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Design of Flexible Gripper Mechanisms and Research Development in Variable Stiffness Technology

Aaron S. Zhang [1, *]

[1] Walt Whitman High School, Bethesda, Maryland, USA

* Corresponding Author Email: aazhang5598@gmail.com

Abstract. As a key executing mechanism of operational robots, flexible grippers have demonstrated significant advantages in unstructured environment operations, gripping of irregular objects, and safe human-machine interaction due to their flexible deformation ability. However, the inherent contradiction between flexibility and load-bearing capacity restricts its wider application. This article systematically reviews the mechanism design principles, research progress on variable stiffness technology, and related key technologies of flexible grippers. Firstly, the design methodology of flexible grippers was analyzed, covering topology optimization, shape and size optimization, and multi-objective optimization strategies; Secondly, classify and sort out the variable stiffness technology, and evaluate the principles and applicable scenarios of various methods; Finally, in response to the shortcomings of existing research, future development trends in multi-objective optimization, intelligent material integration, and biomimetic design are pointed out.

Keywords: Flexible gripper; Compliant mechanism; Variable stiffness technology; Topology optimization; Bionic design.

1. Introduction

Robots are known as the "crown jewel at the top of the manufacturing industry", and the performance of the gripper, as the actuator of the operational robot, directly determines the overall operational capability of the robot. Compared with traditional rigid claws, flexible claws mainly utilize the soft deformation of materials to achieve gripping motion, and have unique advantages in adapting to the shape of the target and ensuring operational safety. Thanks to the flexible deformation ability of the material, flexible claws can effectively resist external impacts and achieve safe grip in unstructured environments [1-4].

However, while pursuing flexible deformation, flexible claws also face problems such as low output force and poor operational accuracy due to insufficient structural stiffness. How to maintain load output capability while ensuring smooth deformation is the core contradiction that urgently needs to be solved. In recent years, with the development of intelligent materials and advanced processing technology, variable stiffness technology has become a key way to solve this contradiction. This article focuses on the mechanism design principles and variable stiffness technology of flexible grippers, systematically reviews the research progress in this field, and evaluates and prospects the existing achievements.

2. Design principles of flexible gripper mechanism

2.1. Basic principles and classification of compliant mechanisms

The essence of a flexible gripper is a compliant mechanism, whose motion depends on the elastic deformation of the structure itself rather than traditional rigid hinges. Unlike traditional rigid grippers that use rigid links and joints, flexible grippers utilize the soft deformation of materials to achieve gripping motion. Their ultra-redundant characteristics enable the gripper to actively or passively adapt to the surface of objects.

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According to the deformation mechanism and material properties, flexible claws can be divided into multiple types. Tarhan et al. classified flexible gripper systems into categories such as particle filled flexible ball gripper, hybrid gripper, and dual finger/Fin Ray gripper. Among them, the particle filled gripper utilizes the particle jamming effect to achieve adaptive gripping, which has the advantages of simple structure and low cost, but has limited load-bearing capacity; Hybrid grippers integrate rigid materials into soft structures, enhancing load-bearing capacity while maintaining a certain degree of flexibility. Park et al.'s research shows that the fingertip pressure of hybrid grippers can be increased by 1.5 to 2 times compared to pure soft grippers [5-7].

2.2. Biomimetic Design Principles and Optimization

Natural organisms achieve flexible movement through the continuous deformation of muscles, and the structural design of flexible claws draws heavily on the structure and movement behavior of biological limbs. Researchers have achieved shape adaptation while realizing grasping function through biomimetic structures and biomimetic movements [6].

From the perspective of biomimetic objects, existing biomimetic designs cover various biological prototypes such as octopus tentacles, snake entanglements, and sea anemone predation. For example, Li et al. designed a high-load soft gripper based on the biomimetic winding effect, effectively improving the gripping force; Hao et al. developed a biomimetic soft gripper with multimodal enveloping capability, combining various gripping mechanisms such as shape configuration, biomimetic adhesion, and expansion-driven suction cups. The core value of biomimetic design lies in transforming the superior mechanical structures formed by billions of years of evolution in nature into engineering and technological solutions [5-9].

The design optimization of flexible grippers usually involves three levels: topology optimization, shape optimization, and size optimization.

Topology optimization determines the basic configuration of the mechanism, that is, determining the distribution of materials within the design domain to obtain the optimal force transmission path and deformation mode. This stage has the most significant impact on the lightweighting and structural efficiency of the gripper. Shape optimization focuses on the contour design of structural boundaries, improving stress distribution and motion accuracy by adjusting geometric shapes. Size optimization is the process of finely adjusting the specific size parameters of each component after determining the topology and shape. Dao et al. pointed out that most compliant mechanism designs (including flexible grippers) integrate the above methods to leverage their respective advantages. Topology optimization provides initial concepts; shape and size optimization for subsequent improvement, ultimately achieving a design that is lightweight, structurally efficient, and meets manufacturing process requirements. Multi-objective optimization methods are widely adopted because flexible gripper designs often need to meet multiple performance indicators simultaneously, but there are often conflicts between these indicators (such as the contradiction between flexibility and stiffness), and how to balance these conflicts is one of the core challenges in this field [5-10].

