The Application and Development of 3D Printing in the Manufacturing of Robot End Effectors

Jiale Wang

School of Electronic & Electrial Engineering University of Leeds, LS29JT, Woodhouse Lane, Leeds, United Kindom

el23jw@leeds.ac.uk

Abstract. With the development of intelligent manufacturing and robotics, end effectors, as the core components of robotics, are gradually attracting attention in terms of their performance and manufacturing methods. 3D printing technology, with its advantages of high customization and high efficiency, provides a new solution for structural innovation in robot end effectors. This paper reviews the current research achievements and progress of 3D printing technology in end effectors, especially in flexible robotic hands, and focuses on analyzing the achievements of several existing end effector designs. At the same time, this paper also points out in detail the shortcomings of current mainstream printing processes, as well as issues and challenges in process optimization and material performance. Finally, summarize existing research and propose future development directions, such as high-performance material research and development, AI-assisted modeling, etc. This paper aims to summarize existing developments and provide theoretical references for cross-disciplinary integration between 3D printing technology and robotics.

Keywords: 3D printing technology, end effectors, flexible robotic hands.

1. Introduction

In recent years, intelligent manufacturing and automation have developed rapidly, and robots have been applied in many industries, such as industry, medicine, and construction. Among these, end effectors are the most critical component of a robot system and directly determine the performance of the robot. In order to meet complex and changing work tasks, the manufacturing standards and process requirements for end effectors have also reached a new level.

Currently, 3D printing technology is becoming increasingly mature, providing more feasible methods for the manufacture of robot end effectors and bringing new ideas to the research and development of end effectors. Traditional craftsmanship has obvious limitations when it comes to creating soft structures and complex structures, while 3D printing technology offers unique advantages in terms of high flexibility, high customization, and high efficiency [1]. These advantages can be leveraged to further advance the structure and performance of robots.

In terms of current trends in robot development, the working environments for robots are becoming increasingly complex, and the demand for precision and highly customized structures is growing day by day. This demand has further driven the development of 3D printing technology in this field, making it an indispensable innovative force for overcoming technical bottlenecks in the future.

As a key component of a robot system that directly interacts with the outside world, end effectors have diverse functions and complex tasks, and are central to operations such as grasping, moving, and sensing. With robots gradually becoming lighter, smarter, and more flexible, traditional rigid end effectors are no longer able to meet the higher demands for adaptability to complex environments and operational flexibility. In contrast, soft end effectors, with their flexibility, deformability, and high safety, show broad application prospects in areas such as human-machine collaboration, medical rehabilitation, and service robots. However, soft actuator structures are typically complex, often involving multi-chamber, multi-material composite designs, which place extremely high demands on manufacturing precision, molding methods, and material performance. Traditional processing methods cannot meet the rapid prototyping and high precision requirements of such structures. For this reason, 3D printing technology, as an advanced manufacturing method that integrates design and manufacturing, has provided unprecedented possibilities for the research and development of soft end effectors. It enables rapid prototyping of complex geometric structures, small-batch customization, and integrated manufacturing of structure and function, and has attracted widespread attention and gradual application in both academia and industry.

This study will focus on the application of 3D printing technology in the manufacturing of robotic end effectors, with particular emphasis on the design and implementation of flexible robotic hands and soft end effectors. First, from the perspective of design requirements and usage environment, combined with the characteristics of flexible structures and application environments, we will explore the requirements for end effectors in terms of gripping accuracy, structural flexibility, strength, and durability. Secondly, we analyze the limitations of traditional manufacturing processes in complex structure forming and performance optimization, argue for the necessity and advantages of 3D printing processes in the manufacture of flexible and customized structures, and further look ahead to their future development potential. On this basis, we will review existing relevant research findings, summarize their innovative value and distinctive features in terms of practicality and reliability, and reveal the application trends of 3D printing technology in this field. Finally, based on the progress made so far, we summarize the key issues in the current research and propose corresponding improvement strategies, with the aim of providing a reference path for the rapid iteration and optimization of high-performance end effectors.

