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A mini review of additive manufacturing in medical, automotive, and construction applications

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A B S T R A C T

Additive manufacturing (AM), commonly known as 3D printing, is a transformative approach to producing complex geometries that uses digital models to directly layer materials. Compared to conventional subtractive methods, AM uses minimal material waste and reduces production time, thereby lowering manufacturing costs. These advantages show the growing demand for 3D printers, especially where precision, customization, and efficiency are important. In this brief review, we focus on AM applications in medicine, where it enables patient-specific solutions; in the automotive sector, where it supports lightweight and optimized designs; and in construction, where it contributes to sustainable and rapid development. This review presents AM as a versatile technology that is reshaping multiple industries.

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1. Introduction

Additive manufacturing (AM), considered one of the most advanced technological approaches, enables the creation of complex geometries and structures by building object layers based on 3D model data [1, 2]. Unlike traditional subtractive methods, which produce parts by removing material from a larger raw block, AM constructs components by adding material layer by layer. Since the process constructs parts directly from design cross-sections, it reduces significantly the generation of materials wastes, decreases production time significantly, and eliminates most manual and skill-intensive steps. As an illustration, while changing from traditional machining to AM procedures has been said to reduce raw materials wastes in metal fabrication by up to 40% [3].

The key advantages of additive manufacture with respect to traditional manufacture are radically precise production of intricate shapes and tailored parts, raw materials wasted during manufacture reduced, superior design greater flexibility and quicker cycle times, particularly for short runs. This process by layer enables in order to achieve accurate control over manufacture process with a view to achieve extremely fine components by a process usually unthinkable with traditional techniques[4]. Moreover, mesh-free fabrication From CAD models without molds provides significant

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benefits to cost savings and lead times, especially when planning or adjusting work to suit unique individual demands [5].

As compared to traditional machining, AM methods that utilize powders, filaments, and resins, along with the reuse of unused materials contribute to further waste reduction [6]. Today, additive manufacturing has a broad range of applications spanning industries such as automotive, healthcare, construction machinery, and consumer products, among others (Fig. 1). Hence, this paper focuses on these applications.

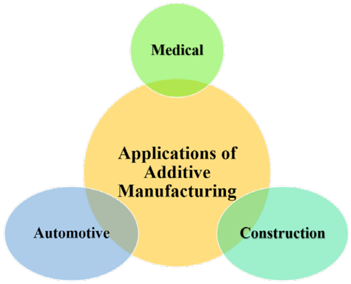

Fig. 1. Different applications of AM.

2. Medical applications

AM has astoundingly changed and is yet significantly influencing healthcare disciplines, especially when it comes to bioprinting cardiac tissues like 3D-printed heart valves, currently being one key area of research work [7-9]. Although the core principles of AM remain the same, there is now greater access to resources and tools to further explore and develop these technologies, paving the way for new medical innovations [10, 11]. However, despite the promising opportunities in medicine and biomechanics, several challenges remain. These include issues such as incomplete vascular networks in fabricated grafts and organ models, the need for large, multidisciplinary teams to support development, limitations in the layer height of printed models, and ethical considerations related to the use of 3D-printed devices in human applications [12].

2.1. Prosthetics and implants

The use of AM, along with advanced medical imaging and reverse engineering (RE), holds significant potential for producing customized implants that offer better clinical and aesthetic results, as well as biocompatible materials with strong mechanical properties [13]. However, it is extremely difficult to achieve tissue compatibility and it can take months to obtain an approval. The implant's characteristic properties are: The membranes can also influence adherence by cells to them. Certain recent studies have explored incorporation of materials to implants such as integrating drug delivery systems [13-16]. For customized implants, AM is uniquely beneficial since it can frequently start with immobilizing the patient's unique anatomy, oftentimes using medical models, and these can act as a template for producing personalized, patient-specific solutions [12].

2.2. Bioprinting and tissue engineering

3D bioprinting has already been patented ever since 2003 and has already been utilized to create tissues and organs. This involved producing three-dimensional tissue-like constructs by printing cells layer by layer on top of a biocompatible scaffold to obtain a defined layering process. This process involves printing cells by using a 3D printer onto a biocompatible matrix, enabling tissue formation close to natural ones [17]. These cells are then allowed to grow inside the scaffold, by itself normally being 3D printed with 3D printing technologies like fused deposition modeling (FDM) [18]. Among its major benefits is its capacity to print personalized designs from a patient's anatomy unique to them and frequently acquired through 3D scanning or medical imaging. Sterility is always necessary to be ensured during the process and frequently through later sterilization after printing [19]. The cell growth at times needs to take place either in vitro or in vivo prior to final application [20]. 3D models in vitro are informative tools as pertains to understanding interactions at an environment and cellular level and can aid researchers' comprehension towards biological processes and helping to further fields such as cancer research [12].

Scaffold printing techniques preserving microstructures with enhanced reproducibility have also been developed by researchers [21]. Though full-fledged, bioprinting is marred by adverse factors like degradation of cells with time and restricted interactions at the cell-to-cell level. To overcome some of these challenges, printing cells sans scaffolds was conceived by Ozbolat [22] and others, and it shows strong potential for the future of tissue engineering and regenerative medicine. Additionally, AI in discovering and developing biocomposites for tissue engineering marks a major biomedical advancement [23].

