Fig. 10(a) shows a functional bracket made by SLS from Nylon 12, and Fig. 10(b) shows an air duct made from flame-retardant Nylon 11 (Nylon 11 FR), demonstrating the range of applications.

Fig. 9. Antenna arrays for satellites by FDM. Adapted from Ref. [78]. Copyright 2019 Stratasys.

3.2.3. *Stereolithography (SLA)*

Stereolithography (SLA), also known as vat photopolymerization, is a method of creating 3D objects using a light-emitting device (laser or digital light processing) that illuminates and cures a liquid photopolymer resin layer by layer [87]. SLA has the ability to produce fine features and provide an excellent surface finish with a minimal stair-stepping effect [88]. Several specialized photopolymer resins can be utilized with SLA, including standard (rigid, opaque), castable, clear, flexible, high-temperature, and dental resins [89]. In aerospace, high-fidelity rapid prototypes for testing, verification, and design of components like aeroelastic airfoils have been produced with low-stiffness resins where model similarity is critical [90]. Cabin accessories such as console control parts with functional knobs, as well as full-size panels, seat backs, and entry doors, have been produced with standard SLA resins [91]. Furthermore, castable and high-temperature SLA resins are used to fabricate mold patterns for indirect rapid tooling and injection molds for direct rapid tooling, respectively [92].

3.2.4. *Material jetting (PolyJet)*

PolyJet, also known as material jetting, uses inkjet printing technology to jet liquid photopolymer droplets onto a build substrate where they are immediately cured by UV light [93]. It can fabricate parts with very fine features and a superior surface finish, while exhibiting little stair-stepping effect [94]. Some PolyJet systems also boast the ability to

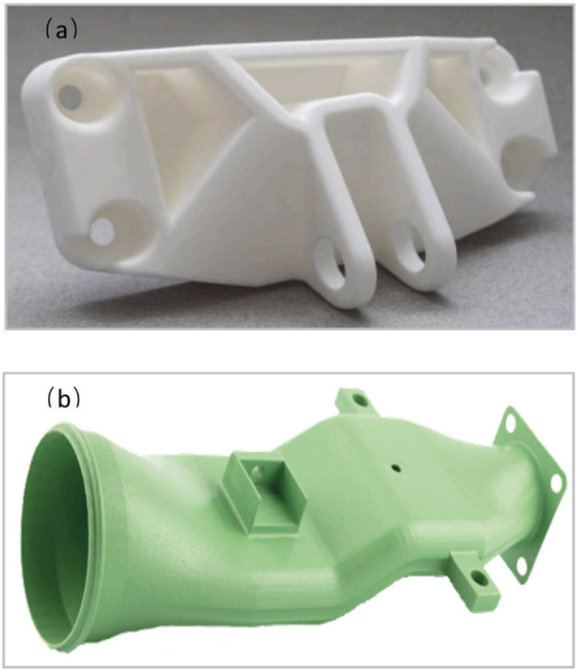

Fig. 10. Application examples of additive manufacturing components via SLS: (a) Functional bracket, (b) Airduct made via SLS.

produce multi-material parts and functionally graded materials (FGM), allowing for a wide range of material properties within a single printed object [95]. The role of PolyJet in the aerospace industry includes rapid prototyping, indirect rapid tooling (mold pattern fabrication), and direct digital manufacturing (DDM) [96]. Material jetting occurs through two primary processes: drop on demand (DOD) and continuous inkjet (CIJ). The DOD process offers high part resolution at the expense of build time, making it favorable for applications requiring a fine surface finish, such as prototype light fittings and intricate wing design prototypes [97]. The CIJ process offers faster build times at lower part resolutions and is better suited for non-critical, non-metallic part fabrication, like interface bezels and cabin interior components [98].

4. Space-grade materials for additive manufacturing

The selection of appropriate materials is fundamental to the successful implementation of additive manufacturing in space applications. The unique demands of the space environment—including extreme temperatures, vacuum conditions, radiation exposure, and mechanical stresses—require materials with exceptional properties. The material palette available for space additive manufacturing is both diverse and continually expanding, encompassing advanced metallic alloys, high-performance polymers, and specialized composites [99].