This paper aims to systematically analyze the current status and development trends of 3D printing technology in the manufacturing of robot end effectors, and to clarify the advantages and challenges of this technology in terms of structural innovation, functional integration, and customized manufacturing. At the theoretical level, provide a systematic reference framework for cross-disciplinary integration; In practical terms, we propose an end-effector design concept that combines manufacturability and high performance, promoting the adoption and implementation of 3D printing technology in complex application scenarios such as industrial automation and human-machine collaboration. This lays the foundation for the manufacture of robot end-effectors that are highly adaptable, highly accurate, and low-cost.

2. Existing research results

2.1. 3D-printed soft robotic hand with integrated flexible sensors

Hao Zhou and his research team proposed a soft robotic hand system based on multi-material 3D printing manufacturing [2]. Its core innovation lies in integrating flexible sensors into the structure, enabling the robotic hand to perform natural and fluid gesture transitions while avoiding collisions between fingers, and precisely executing grasping and handling tasks based on different gestures [2]. This study fully demonstrates the unique advantages of 3D printing technology in the manufacturing of complex structures and multifunctional integration. The robotic arm adopts an integrated five-finger soft structure design and uses FDM technology. All components are formed in one piece through multi-material 3D printing, eliminating the cumbersome assembly process and improving structural strength and response speed. The pressure sensors embedded in the system are placed inside the hollow spaces of each finger (as shown in Figures 1 and 2), enabling real-time monitoring of fingertip contact force and grip status. The data is then fed back to the control system, which automatically switches between gesture modes based on specific task requirements. This technology implements a closed-loop control logic of perception-judgment-execution, greatly improving the accuracy and stability of robots in the process of picking up objects. Experiments have shown that this soft robotic hand can recognize a variety of typical gestures, such as a fully open palm, thumb and index finger pinching, and thumb raised (as shown in Figure 3), and can switch functions with precision control based on these gestures. This design not only achieves lightweight and flexibility in mechanical performance, but also offers application advantages such as low cost, compact structure, and fast response.

This study provides technical references for fields such as human-computer interaction systems, service robots, and wearable smart devices. This further demonstrates the broad prospects of 3D printing in the manufacture of integrated intelligent end effectors, especially in terms of its important application value in multi-degree-of-freedom coordinated control and human motion mimicry.

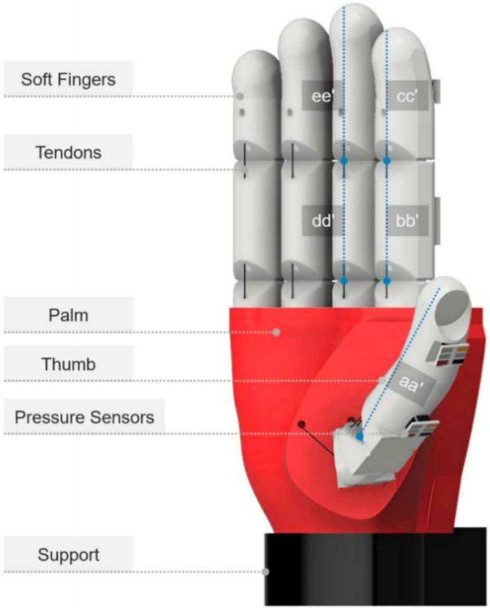

Figure 1. CAD-assisted design model [2]

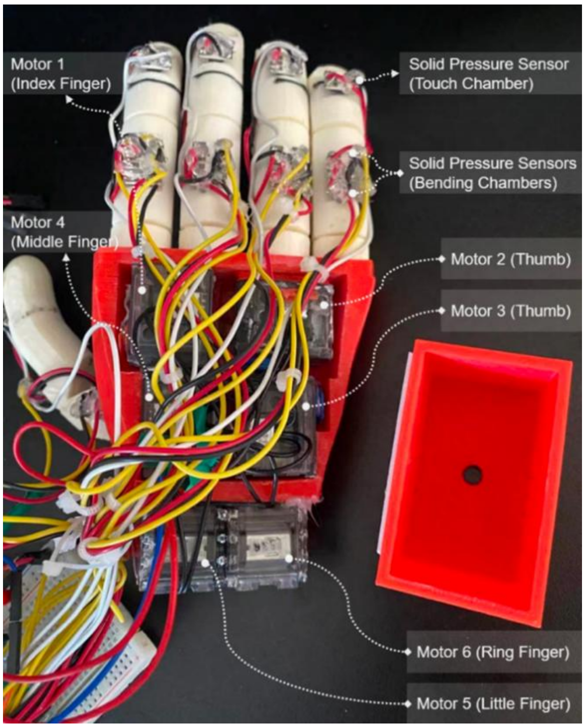

Figure 2. Robot hand back structure diagram [2]