2.3. Surgical tools

AM has proved to be a most critical technology with different medical uses like planning surgery, designing implants, and teaching. Surgeons can practice and meticulously schedule surgeries preoperatively by virtue of using AM and it can boost their confidence and accuracy. Due to planning ahead, operation time can reduce and risks during surgery can reduce substantially. Apart from this, 3D printed prototypes are valuable graphic resources to communicate complex concerns to peers or students. Apart from this, AM has wide applicability to develop accurate 3D anatomical models to allow effective teaching and understanding of human anatomy among health care workers and students [24].

3. Automotive applications

The automotive industry is heavily dependent upon new-product innovation, yet it can be difficult and cost-intensive at times. The additive manufacturing process has thus become a main vehicle through which to decrease development time and expenditure and significantly lower cost of manufacture to enhance vehicle design and construction procedures components [5, 25, 26]. However, AM is confronted with some major challenges for this industry, some of them being: (i) generation of thermal stresses during printing, producing performance and consistency issues with parts [27], (ii) surface finish and dimensional accuracy issues [28], and (iii) challenges with producing large-volume components efficiently by [29].

3.1. Rapid prototyping

Employing AM to achieve rapid prototyping has some benefits like quicker product advancement and reduced manufacturing cycles later on, thereby reducing total costs [30]. The process lets manufacturers make tangible prototype models fast from CAD data to support design verification and testing. Technologies involving stereolithography [31-34] and selective laser sintering [35, 36] permit engineers to repeat on design quickly compared to orthodox techniques. It streamlines the process advancement and supports enhanced design teams' cooperation by offering prototype models to test and evaluate for fit, form, and functionality. Early customer feedback incorporation through prototype application further supports enhanced vehicle performance and user satisfaction [37].

3.2. Custom parts and structures

Examples of structural elements like engine valves and turbocharger turbines show how automotive specialized parts can be made using AM [38]. Component customization makes it possible for manufacturers to create tailor-made solutions for high-performance vehicle applications with premium specifications. The technology facilitates realization of intricate geometries impossible with conventional techniques such as tailor-made brackets, housings, and engine parts, all optimized to achieve maximized functionality, minimum weight, and materials efficiency. This flexibility supports low-volume production, making it cost-effective to manufacture niche or personalized parts without the high tooling costs associated with conventional methods [39-41].

3.3. Lightweight component manufacturing

Reducing vehicle weight is vital for improving fuel efficiency and lowering emissions. AM facilitates the production of lightweight parts through advanced design strategies like topology optimization and lattice structures, which remove unnecessary material while maintaining strength and durability [42]. This approach has been successfully applied in manufacturing lightweight brackets [40], chassis components [43], and even entire vehicle frames. These innovations help decrease overall vehicle weight, boosting performance and aligning with industry sustainability goals [44, 45].

3.4. Tooling and manufacturing aids

Aside from creating final parts, AM is essential in developing tooling and aids for automotive production lines. AM enables quick, customized production of jigs, fixtures, and molds, which enhances precision and efficiency in assembly processes [46, 47]. The ability to rapidly produce complex tooling geometries at a lower cost allows manufacturers to adapt swiftly to changing demands or design updates [48]. Furthermore, using AM for tooling significantly reduces lead times compared to traditional manufacturing, fostering more flexible and responsive manufacturing operations [49, 50].

4. Construction applications

AM is developing the construction industry by making it possible to create building components directly from digital models.

4.1. 3D Printed building components

This technology enables the quick production of customized parts such as structural panels, cladding, columns, and even entire sections of a building [51-53]. Unlike traditional construction methods, 3D printing can craft intricate designs and personalized elements on demand, reducing dependence on standard prefabricated parts and providing greater flexibility in architectural design [39, 54]. The materials employed for 3D printing in construction include specialized concrete mixes, recycled plastics, and advanced composites, offering the ability to tailor properties and performance to specific project needs [55].

4.2. Advantages and sustainability in 3D printing for construction

3D printing technology in construction offers significant advantages over traditional methods, combining enhanced construction efficiency with sustainable practices [56]. Moreover, sustainability is a key advantage of additive manufacturing in construction [57]. The technology supports environmentally friendly building approaches. The capacity to print complex, energy-efficient structures allow incorporation of features like integrated insulation, reduced thermal bridging, and other energy-saving elements directly into building components [58]. A summarized Table 1 shows some of these benefits across various construction applications.

Table 1
Advantages of 3D printing in construction across performance and environmental dimensions.

Benefit	Brief description	Refs.
Speed & efficiency	Faster construction, ideal for urgent needs and on-site builds.	[59, 60]
Design flexibility	Creates complex, innovative shapes that traditional methods can't easily achieve.	[61, 62]
Cost savings	Lower labor costs, reduced errors, and optimized material use.	[63]
Material efficiency and waste reduction	Significantly reduces raw material consumption and landfill waste; supports circular economy via recyclable materials.	[64]
Energy conservation	Lowers carbon footprint throughout the lifecycle of the building, from production to use.	[41]
Automation & safety	Continuous, minimal-supervision operations improve safety and reduce downtime.	[65]

5. Conclusion

Additive manufacturing is developing different industries like medical, automotive, and construction by boosting rapid prototyping, allowing for personalized parts, supporting the production of lightweight components, and streamlining tooling processes. As technological progress persists, additive manufacturing is anticipated to become even more vital in fostering innovation and enhancing efficiency within various sectors. Overall, this technology is set to speed up production, reduce costs, and promote sustainability, paving the way for innovative and eco-friendly solutions.

Author contributions

Fatemeh Heidari: Writing – original draft, Writing – review & editing; **Saeid Gholizadeh:** Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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