4.1. Metallic materials

4.1.1. Titanium alloys (e.g., Ti-6Al-4 V)

Titanium alloys, particularly Ti-6Al-4 V, remain indispensable for space applications due to their exceptional strength-to-weight ratio, excellent corrosion resistance, and good performance at elevated temperatures [100]. These alloys can be readily manufactured by AM processes, whereas conventional production methods require special tools and fixtures, making traditional fabrication tedious and time-consuming [101]. The aerospace-grade titanium alloys are particularly valuable for critical structural components where weight reduction is paramount for fuel efficiency and payload capacity [102,103].

4.1.2. Nickel-based superalloys (e.g., Inconel 625, Inconel 718)

Nickel-based superalloys such as Inconel 625 and Inconel 718 are vital for propulsion and thermal management applications in space systems [104]. These materials maintain their mechanical properties at high temperatures and offer excellent resistance to oxidation and corrosion, making them ideal for rocket engine components, turbine blades, and other high-temperature applications [105]. Their processability through various AM techniques, particularly powder bed fusion and directed energy deposition, has expanded design possibilities for complex high-temperature components [106].

4.1.3. Aluminum alloys

Aluminum alloys continue to underpin lightweight structures in space applications due to their low density, good mechanical properties, and relatively low cost [107]. Aerospace-grade aluminum alloys are increasingly being processed through AM methods, offering new opportunities for manufacturing complex, lightweight components that were previously difficult or impossible to produce through conventional methods [108]. The development of specialized aluminum alloys optimized for AM processes is an active area of research, aiming to overcome challenges such as hot cracking and porosity [109,110].

4.1.4. Emerging alloys (e.g., high-entropy alloys, refractory metals)

The introduction of functionally graded materials and emerging alloy systems further enhances the potential of AM for space applications [111]. High-entropy alloys (HEAs), consisting of multiple principal elements in approximately equal proportions, offer unique combinations of strength, toughness, and thermal stability [112]. Refractory metals and their alloys, capable of withstanding extreme temperatures, are being explored for specialized applications in propulsion and thermal protection systems [113]. These materials science innovations allow for the tailoring of grain structure, residual stress, and mechanical response within a single component, aligning directly with the multifunctional demands of aerospace systems [114].

4.2. Non-metallic materials

4.2.1. High-performance polymers (e.g., PEEK, PEKK, Nylons)

High-performance polymers have gained significant importance in space applications for weight reduction and specialized functional requirements [115]. Materials such as Polyether ether ketone (PEEK), Polyether ketone ketone (PEKK), and advanced nylons offer excellent mechanical properties, thermal stability, and resistance to space environmental factors [116]. These polymers are processed through various AM technologies including fused deposition modeling (FDM) and selective laser sintering (SLS), enabling the production of complex components such as antenna arrays, cabin accessories, and ducting systems [117]. NASA's incorporation of production-grade thermoplastic parts in Mars rovers demonstrates the growing acceptance of these materials for critical space applications [118].

4.2.2. Composites and ceramics

Composite materials and ceramics represent emerging frontiers in space additive manufacturing, offering unique properties for specialized applications [119]. Continuous fiber-reinforced composites produced through AM processes combine the design freedom of additive manufacturing with the exceptional strength and stiffness of continuous fibers [120]. Ceramic materials, processed through techniques such as stereolithography and binder jetting, offer exceptional thermal stability, wear resistance, and electrical insulation properties for extreme environment applications [121]. These materials are particularly valuable for components requiring ultra-high temperature resistance, such as thermal protection systems, insulators, and specialized sensors [122].

Table 5
Comparison of material efficiency between conventional and additive manufacturing.