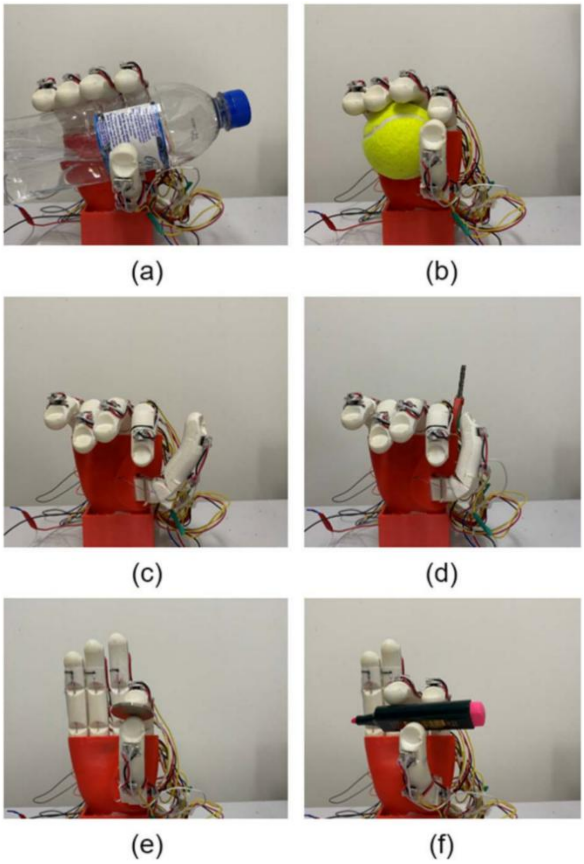

Figure 3. Demonstration of the robot arm's movements [2]

2.2. Soft robot hand with stacked compliant units

Metodi Netzev's research team proposed a soft robot end-effector design for industrial complex part handling tasks. Its core structure is based on a compliant unit stacking system and is manufactured using FDM and SLA processes in 3D printing technology [3]. This solution is particularly suited to workpieces that are irregular, fragile, or made of special materials, effectively addressing the poor adaptability and excessive gripping force commonly associated with traditional rigid grippers in such tasks. The robot gripper adopts a highly modular structural design, allowing flexible adjustment of the end effector's gripping range and motion form, thereby quickly adapting to objects of different sizes and shapes without replacing the entire gripper. Researchers used 3D printing technology to precisely print flexible materials (such as silicone) into controllable deformable unit modules, enabling the entire gripper to maintain overall structural strength while also possessing excellent flexibility and deformability. Experiments have shown that this structure can achieve enveloping gripping when faced with irregularly shaped or soft objects, i.e., the gripper applies force in multiple directions simultaneously to "envelop" the target object within itself, thereby providing a more stable and secure grip. This structure evenly distributes contact pressure during gripping, significantly reducing the risk of damage to fragile or soft objects, while also improving stability in dynamic gripping environments. In addition, the study also pointed out that this flexible gripper system has good scalability and cost control advantages. 3D printing manufacturing has significantly reduced prototype development cycles and costs, enabling rapid iteration in different application scenarios and providing strong support for customized industrial automation gripping solutions.

In summary, this study demonstrates the significant potential of 3D printing technology in the design of soft robot end effectors, particularly in unstructured, highly variable environments, providing technical support and theoretical reference for future intelligent manufacturing and flexible automated production lines.