3. Three-variable stiffness technology

3.1. The necessity and classification of variable stiffness technology

The core contradiction faced by flexible grippers is that flexibility requires materials with low stiffness to facilitate deformation adaptation, while load-bearing and precise positioning require high stiffness. Variable stiffness technology is a key technological direction developed to solve this contradiction.

In their review of agricultural harvesting soft gripper, Zhang et al. systematically reviewed the research progress of variable stiffness methods in the past five years, classified various variable stiffness technologies into different categories according to their mechanisms, and compared and analyzed them from dimensions such as bearing capacity, stiffness adjustment range, flexibility,

integration, response speed, and energy consumption. This review points out that the combination of material variable stiffness technology and motor-driven gripper structure performs better in unstructured environments for harvesting of woody crops (such as apples and citrus) and herbaceous crops (such as tomatoes and cucumbers) [4-6].

3.2. Main variable stiffness strategy

3.2.1. Granular Jamming.

Particle blockage is one of the early proposed variable stiffness methods. The principle is to encapsulate the granular material in a flexible capsule and lock the particles by friction through vacuum pumping, thereby achieving a significant increase in stiffness. Amen et al. developed a blocking gripper using coffee particles as a medium, which only requires a single air pump to complete the gripping and releasing actions, with an extremely simple structure. Gao et al. designed a new type of variable stiffness compliant gripper based on layered blocking, further expanding the application scope of this technology. The advantage of particle blockage lies in its large stiffness variation and rapid response, but it requires continuous vacuum to maintain stiffness, which poses energy consumption issues.

3.2.2. Variable stiffness of intelligent materials.

Intelligent materials, such as shape memory alloys, dielectric elastomers, magnetorheological materials, etc., provide new avenues for variable stiffness. Shape memory polymers can achieve reversible changes in stiffness through temperature regulation; magnetorheological elastomers can achieve rapid stiffness adjustment under the action of a magnetic field; Conductive polylactic acid materials can be used for 3D printing software drivers, with both stiffness and shape control capabilities. The advantage of the variable stiffness method for smart materials lies in its high integration and the ability to achieve local stiffness control, but it still faces limitations in response speed, fatigue life, and driving conditions.

3.2.3. Layered Blocking and Mixed Structures.

In addition to particle blockage, layer jamming also achieves stiffness adjustment by compressing multiple layers of thin film materials under vacuum to increase interlayer friction. The hybrid structure combines rigid and flexible components organically, providing basic support through a rigid skeleton, while the flexible part ensures shape adaptation. This strategy does not pursue a wide range of stiffness adjustment of the same material, but balances the dual requirements of flexibility and load-bearing through structural design.

4. Relevant Key Technologies

The driving methods of flexible grippers include tendon driving, fluid driving (pneumatic/hydraulic), intelligent material driving (dielectric elastomers, shape memory alloys, etc.), and chemical reaction driving, among others. Pneumatic drive is widely used due to its simple structure, cleanliness, and pollution-free nature; Tendon drive can mimic the movement of biological tendons and is suitable for multi-finger coordinated grasping; Intelligent material drive has unique advantages in small-scale and highly integrated applications.

Accurate modeling of flexible grippers is crucial for performance prediction and control. Due to the involvement of large deformations and material nonlinearity, its modeling is much more complex than that of rigid mechanisms. Research has shown that the choice of modeling methods directly affects the optimization design and formulation of control strategies. In terms of manufacturing, mold casting and additive manufacturing (3D printing) are currently the mainstream methods. Additive manufacturing technology is profoundly influencing the design decisions of flexible grippers; it enables rapid prototyping of complex topological structures and provides conditions for integrated molding of multiple materials.

Sensor integration endows flexible grippers with intelligent capabilities. Current research involves force/torque sensing, tactile sensing, and self sensing technologies based on the inherent properties of materials. The control strategy has evolved from traditional PID control to machine learning-based methods to meet the adaptive grasping requirements in unstructured environments [6-9].

5. Limitations and Prospects

5.1. Current research limitations

Although the field of flexible grippers has achieved fruitful results in mechanism innovation and variable stiffness technology, a systematic review of existing literature reveals that there are still several structural deficiencies in the methodology of this field that cannot be ignored.

Firstly, the design methodology exhibits obvious fragmentation characteristics. Topology optimization, shape optimization, and size optimization are the three core levels of compliant mechanism design, each of which has been deeply explored and has a mature methodology system. However, the system integration between the three still lacks a universal design framework. In the actual design process, the selection and connection of optimization strategies often heavily rely on the personal experience and engineering intuition of researchers, rather than following standardized design paradigms. This not only reduces design efficiency, but also limits the possibility of finding the optimal solution, making it difficult to discover a large number of potential configurations through systematic approaches.