Parameters	Conventional manufacturing	Additive manufacturing
Typical buy-to-fly ratio	20:1–40:1	1:1–3:1
Material waste	Up to 95 %	Approximately 5 %
Energy consumption	Higher due to multiple processing steps	Lower, direct digital manufacturing
Environmental impact	Significant material waste and energy use	Reduced waste, sustainable production

4.3. Material economy and sustainability

The buy-to-fly ratio, representing the weight ratio between raw material and the final component, is a critical economic and environmental consideration in aerospace manufacturing [123]. For complex aerospace components with high volume-to-envelope ratios, such as turbine blades and thin-walled structures, conventional manufacturing methods typically exhibit buy-to-fly ratios of 20–40:1, resulting in significant material waste and requiring extensive CNC tool planning [124]. In stark contrast, additive manufacturing enables near-net-shape production with buy-to-fly ratios approaching 1:1, dramatically reducing material consumption and waste [125]. Table 5 summarizes the comparative material efficiency of conventional manufacturing versus additive manufacturing processes, highlighting how additive methods substantially reduce raw material waste and improve utilization rates.

Powder bed fusion operations typically produce only about 5 % waste compared to traditional milling, which can yield up to 95 % waste [126]. This dramatic reduction in material waste, combined with component weight optimization, offers major environmental benefits throughout the product lifecycle [127]. The environmental advantages of AM extend beyond material efficiency to include reduced energy consumption during manufacturing, minimized need for hazardous cutting fluids used in machining, and possibilities for part repair and remanufacturing [128]. Furthermore, the opportunity to recycle metal powders and integrate additive with subtractive processes in hybrid manufacturing systems further enhances the sustainability potential of AM for space applications [129]. This alignment with environmental objectives is increasingly important as space agencies and commercial space companies emphasize sustainable practices across their supply chains [130].

5. Special applications and case studies in the space sector

As stated in market assessments, the aerospace sector represents one of the most promising fields for additive manufacturing, currently accounting for approximately 18.2% of the total AM market [131]. AM technology has demonstrated capability in developing and repairing diverse metallic and non-metallic aerospace components, including engine parts, turbine blades, and heat exchangers [132]. The practical implementation of AM in space applications spans multiple domains, from propulsion systems to in-situ manufacturing, as demonstrated by numerous successful case studies from leading aerospace organizations [133].

5.1. Propulsion systems: fuel nozzles, combustion chambers, and rocket engines

Additive manufacturing has revolutionized the design and manufacturing of propulsion system components, enabling complex geometries that were previously impossible to produce. A noteworthy example is the effective AM manufacturing of nineteen distinct titanium fuel nozzles by CFM International for use in the leading edge aviation propulsion (LEAP) engine as shown in Fig. 11, which powers aircraft including the B737MAX and A320neo [134,135].

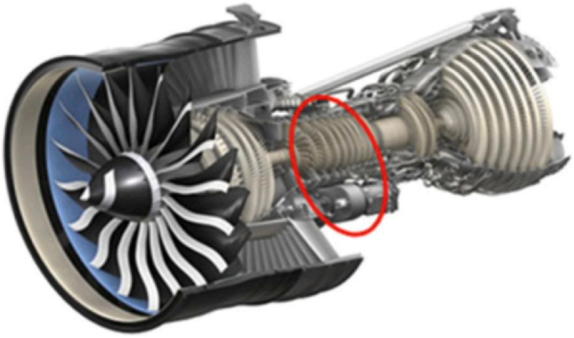

Fig. 11. LEAP engine fuel nozzle (Courtesy GE Aviation).

This component consolidation represents a significant advancement, as GE Aviation reported reducing parts from 855 using conventional manufacturing to just a dozen using AM technologies, achieving 20% improved fuel efficiency and 10% more power [136]. Another prominent example is the Vulcain 2 rocket engine nozzle, which incorporated nearly 50 kg of material produced through Directed Energy Deposition (DED) technology [137]. This application demonstrates AM's capability for large-scale component manufacturing in propulsion systems. Similarly, GE developed an advanced single turboprop engine for the Cessna Denali aircraft using additive manufacturing, reducing the assembly from 855 parts to just 12 components [138]. These advancements highlight how AM enables the production of complex internal geometries and cooling channels that enhance engine performance and efficiency while reducing weight and part count [139].