2.3. Pneumatic Soft Gripper

Dongbum Kim's team designed a gas-driven soft gripper based on 3D printing manufacturing, which was structurally optimized and innovated based on the original design [4]. This design is manufactured using FDM technology, focusing on solving the common problem of angle deviation instability under pressure in traditional pneumatic soft clamps, and proposing a new structural solution with higher bending stability. Comparative experiments have shown that the new design improves stability at bending angles by approximately 15% compared to traditional structures, significantly enhancing the repeatability and controllability of the actuator in actual operation. This improvement not only enhances the performance of the actuator but also further validates the critical role of structural design optimization in the performance of soft actuators. This research demonstrates the potential applications of 3D printing technology in the construction of complex aerodynamic structures, rapid prototyping, and low-cost manufacturing, providing a strong technical foundation for the future development of end effectors designed for diverse gripping methods. At the same time, the successful development of this gripper has also provided new ideas for the in-depth application of 3D printing technology in the field of soft robotics, laying the foundation for flexible gripping tasks involving target objects of different sizes, shapes, and mechanical properties.

3. Limitations and future developments

Although 3D printing technology offers a milestone opportunity for the rapid development of robotic end effectors, from the perspective of current technological capabilities, there are still many limitations and challenges in its practical application. 3D printing technology offers a variety of processes, each with its own advantages and disadvantages. While it provides convenient and feasible solutions, it also presents technical bottlenecks at different levels, which greatly limit its deployment in the manufacture of robot end effectors

3.1. Limitations of the FDM Process

FDM is currently one of the most widely used 3D printing technologies. Its low manufacturing costs and fast speed have enabled it to quickly capture the social market. However, it has the following limitations in robot end-effector manufacturing applications [5]: Firstly, the dependency and complexity of support structures. In the FDM printing process, a large number of support structures are often required to ensure the stability of the printed parts. This not only significantly increases the time required for printing but also greatly increases the difficulty of post-processing. Secondly, there is the issue of errors caused by secondary processing of complex support structures. When removing support structures, machine cutting and other processes are relied upon, which can lead to errors in critical connection areas of the printed parts, thereby reducing the compatibility and stability of the connection between the component and the main body. Finally, it is difficult to meet the high precision requirements for printed parts. Due to the layer-by-layer fused deposition modeling process used in FDM, the surface finish of printed parts has inherent defects compared to other processes, making it impossible to meet the manufacturing requirements for high-precision end effectors.

3.2. Limitations of SLA Process

SLA demonstrates its advantages in the manufacture of complex components with its high manufacturing precision, and is particularly well-suited to the manufacture of small, high-precision, complex structural components. However, it has obvious disadvantages in the manufacture of robot end effectors: Firstly, SLA technology uses materials with low strength [6]. SLA technology mainly uses photosensitive resin as a raw material for printing, but photosensitive resin has the disadvantages of high brittleness and poor ductility. This will make it difficult to withstand the impact and fatigue of high-intensity working environments. Secondly, SLA technology is relatively expensive [7], with high costs for SLA equipment and materials, and a relatively complex usage process. These shortcomings have significantly reduced its promotion in the industrial field.

Apart from the two mainstream processes mentioned above, other processes and technologies have performance advantages in the manufacture of robot end effectors, but they generally have shortcomings in terms of cost and materials. Therefore, 3D printing technology faces several challenges in the manufacturing of robotic end effectors, including how to ensure the accuracy of complex structures while improving the strength and reliability of printed parts; how to reduce the dependence on supports, thereby enhancing printing accuracy and efficiency; and how to optimize structural design to improve the adaptability of printed parts. These challenges will be major bottlenecks in future development, and the application of 3D printing technology in the robotics field still requires breakthroughs.

Looking ahead, the development of 3D printing technology in the manufacture of robot end effectors will mainly focus on the following areas: First, the development of high-performance printing materials will be crucial, especially composite materials with high strength and durability to meet the demands of complex and high-intensity working environments [8]. Secondly, optimizing existing printing technology processes is the most direct path for development. By introducing new control strategies to address process defects, the surface smoothness and precision of printed parts can be improved, edge roughness reduced, and the further promotion and application of 3D printing technology in this field ensured [9, 10]. Furthermore, with the introduction of artificial intelligence, 3D printing modeling methods and manufacturing processes will be significantly optimized. AI will not only improve printing efficiency and accuracy, but also further tap into the potential of 3D printing technology in the manufacture of robot end effectors, gradually making it a core technology [11]. Finally, structural design optimization will become an important direction for technological advancement. Topology optimization algorithms can maximize the performance of printed parts, while the introduction of biomimetic design provides feasible solutions to manufacturing challenges. This not only enhances the flexibility of end effectors but also improves overall cost-effectiveness [12, 13].

