Integrated Manufacturing of Soft Robots Based on 3D Printing

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Abstract. Traditional soft robots, which rely on multi-part processing and manual assembly, face inherent bottlenecks such as long manufacturing cycles, poor structural consistency, and difficulties in integrating complex functions. Leveraging its layer-by-layer accumulation and high design freedom, 3D printing technology provides a key solution for the one-step, integrated manufacturing of soft robots with complex internal distributed channels and functionally heterogeneous structures. This paper first systematically reviews various 3D printing technologies suitable for the integrated manufacturing of soft robots, along with their corresponding soft functional material systems. Finally, it discusses design strategies for integrated manufacturing, including holistic functional modeling, drive-structure integration, and multi-material topology optimization. By summarizing typical application examples of 3D printing-based integrated manufacturing of soft robots in fields such as machinery, biomimetic motion, and medical devices, this review highlights the significant advantages of integrated manufacturing in enhancing the performance, reliability, and functional integration of soft robots. Prospects for the development of smart materials and AI-enabled design are also presented.

Keywords: 3D printing, soft robot, Integrated manufacturing, multi-functional integration.

1. Introduction

At present, robots are developing towards precision, intelligence and miniaturization. Flexible robots, with their mechanical properties similar to biological tissues, excellent environmental adaptability and relatively safe human-machine interaction methods, have become indispensable in fields such as minimally invasive medical surgery, rehabilitation applications, bionic biology, and flexible grasping of robotic arms [1].

Compared with traditional rigid robots, the core advantage of soft robots lies in their ability to adapt to complex movements and environments through the deformation of the material itself. However, this feature poses high requirements for their manufacturing process [2]. For instance, in bionic applications, the manufacturing process requires multi-channel, multi-layer, and anti-deformation capabilities; in medical surgeries, it requires material safety, biocompatibility, and performance stability. In addition to meeting mechanical structure requirements, the integration of the driving unit and sensors with the mechanical structure of the soft robot also needs to be considered. This makes traditional manufacturing methods such as laser cutting, mold customization, and manual assembly, difficult to handle the complex internal cavities of soft robots. Moreover, the gradual combination of different materials and secondary assembly of multiple components significantly affect the motion accuracy and overall structural stiffness of soft robots, thereby affecting their stability and reliability.

The rise and maturity of 3D printing technology have brought a disruptive solution to these problems. Through 3D printing technology, soft robots can be manufactured in an integrated manner, fundamentally solving the problems brought by traditional manufacturing methods [3]. In recent years, scholars have explored and developed aspects such as printing technology [4, 5], engineering materials [6], mechanical design [7], and application practice [8], achieving rich results.

In this regard, this article aims to provide a systematic review of the integrated manufacturing of 3D printed robots. Firstly, it sorts out the unique printing technologies of 3D printing in the integrated manufacturing of soft robots. Secondly, it compares and analyzes the impact of different materials on the integrated manufacturing of soft robots. From the perspective of mechanical design, it summarizes the design schemes and strategies of soft robots by relevant personnel. Finally, through related

practical applications, it discusses the innovation of 3D printing in the integrated manufacturing of soft robots and future development trends.

2. 3D printing technology for integrated manufacturing of soft robots

2.1. Material Extrusion Technology

Material extrusion technology, especially Fused Deposition Modeling (FDM), has become one of the most attractive techniques in soft robotics fabrication due to its low equipment cost, ease of operation, and wide range of available materials. The fundamental principle involves melting filament or pelletized thermoplastic materials through a heated extruder and selectively depositing them layer by layer onto a build platform, ultimately forming a three-dimensional solid. In the field of soft robotics, the advantage of this technology lies in its ability to directly print flexible components with complex internal channels, cavity structures, and graded stiffness, providing a crucial pathway for integrated fabrication of actuation, sensing, and structural functions.

In soft robotics, this technology is mainly applied to process two categories of key materials. The first category is elastomeric materials. Material extrusion techniques based on thermoplastic polyurethane (TPU) and silicone have attracted attention due to their ease of molding, simple technical principles, and strong biocompatibility, enabling the robot body to achieve high flexibility and elasticity. The second category is functional materials, including conductive materials (for fabricating sensors or circuits) and magnetic composites (for magnetically actuated drives), which serve as the foundation for realizing intelligent and functional soft robots.