5.2. Structural components: brackets, frames, and housing

In the aerospace industry, brackets, structures, and frames represent typical applications benefiting from additive manufacturing and topology optimization. Compared to conventional methods, AM permits increased design complexity that can be fully leveraged using topology optimization to further reduce component mass in aerospace applications [140,141]. The A350 cabin bracket connector stands as a pioneering example of a structural, topology-optimized, AM component utilized in commercial aircraft interior design as illustrated in Fig. 12 [142].

The first AM spacecraft structures deployed in space were eight brackets installed on the Juno mission to Jupiter in 2011 as shown in

Fig. 12. Topology optimized and additively manufactured Airbus A350 XWB cabin bracket connector by LPBF of Ti6Al4V. Adapted from Ref. [142]. Copyright 2016 airbus.

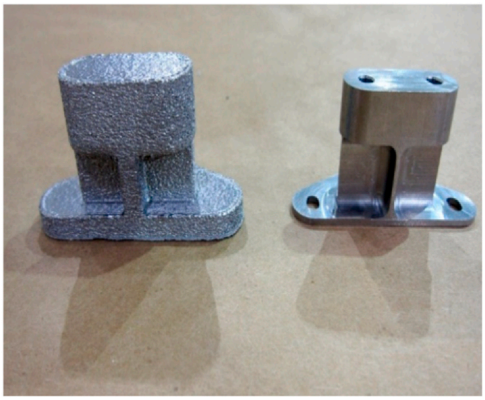

Fig. 13. Waveguide bracket for the Juno mission. Adapted from Ref. [145]. Copyright airbus.

Fig. 13. These brackets connected waveguides that transmit radio frequency signals between components, demonstrating the viability of AM for critical space structures [143,144]. The aerospace industry's embrace of AM extends to economic activities including orbital launch vehicles, manufactured parts for space exploration, and associated activities, with structural components representing a significant application area [145].

5.3. *In-space manufacturing and repair: the future of on-demand fabrication*

Additive manufacturing holds transformative potential for in-space manufacturing and repair capabilities, representing perhaps the most ambitious frontier for this technology. The ability to perform rapid, affordable repair of highly valuable components could revolutionize space mission sustainability and longevity [139,146]. A significant portion of the time and expense required in AM repair involves preparing the affected part for repair. The automation of preparatory procedures can lead to a cost-effective and faster repair process compared to manufacturing new parts [140,147]. This capability is particularly valuable for long-duration missions and space stations, where resupply opportunities are limited and component failures could jeopardize mission success. The emerging concept of in-situ resource utilization (ISRU), where regolith or extraterrestrial minerals are processed via additive technologies to build infrastructure on the Moon or Mars, represents the ultimate extension of this capability [141,148].

5.4. *Thermal management systems: heat exchangers and cooled components*

Thermal management represents another critical application area for additive manufacturing in space systems. AM enables the production of complex internal cooling channels and advanced heat exchanger designs that significantly improve thermal management efficiency. Companies like Safran Group have recognized additive manufacturing as next-generation technology for engine components, implementing AM in Turbomeca and Sneema prototypes and engines [149]. Sneema has employed AM to produce guide vanes as shown in Fig. 14 for the Silver Crest business jet engine, manifolds supporting Vinci rocket engines, and hydrogen turbo pumps [150].

Rolls-Royce has conducted tests on large engine components produced through AM, including the 'front bearing housing' developed via electron beam melting technology [151]. This complex titanium component measures 1.5 m in diameter and 0.5 m in thickness, accommodating 48 air foils, and serves as the front bearing housing for the low and intermediate pressure compressor in the Rolls-Royce Trent XWB-97 engine [152]. Using this AM technology, Rolls-Royce achieved 30% reduction in manufacturing time compared to conventional processes [153,154]. These applications demonstrate AM's growing role in producing critical thermal management components that withstand extreme temperatures and operational conditions in space environments.