4. Conclusion

This paper focuses on the application of 3D printing technology in the manufacturing of robotic end effectors. Current results show that the introduction of 3D printing in areas such as soft grippers has not only improved the adaptability of industrial parts handling but also verified the feasibility of complex structural design and functional integration. However, current mainstream processes still have bottlenecks: FDM has the advantages of low cost and high-speed molding, but it relies on support structures, has limited precision, and poor surface quality; SLA has high precision and is suitable for complex microstructures, but the material strength is insufficient, and the cost is relatively high. These issues limit its large-scale application in high-performance end effectors. End effectors are key components that enable robots to interact with the outside world, and their performance directly determines operational efficiency and scope. Compared with traditional manufacturing methods, 3D printing offers advantages such as rapid prototyping, complex structures, and functional integration, providing end effectors with more flexible design space and higher customization capabilities. This study analyzes its applicability and limitations, summarizes the main development directions of existing research results and their phased progress and innovations, and provides reference value for further research on material optimization, structural innovation, and process improvement.

Looking ahead, the development of 3D-printed robotic end effectors will focus on the following key areas: first, material innovation, with the development of composite materials featuring high strength and high toughness to address the high-load conditions encountered in industrial production; second, optimizing printing processes by introducing new control strategies to address existing process limitations; third, incorporating AI-assisted and topological optimization algorithms to achieve structural light weighting and performance maximization; Finally, integrating biomimetic design principles to optimize the structure of the end effectors and enhance their adaptability.

Breakthroughs in the above development directions will promote the in-depth application and industrialization of 3D printing technology in the field of robotics.

References

[1] Blanco, K., Navas, E., Emmi, L., & Fernandez, R. (2024). Manufacturing of 3D printed soft grippers: A review.

[2] Zhou, H., Tawk, C., & Alici, G. (2022). A 3D printed soft robotic hand with embedded soft sensors for direct transition between hand gestures and improved grasping quality and diversity.

[3] Netzev, M., Angleraud, A., & Pieters, R. (2020). Soft robotic gripper with compliant cell stacks for industrial part handling.

[4] Kim, D., Baek, S. R., Kim, M. S., Park, C. Y., & Lee, I. H. (2024). Design and manufacturing process of pneumatic soft gripper for additive manufacturing.

[5] Carta, M., Loi, G., El Mehtedi, M., Buonadonna, P., & Aymerich, F. (2025). Improving surface roughness of FDM-printed parts through CNC machining: A brief review.

[6] Palmer, J. H., Harper, J. D., & Marc, J. (2001). Control of brittleness in butyl-methylmethacrylate resin embedding mixtures to facilitate their use in immunofluorescence microscopy.

[7] Abbasi, M., Váz, P., Silva, J., & Martins, P. (2025). Head-to-head evaluation of FDM and SLA in additive manufacturing: Performance, cost, and environmental perspectives.

[8] de Sousa Filho, V. A., de Alencar Lira, M. C., & Bonfim, R. L. P. (2025). Reactive and non-reactive compatibilization of polyethylene terephthalate glycol/thermoplastic polyurethane (PETG/TPU) blends for 3D/4D printing applications.

[9] Zhou, R., Jiang, J., Li, P., Lu, S., Li, B., & Du, C. (2025). Optimized compound control strategy for high-speed 3D printing: Enhancing surface quality and printing precision.

[10] Heiss, A., Thatikonda, V. S., & Klotz, U. E. (2025). Multi-objective optimization of LPBF manufacturing with Zn-4Al-1Cu alloy for technical applications.

[11] Hassan, M., Misra, M., Taylor, G. W., & Mohanty, A. K. (2024). A review of AI for optimization of 3D printing of sustainable polymers and composites.

[12] Yang, W., Wang, L., Ma, G., & Feng, P. (2023). An integrated method of topological optimization and path design for 3D concrete printing.

[13] Du, G., & Qian, Y. (2024). Bio-inspired innovations in 3D concrete printing: Structures, materials and applications.