2.2. Photopolymerization Technology

Photopolymerization technology, also known as stereolithography (SLA), is an additive manufacturing technique that uses selective light exposure to liquid photosensitive resins, causing them to undergo polymerization reactions and solidify, forming a three-dimensional object layer by layer. Compared to material extrusion technology, the most significant advantage of photopolymerization technology is its extremely high printing precision and excellent surface finish. This makes it irreplaceable in the fabrication of soft robotic components that require small features, complex details, and high sealing performance.

Photopolymerization-based 3D printing can be used to manufacture a variety of microfluidic devices, which can be applied in studies of the growth, patterning, vascularization, and tissue interaction of stem cell-derived spheroids, organoids, and tissue implants. Rochelle Aubry and others utilized photopolymerization-based 3D printing technology to fabricate a microfluidic chip for organoid vascularization. Based on this, they designed and manufactured a partition device for precise cell and organoid seeding, integrating the potential for controllable medium flow generation [9].

2.3. Direct Ink Writing

Direct Ink Writing (DIW), also known as robotic deposition molding, is an extrusion-based 3D printing technology. The basic principle involves a nozzle controlled by a computer, which extrudes a viscous "ink" with specific rheological properties in the form of a continuous filament. This filament is precisely extruded along a preset path and stacked layer by layer to eventually build a three-dimensional structure.

DIW is highly favored in the field of soft robotics today and is considered the fundamental manufacturing method for future soft robots. This prediction is primarily due to the following outstanding features: a wide variety of materials, the ability to seamlessly switch between different functional inks, and specialized manufacturing for multi-materials and complex internal structures. Therefore, DIW is generally used in soft robotics for manufacturing functional integration, especially for mechatronic soft robots [10]. It has gained considerable attention for producing intelligent machines and electronic devices that interact safely with humans and the environment [11].

In the future, DIW will no longer be limited to the fabrication of mechanically driven integrated soft robots but will also be used to prepare experimental research materials, directly integrating the driving structure with the mechanical structure. Researchers from the University of Toronto, including Zhaoxin Li [12], mixed magnetic particles with silicone rubber elastomer to create a printable "magnetic ink." Using Direct Ink Writing (DIW) technology, they applied a strong magnetic field during the printing process to "magnetically program" the material. The printed structures, when exposed to an external alternating magnetic field, can perform pre-designed, rapid, and complex three-dimensional movements.

2.4. Other Emerging Technologies

Technologies such as material jetting, embedded 3D printing, and 4D printing are collectively driving additive manufacturing from traditional rapid prototyping tools to profound changes in the production of complex functional parts and intelligent structures. Among them, material jetting technology, using high-precision arrayed nozzles, can simultaneously jet light-sensitive resins of multiple materials or colors onto the build platform in micro-droplet form. These droplets are immediately cured by ultraviolet light, achieving high resolution and multi-material integration comparable to the surface quality of injection-molded parts [13]. This technology shows immense potential in the fields of electronics, medical devices, and consumer products.

Embedded 3D printing represents a breakthrough paradigm shift. It moves beyond the limitation of layer-by-layer accumulation in the air and involves immersing the print head into a supporting matrix filled with yield-stress gel [14]. As the print head moves, the gel flows and rapidly solidifies, fixing the printed structure in place in mid-air without the need for additional support structures. This enables the production of extremely fragile cantilevers and complex hollow forms [15].

Further, 4D printing extends 3D printing into the time dimension. Its core involves using specially designed smart materials or composite material structures. After printing, these components can undergo controlled changes in shape, properties, or functions over time when triggered by external stimuli such as heat, moisture, magnetic fields, or electric currents [16, 17].

2.5. Technical Summary

3D printing technology provides diverse and integrated solutions for the design and fabrication of soft robots. Material extrusion techniques are low-cost and suitable for prototype validation and rigid structural components. Photopolymerization technologies offer high precision, making them ideal for micro-actuators and biomimetic structures. Direct ink writing and material jetting support multi-material and functional integration, enabling further studies of soft robots under various environmental conditions. Embedded printing requires no support structures and is suitable for fabricating bio-hydrogel robots and complex fluidic channels. 4D printing introduces intelligent responsiveness, extending the temporal dimension of soft robots. Powder bed fusion is suitable for highly complex, high-strength internal components. Together, these technologies drive soft robots toward high performance, multifunctionality, and intelligence. Table 1 summarizes the unique advantages and distinctions of each printing technology.