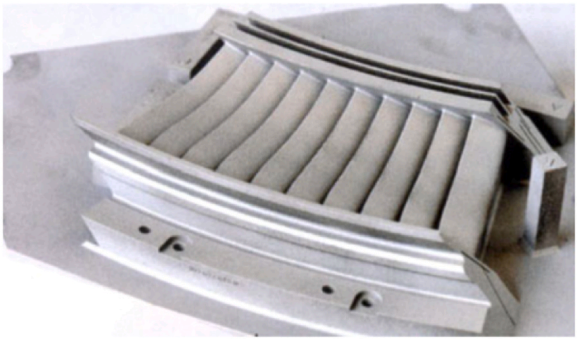

Fig. 14. Engine stator vane for aircraft employing high-temperature alloys.

6. Challenges and limitations

Despite its significant advantages and growing adoption, additive manufacturing faces several persistent challenges that limit its widespread implementation in the space sector. These challenges span technical, procedural, material, and economic domains, requiring concerted research and development efforts to overcome [155]. Understanding these limitations is crucial for realistic assessment and future advancement of AM technologies for critical space applications.

6.1. *Technical challenges: resolution, porosity, surface finish, and residual stresses*

Additive manufacturing technologies face several technical challenges that are particularly relevant to the stringent requirements of the aerospace sector [156]. Metal sintering techniques limit component resolution to approximately 90% of the powder size used in the process. The use of large powder particles in melting processes further reduces component resolution and increases melt pool size, affecting final part accuracy [157]. Additional resolution limitations arise from the minimum incremental length of servo motors and the translation accuracy from CAD model to actual toolpath execution [158].

Beyond resolution constraints, AM processes struggle with inherent material issues including porosity, surface roughness, and residual stresses that can impact the strength and reliability of final products [159]. Characteristics like porosity and surface finish significantly affect mechanical properties and may impede the production of certain critical aircraft components using additive manufacturing technology [160]. These technical constraints necessitate extensive post-processing in many cases, adding time and cost to the manufacturing process [161,162].

6.2. *Process limitations: build volume constraints and production speed*

Current additive manufacturing machines have confined build volumes that limit the size of components that can be produced in a single build [163]. This restriction precludes the manufacture of very large structures such as complete wings or fuselage sections, requiring alternative joining methods that may compromise structural integrity [164]. Additionally, production speed remains slower than established traditional methods for most AM processes, restricting high-volume production cycles and making AM less suitable for mass production scenarios [165].

Massive build volumes present particular challenges for AM technologies that require an inert environment or vacuum, as creating and maintaining such conditions for large-scale systems can be prohibitively expensive or technically impossible with current technology [166]. The spot diameter of energy sources may vary considerably depending on the specific technology and metallic powder used, with powders exhibiting strong emissivity and reflectivity potentially not melting completely due to significant reflection of energy sources [167].

6.3. Material and certification hurdles: standardization and qualification for flight

The rigorous certification standards inherent to the aerospace industry introduce lengthy validation cycles for additively manufactured components [168]. The lack of comprehensive models linking processing parameters to material behavior complicates standardization and makes qualification processes particularly challenging [169]. Material availability in appropriate powder or wire feedstock form also lags behind design aspirations, limiting the range of materials that can be effectively utilized in AM processes for space applications [170].

The absence of established standards for additive manufacturing materials and processes presents a significant barrier to widespread adoption in safety-critical aerospace applications [171]. Each new material and process combination requires extensive testing and validation to ensure reliability under the extreme conditions encountered in space environments [172]. This certification burden increases development time and cost, particularly for small production runs where the advantages of AM might otherwise be most pronounced [173].

6.4. Economic and supply chain considerations

While additive manufacturing offers potential cost savings through material efficiency and part consolidation, the economic case is not always straightforward [174]. The high cost of metal powders suitable for aerospace applications, particularly specialized alloys, contributes significantly to overall production expenses [175]. Additionally, the requirement for specialized equipment, controlled operating environments, and skilled operators adds to the operational costs of AM implementations [176].

Supply chain considerations present both opportunities and challenges for AM adoption. While distributed manufacturing and on-demand production offer potential supply chain resilience, the current lack of standardization and quality assurance protocols across different AM systems and facilities complicates supply chain integration [177]. The aerospace industry's conservative approach to supplier qualification and the long certification cycles for new manufacturing methods further slow the integration of AM into established supply chains [178].

Despite these concerns and limitations, the aerospace industry continues to invest in additive manufacturing and explore techniques to overcome these barriers to harness its benefits [179]. The technical challenges are actively being addressed through research into process optimization, in-situ monitoring, and advanced post-processing techniques, while standardization bodies are working to develop comprehensive certification frameworks for additively manufactured aerospace components [180].

7. Future scope and potential applications

The trajectory of additive manufacturing in the space sector is unequivocally upward, with its full potential requiring sustained scientific and industrial commitment. While current applications demonstrate significant capabilities, the future promises even more transformative advancements that could fundamentally reshape space hardware design, manufacturing, and operation [181]. The emerging applications span multiple domains, from massive structural components to intelligent manufacturing systems and extraterrestrial construction.

7.1. Large-scale additive manufacturing (e.g., entire wings, fuselage sections)

The future scope of AM lies significantly in the maturation of large-area additive platforms capable of producing both micro-scale precision parts and macro-scale structural components [182]. Although AM techniques are currently used to manufacture small aircraft parts, the aerospace industry anticipates large-scale components, including entire airplane wings or fuselage sections, being printed in the future [183]. The scaling of current successes with brackets, ducts, and nozzles toward full wings, fuselage sections, or propulsion systems will mark the next great leap in aerospace manufacturing [184]. This advancement requires overcoming current build volume constraints and developing new AM technologies capable of maintaining precision and material properties at significantly larger scales [185].

7.2. In-situ resource utilization (ISRU) for lunar and martian infrastructure

Perhaps the most ambitious yet plausible frontier for space additive manufacturing is the emergence of in-situ resource utilization (ISRU) strategies [186]. This approach involves processing regolith or extraterrestrial minerals via additive technologies to build infrastructure on the Moon or Mars, potentially revolutionizing deep space exploration and colonization [187]. By utilizing local materials, ISRU could dramatically reduce the cost and complexity of space missions by minimizing the need to transport construction materials from Earth [188]. Research is already underway to develop AM processes capable of using simulated lunar and Martian regolith to create structural components, radiation shielding, and habitat structures [189]. This capability would enable sustainable, long-term presence in space by leveraging local resources for construction and manufacturing needs [190].

7.3. Integration of AI and machine learning for process control and certification

The integration of artificial intelligence and machine learning into process monitoring and control is expected to revolutionize reproducibility and certification processes [191]. AI-enabled systems can facilitate closed-loop correction during builds, reducing defects, minimizing the need for post-processing, and shortening qualification cycles [192]. Machine learning algorithms can analyze vast amounts of process data to identify optimal parameter combinations, predict potential defects, and automatically adjust printing parameters in real-time to ensure consistent quality [193]. This intelligent automation could significantly reduce the time and cost associated with certifying AM components for flight, addressing one of the major current limitations [194]. Furthermore, AI-driven design optimization tools can generate novel structures that maximize performance while minimizing weight and material usage [195].

7.4. Multifunctional and smart structures: embedding sensors and electronics

The future of space components lies in multifunctional designs that embed sensors, circuits, and thermal management systems directly into printed structures [196]. This capability will redefine the concept of what a component is, transforming spacecraft and aircraft from assemblies of isolated parts into integrated, monolithic constructs with embedded functionalities [197]. Rather than simply producing passive structural elements, AM will enable the creation of "smart" components that can monitor their own health, communicate status, and even adapt to changing conditions [198]. These structures will be optimized for weight, resilience, and adaptability, incorporating capabilities such as strain sensing, temperature monitoring, and damage detection directly within their material matrix [199]. The ability to print with multiple materials simultaneously will further enhance this functionality,

Table 6
Future applications and their potential impact on space sector.