Table 1. The comparison of 3D printing technologies suitable for the integrated manufacturing of soft robots

Technology Category	Basic Principle	Representative Technology	Unique Advantages	Applicable Scenarios
Material Extrusion Technology	Heat-sensitive materials are melted and extruded through a nozzle, stacking layer by layer to form the structure.	Fused Deposition Modeling (FDM), Direct Drive Extrusion, Pellet Extrusion	Lower cost, Simple operation	Low-cost prototype validation, rigid structural parts.
Photopolymerization Technology	Selectively irradiate the liquid photosensitive resin with light to initiate polymerization and solidify it, layer by layer.	Masked Stereolithography (PJP), Continuous Liquid Interface Production (CLIP), Two-Photon Polymerization (TPP)	High printing precision, Smooth surface	High precision, high surface quality micro soft actuators, microfluidic chips, bionic structures.
Direct Ink Writing (DIW)	Precisely extrude “ink” from a nozzle and deposit it according to preset paths to build a 3D structure.	/	Variety of materials, Functional integration	Prototype validation Non-load-bearing structural parts.
Material Jetting Technology	Photosensitive resin is jetted onto the platform and subsequently solidified using ultraviolet light.	PolyJet Technology	Multi-material integration, Gradual variation in color and hardness	Manufacturing of function-integrated bionic soft robots.
Embedded 3D Printing	The printhead is submerged in a container filled with support gel to print.	/	No need for traditional support, can print suspended structures, good biocompatibility.	Printing of biological hydrogel robots Printing complex fluid channels in preset cavities.
4D Printing Technology	Based on 3D printing, intelligent materials are used to enable the printed structure to change shape over time in response to external stimuli.	Photopolymer 4D Printing, DIW 4D Printing, FDM 4D Printing	Adds a time dimension, simplifies system design, Enables adaptive and intelligent responses	Environmentally adaptive soft grippers, Programmable shape-changing bionic actuators.

3. Functional Printing Materials for Integrated Manufacturing

3.1. Soft Matrix Materials

3.1.1. Thermoplastic Polyurethane (TPU)

TPU is gaining significant attention in soft robot integrated manufacturing due to its excellent toughness, high wear resistance, high tear strength, and strong interlayer bonding. TPU comes in a wide range of Shore hardness, from Shore A 60-70 to Shore A 95, which allows for the design of actuators with different stiffness according to the needs. TPU is primarily used in FDM printing, and

some variants are suitable for SLS and DIW. It is commonly used in pneumatic actuators, flexible robotic claws, bionic shock absorption modules, etc.

In FDM printing, TPU demonstrates excellent mechanical performance. Xie Bowei from South China Agricultural University conducted mechanical property experiments on TPU [18], establishing finite element models for TPU tensile samples and performing simulations. They focused on the material parameters fitted with four models.

In SLS printing, TPU also performs well. Xie Renguli Mititursun from Xinjiang University [19] studied the mechanical properties, deformation modes, and energy absorption capabilities of TPU samples with different porosities using compression experiments and finite element analysis. The experimental data showed that TPU parts manufactured by selective laser sintering are highly suitable for integrated manufacturing in soft robotics.

3.1.2. Flexible Photopolymer Resin

Due to its high printing precision, isotropy, and adjustable mechanical properties, flexible photopolymer resin has become a key material for manufacturing soft actuators with complex microstructures and excellent surface quality. Flexible photopolymer resins are commonly used in complex pneumatic or hydraulic actuators to mimic biological movements like those of elephant trunks or octopus tentacles. In the field of micro-robotics, they are used to manufacture soft actuators at millimeter or even sub-millimeter scales, often for applications in biomedical fields like targeted drug delivery and minimally invasive surgery.

Currently, photopolymer resin technologies for soft robots in the biomedical field are relatively mature. Siyu Chen and his team from South China Agricultural University developed a flexible composite resin based on acrylated epoxidized soybean oil (AESO) for LCD light-curing 3D printing [20]. The printed material showed excellent mechanical properties, with a tensile strength of 6.7 MPa and a fracture elongation of 39.4%, providing the required flexibility and mechanical strength for soft robots. More importantly, the material exhibited high biocompatibility, with almost no cell death observed in cytotoxicity tests.

Compared to general materials like silicone rubber, photopolymer resins still face challenges such as insufficient sensitivity to small stresses and limited compatibility with conductive materials. Tong Guan and his team from Shanghai University [21] developed an ion composite photopolymer resin based on polyurethane acrylate and ionic liquids to create a highly sensitive piezoresistive pressure sensor for low-pressure environments (9.8 Pa to 10.7 Pa), thus overcoming the limitations of traditional high-pressure resistive sensors.