Application area	Timeframe/years	Key technologies required	Potential impact
Large-scale structures	5–10	Large-format AM systems, new alloy development	30 %–50 % weight reduction for major airframe components
ISRU construction	10–20	Regolith processing, in-situ manufacturing systems	90 % reduction in material transport from Earth
AI-integrated AM	3–7	Machine learning algorithms, advanced sensors	70 % reduction in certification time, near-zero defect production
Smart structures	5–15	Multi-material printing, embedded electronics	Real-time health monitoring, adaptive structures
Full spacecraft AM	15–25	System-level DfAM, multi-process integration	Completely new spacecraft architectures

enabling the integration of conductive traces, insulating layers, and structural elements in a single manufacturing process [200].

7.5. The path towards fully additive spacecraft

The broader vision for the coming decades is the realization of entire subsystems, and ultimately complete spacecraft, built largely or entirely through additive routes [201]. While individual brackets, ducts, and nozzles are now routine, the scaling of these successes toward complete spacecraft represents the ultimate goal of space additive manufacturing [202]. This path involves not only overcoming technical challenges related to scale and material properties but also rethinking spacecraft design methodologies to fully leverage AM capabilities [203]. The concept of "design for additive manufacturing" will evolve to encompass system-level optimization, where traditional assemblies are reimagined as unified, multifunctional structures [204]. This approach promises spacecraft that are lighter, more reliable, and better optimized for their specific missions than anything achievable with traditional manufacturing methods [205]. The continued advancement of AM materials, processes, and design tools will gradually make this vision a reality, potentially transforming how we explore and utilize space [206]. Table 6 outlines future applications of additive manufacturing in the space sector and explores their potential impacts, including enabling in-space fabrication, reducing payload mass through optimized designs, facilitating sustainable habitats using in-situ materials, and supporting autonomous manufacturing for long-duration missions.

8. Summary and conclusion

Additive manufacturing has emerged as a defining technological shift in the context of aerospace and space exploration, representing more than merely an incremental improvement over conventional processes but rather a fundamental transformation in how complex parts and systems are conceived, designed, and manufactured. The central attraction of additive methods lies in their ability to fabricate intricate geometries without the penalties of material wastage, tooling, or multi-stage fabrication that have long characterized traditional subtractive techniques. For aerospace applications where performance margins are narrow and cost per kilogram of payload is substantial, these advantages are not peripheral but mission-critical.

This review has underscored the limitations of conventional subtractive manufacturing, which remains heavily dependent on machining, casting, and welding. While these techniques are mature, they are constrained by high material waste, complex assembly requirements, and limited design flexibility. A turbine blade or satellite bracket fabricated through traditional routes may entail multiple processing stages, extensive inspection, and considerable scrap material, all of which increase cost and reduce efficiency. Additive manufacturing inverts these constraints by enabling freeform fabrication, optimized mass distribution, and multifunctionality within single consolidated units. This capacity to reimagine the very architecture of aerospace components distinguishes additive manufacturing as more than a replacement technology; it serves as a design enabler that unlocks concepts previously regarded as unattainable.

The advantages of AM extend significantly beyond material efficiency. Part consolidation has emerged as one of the most influential shifts enabled by additive technologies, allowing components that once required hundreds of individual elements joined by fasteners, welds, or brazes to be realized as single units. This approach not only simplifies supply chains and assembly procedures but also eliminates potential points of failure. Industrial cases demonstrate that the consolidation of aircraft ducts, brackets, and fuel nozzles into monolithic structures can achieve weight reductions exceeding 40% and cost reductions approaching 60%. The resulting improvements in reliability, manufacturability, and maintenance reinforce the case for widespread adoption across both terrestrial aerospace and extraterrestrial missions.

The review has highlighted the principal manufacturing technologies relevant to the space sector, with powder bed fusion and directed energy deposition dominating current metallic applications. Laser powder bed fusion, with its high precision and compatibility across a range of alloys from lightweight aluminum to advanced high-entropy materials, has become the benchmark for critical aerospace parts. Its electron beam counterpart, typically employed in vacuum environments, offers additional benefits in reduced oxidation and suitability for large titanium components. Directed energy deposition provides versatility in repairing high-value parts such as turbine blades and is increasingly deployed for large-area additive manufacturing. The flexibility of wire- or powder-based deposition aligns well with the need to manufacture or repair structures directly in orbit or on extraterrestrial surfaces, an application area now under active investigation.