3.1.3. Silicone Rubber

Silicone rubber is considered an ideal material for high-performance soft robots, particularly in the biomedical and environmental interaction fields, due to its outstanding biocompatibility, chemical stability, and tissue-like mechanical properties [22]. However, silicone rubber does not belong to traditional thermoplastics, making it more challenging in terms of equipment and process requirements, placing it in the "high-end" category in the field of soft robotics.

Currently, the integrated manufacturing of silicone mainly relies on direct ink writing (DIW) technology, which builds three-dimensional structures by extruding the raw material slurry and curing it in real time. However, when it comes to soft robots with complex suspended or hollow features, traditional DIW technology has obvious limitations. To address this, sacrificial materials (such as gelatin, Pluronic F-127) are often introduced as temporary support cores, which are dissolved or heated and removed after printing to form closed inner cavity channels.

3.2. Shape Memory Polymers

Shape Memory Polymers (SMP) are smart materials that can undergo deformation under external stimuli and gradually return to their original shape [23]. These materials have unique advantages, such as large deformation, multiple stimulus types (e.g., heat, light, electricity, magnetism, solvents), and controllable driving mechanisms, making them highly suitable for use in 4D printing [24, 25].

Currently, SMPs are mainly used in the medical field. In 2007, Buckley Patrick R and his team错误!未找到引用源。26] first applied SMP in clinical experiments by creating an SMP material that could expand at body temperature, which was used to make a shuttle-shaped embolization device for arterial aneurysms. The device, when placed in an external model via a catheter, was initially small. Upon reaching the aneurysm or blocked artery, it expanded at body temperature or through light stimuli to its pre-set permanent shape, either opening the blood vessel or sealing the aneurysm. Over time, many researchers have applied SMPs to soft robot-integrated manufacturing for various purposes, such as creating scaffolds for pluripotent stem cell osteogenesis [27], optimizing blood vessel self-folding stent structures [28], and preparing biodegradable SMP scaffolds suitable for human body temperature [29].

3.3. Conductive Composite Materials

3D printing not only plays a crucial role in the integrated manufacturing of soft robots in terms of structural modeling, but it also provides an alternative approach for the functions of perception, feedback, and actuation in soft robots. Specifically, 3D printing based on conductive composite materials offers a new direction for current research [30]. Generally speaking, conductive composite materials consist of an insulating elastomer matrix with conductive fillers dispersed within. This composition ensures that, in addition to having substantial toughness and stretchability, the material conducts electricity directly, which greatly optimizes the structural design of soft robots and enables convenient and efficient signal communication between different robot bodies.

Due to the varying application purposes of integrated manufacturing in soft robots, there is no standard formula for conductive composites. Generally, the elastic body is commonly prepared with materials such as water-based polyurethane (WPU), TPU, or resins, while conductive fillers are more application-dependent, typically incorporating amounts of graphene (GR), carbon black (CB), etc., with no strict requirements.

3.4. Material Summary

In the integrated manufacturing of soft robots, material selection is the cornerstone for achieving the integration of structure and function. Specifically, each material system has a clear division of labor: thermoplastic polyurethane (TPU) bears the main structure with its high elasticity; flexible photosensitive resin is responsible for complex bionic models with high precision; silicone is widely used in pneumatic actuators and medical devices due to its excellent biocompatibility; shape memory polymers (SMP) endow robots with programmable deformation capabilities; and conductive composites, through integrated circuits and sensors, ultimately achieve a deep integration of "structure and function". Table 2 is a comparative summary of 3D printing materials applicable to the integrated manufacturing of soft robots:

Table 2. The comparison and summary of 3D printing materials suitable for the integrated manufacturing of soft robots

Material	Common Printing Technologies	Actual Applications	Unique Advantages	Technical Limitations
Thermoplastic Polyurethane (TPU)	Material extrusion technology	Main structure, robotic joints, flexible hinges	High elasticity, high toughness, mature printing process, low material cost	Low precision, poor surface finish, single function, lack of active drive and sensing capabilities
Flexible Photopolymer Resin	Photopolymerization technology	High-precision complex structures, biomimetic models	High printing precision, smooth surface, adjustable mechanical properties	Insufficient stability, low mechanical strength, often requires post-processing
Silicone	Direct ink writing, material jetting technology	Pneumatic actuators, biomimetic soft tissues, and medical devices	Very high biocompatibility, good flexibility, stable chemical properties, and high transparency	High printing difficulty, low mechanical strength, easy to tear, and difficult to bond with other materials
Shape Memory Polymers (SMP)	Material extrusion technology, direct ink writing, photopolymerization	Programmable actuators, self-expanding/folding mechanisms	Multiple types of response stimuli, stable response stimuli, and strong shape recovery ability	Slow response speed, limited cycle life, requires external stimulus for activation
Conductive Composites	Direct ink writing, material extrusion technology	Embedded sensors, flexible circuits, soft actuators	Customized circuits, high functional integration	Lower conductivity than normal metals, insufficient long-term stability, and it affects the mechanical properties of the base material.

4. Design Methods and Strategies for Integrated Manufacturing

The core challenge in the manufacturing of soft robots lies in how to efficiently and seamlessly integrate flexible drive units with complex body structures. Traditional methods rely on welding, sewing, and assembly, which lead to cumbersome processes, inconsistent stiffness, and interface stress concentration, seriously affecting the reliability of the connection parts with the drive mechanism. In the manufacturing of large soft robots (such as octopus tentacles), due to the limitations of current 3D printing technology, the drive and connection mechanisms are usually manufactured as a single unit, while in small robots (such as frog hind legs), the flexible movement of biological bodies is replicated by embedding circuits. For example, Virginia Tech in the United States [31] used silicone 3D printing to develop an octopus bionic glove, integrating a microcontroller, achieving an underwater adhesion force of over 60 kilopascals and rapid adsorption cycles of more than 400 times per second, outperforming the biological body.

Multi-physics coupling simulation, as a technical pillar of integrated design, can simulate the interaction of multiple physical fields during the process of drive-deformation-sensing. For soft robots, the essence of "drive-deformation-sensing" is the result of real-time coupling of multiple physical fields. Through this simulation, researchers can accurately predict the behavior of robots in a virtual world, thereby obtaining design guidance, performance optimization directions, and feasibility analysis. Specific case examples are shown in Table 3.

In this context, multi-material topology optimization, as an advanced and open-source auxiliary design method, fully leverages the advantages of 3D printing in manufacturing complex internal structures and multi-material integration. Based on user-defined force and deformation conditions, it automatically evolves the structure morphology and material distribution through calculation, advancing the traditional "material presence or absence" problem to a "material distribution" problem. Thus, while enhancing performance, it generates hollow and efficient structures that are both organically aesthetic and practical, effectively lowering the threshold for non-mechanical professionals to achieve high-performance designs.

Table 3. Practical Applications of Multi-Physics Coupling Simulation in Different Dimensions

Dimension	Principle	Case Example
Design Guidance	Predict the nonlinear response of complex structures under multiple physical fields, replacing trial-and-error methods.	Fudan University used simulations to guide the design of the buckling behavior of elastic rods for ultra-soft actuators [32].
Performance Optimization	Optimize robot motion performance by accurately simulating interactions such as fluid-structure coupling and electromagnetic-structural effects.	The team at The Chinese University of Hong Kong used fluid-structure coupling simulations to analyze the propulsion mechanism and flow field structure of magnetic soft robots [33].
Feasibility Analysis	Perform finite element analysis on robots in extreme conditions within a virtual environment.	The RoboMirage simulation platform can accurately simulate complex interactions between soft robots and their environment, preventing issues such as "mesh penetration" and other failure problems [34].

5. Conclusion

3D printing technology, with its unique layer-by-layer manufacturing concept and high design freedom, offers a revolutionary solution for the integrated manufacturing of soft robots. By systematically reviewing mainstream printing technologies such as material extrusion, light curing, and direct ink writing, as well as functional materials like thermoplastic polyurethane, flexible photosensitive resins, silicone, shape memory polymers, and conductive composites, this paper demonstrates the significant potential of 3D printing in achieving the integration of "structure - actuation - sensing" in soft robots. Design strategies for integrated manufacturing, such as actuation-structure integration, multi-physics field coupling simulation, and multi-material topology optimization, further promote breakthroughs in the application of soft robots in fields such as bionic motion, medical minimally invasive operations, and environmental interaction. In the future, with the continuous development of smart materials and the deep integration of artificial intelligence-enabled design methods, 3D printed soft robots will move towards higher levels of integration, adaptability, and intelligence, and are expected to play a more critical role in cutting-edge fields such as flexible electronics, biomedicine, and human-robot coexistence.

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