Non-metallic processes provide complementary advantages, with fused deposition modeling, selective laser sintering, stereolithography, and PolyJet printing each contributing to weight reduction, prototyping, and the fabrication of non-structural yet mission-critical components. The material palette available for space applications continues to expand, with titanium alloys remaining indispensable due to their exceptional strength-to-weight ratio and corrosion resistance. Nickel-based superalloys are vital for propulsion and thermal management applications, while aluminum alloys continue to underpin lightweight structures. The introduction of functionally graded materials and multi-material builds further enhances AM potential, allowing the tailoring of grain structure, residual stress, and mechanical response within single components.

Applications already realized in practice illustrate both the maturity and potential of the technology. Rocket nozzles with conformal cooling channels, aircraft brackets optimized through topology algorithms, and fuel nozzles consolidated from dozens of parts into single units all testify to the disruptive impact of additive methods. Components used in the Juno mission and hydraulic reservoirs in Airbus aircraft mark the transition of AM parts from laboratory prototypes to flight-qualified hardware. In engine manufacturing, components such as heat exchangers, stator vanes, and front bearing housings demonstrate the feasibility of scaling additive processes to critical large structures.

Despite these evident advantages, significant challenges remain. Resolution limitations, porosity, surface roughness, and the need for extensive post-processing continue to constrain the reproducibility and reliability of printed components. Build volumes of existing machines remain limited, precluding the manufacture of very large structures such as complete wings or fuselages in single builds. Processing times are generally slower than established methods, restricting mass production capabilities. Material availability in appropriate powder or wire feedstock form also lags behind design aspirations, while rigorous certification standards introduce lengthy validation cycles.

Looking forward, the trajectory of additive manufacturing in the space sector is unambiguously upward, though its full realization requires sustained scientific and industrial commitment. Future progress depends on the maturation of large-area additive platforms capable of producing both micro-scale precision parts and macro-scale structural components. The integration of artificial intelligence and machine learning into process monitoring and control is expected to revolutionize reproducibility by enabling closed-loop correction during builds, reducing defects, and shortening qualification cycles. Advances in feedstock design, particularly in high-entropy alloys, refractory metals, and multifunctional composites, will expand the materials available for high-performance space systems.

The increasing emphasis on sustainability provides further impetus for additive methods, as AM drastically reduces material waste and energy consumption relative to conventional processes. The opportunity to recycle powders, tailor buy-to-fly ratios, and integrate additive and subtractive hybrid systems further enhances this potential. Beyond environmental gains, such approaches also promise cost efficiencies and the ability to rapidly adapt production lines to shifting mission requirements. The broader vision for coming decades involves the realization of entire subsystems, and ultimately complete spacecraft, built largely or entirely through additive routes. Rather than isolated parts joined together, spacecraft and aircraft may increasingly emerge as integrated, monolithic constructs with embedded functionalities, optimized for weight, resilience, and adaptability.

In conclusion, additive manufacturing has progressed from promise to practice within the aerospace sector, yet it still stands at the threshold of its transformative potential. With sustained investment in materials, process control, and certification, and with the integration of intelligent computational design tools, the role of additive manufacturing in space exploration is set to expand far beyond current applications. It will not merely complement traditional manufacturing but redefine the architecture of space systems, enabling lighter, stronger, more efficient, and more sustainable aerospace solutions. The future of space manufacturing is thus inseparably tied to the continued maturation and integration of additive technologies into the fabric of design and production.

CRediT authorship contributions statement

Dhanesh G. Mohan: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Supervision. **Saiyathibrahim A.**: Data curation, Investigation, Methodology, Writing – original draft. **Gopi S.**: Formal analysis, Investigation, Software, Writing – original draft. **Vijaykumar S. Jatti**: Investigation, Writing – original draft, Resources, Software. **Kumar S.**: Validation, Visualization, Writing – review & editing. **Murali Krishnan R.**: Validation, Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given his role as an Editorial Board Member of China Welding, Dhanesh G. Mohan had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported this paper.

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