Secondly, the serious lack of research on fatigue and reliability constitutes a key bottleneck restricting the engineering application of flexible grippers. The essential characteristic of a compliant mechanism is that it relies on the elastic deformation of the material to achieve its motion function, which means that fatigue failure is an unavoidable physical limit problem under cyclic loading. However, the literature review clearly points out that research on fatigue life assessment and reliability design of flexible grippers under repeated grasping and releasing conditions is "extremely rare". Considering the strict requirements for the durability of actuators in industrial scenarios such as high-speed picking and placing, this research gap has resulted in a lack of necessary engineering credibility support for the transition of flexible grippers from laboratory prototypes to actual deployment.

In addition, the absence of quality evaluation in the optimization process is also worth paying attention to. In the existing research on topology optimization of flexible grippers, the optimization objectives are mostly focused on mechanical indicators such as deformation capacity, stress distribution, or stiffness characteristics of the structure, while the direct measurement of gripping quality is often excluded from the optimization objective function. The result is that the optimized structural scheme may meet the design requirements in terms of deformation response, but the actual gripping effect may not be ideal, and there is a deviation between the optimization objectives and the actual operational performance.

5.2. Future Development Direction

Based on the above limitations and a prospective analysis of multiple reviews, future research on flexible grippers is expected to make breakthrough progress in the following directions.

In terms of multi-objective optimization, researchers are committed to breaking the limitations of single mechanical performance optimization and incorporating multiple physical fields such as structural mechanics, drive control, perception feedback, and even thermal management into a unified design optimization framework. The concept of multi physics field collaborative optimization aims to achieve global optimization of system level performance, rather than simply stacking the performance of each subsystem, and is expected to fundamentally solve the core contradiction between flexibility and carrying capacity.

Multi material and multifunctional integration is another important trend. With the continuous maturity of additive manufacturing technology, integrating different materials such as metamaterials, shape memory polymers, dielectric elastomers, and other smart materials in the same gripper structure has become technically feasible. This multi material strategy enables multiple functions such as driving, variable stiffness adjustment, and tactile perception to coexist and work together in a single structure, greatly improving integration without increasing the mechanical complexity of the system.

The deep intervention of artificial intelligence technology is reshaping the design paradigm of flexible grippers. Traditional design methods rely on researchers' experience judgment and limited simulation iterations, while artificial intelligence methods are expected to achieve data-driven integrated design generation - through training with a large amount of data, automatically completing topology optimization, parameter optimization, and even direct generation of design schemes, pushing the design process from "experience guidance" to a new stage of "intelligent guidance".

Finally, the development of flexible grippers is showing a trend towards customization for specific application scenarios. There are significant differences in the shape, size, surface characteristics, and vulnerability of gripping objects in different fields, and universal grippers are difficult to exhibit optimal performance in all scenarios. Taking agricultural harvesting as an example, developing specialized variable stiffness grippers has become a clear research direction for the different mechanical properties of woody crops such as apples and citrus, and herbaceous crops such as tomatoes and cucumbers. This deep customization for application scenarios is expected to achieve substantial breakthroughs in performance in specific tasks.

6. Conclusion

As a new type of robot end effector, flexible grippers demonstrate irreplaceable advantages over rigid grippers in adaptive grasping in unstructured environments. This article summarizes the research progress in this field from two main lines: mechanism design principles and variable stiffness technology. It analyzes the application of topology shape size optimization methods in gripper design, categorizes and elaborates on the main technical strategies such as particle blockage and intelligent material variable stiffness, and evaluates related driving, manufacturing, perception, and control technologies. The existing research has achieved significant results in biomimetic innovation and breakthroughs in individual technologies, but there are still significant shortcomings in systematic design methods, fatigue reliability, and grasping quality evaluation. In the future, design methods driven by multi-objective optimization, multi material integration, and artificial intelligence are expected to drive the development of flexible grippers towards higher performance.

References

[1] Dao T P, Le H G, Ho N L. Topology-shape-size optimization design synthesis of compliant grippers for robotics: A comprehensive review and prospective advances. Robotics and Autonomous Systems, 2025, 185: 104876.

[2] Pan J, Yu J J, Pei X. Development of flexible gripper mechanism design and variable stiffness technology. Journal of Mechanical Engineering, 2024, 60(13): 281-298.

[3] Tarhan B, Asif S, Webb P, et al. A review of flexible robotic gripping systems. Frontiers in Manufacturing Technology, 2025, 5: 1517727.

[4] Zhang D D, Zhang W, Yang H L, et al. A review of variable stiffness methods for soft grippers in agricultural harvesting. Machines, 2025, 13(1): 55.

[5] Abdelhafiz M H, Andreasen Struijk L N S, Dosen S, et al. Biomimetic tendon-based mechanism for finger flexion and extension in a soft hand exoskeleton: Design and experimental assessment. Sensors, 2023, 23(4): 2272.

[6] Soft robotic grippers: From design concept to fabrication and application scenarios. Journal of Field Robotics, 2026, 43(4).

[7] Hermoza Llanos E, Corves B, Huesing M, et al. Systematic mapping of synthesis methods for compliant grippers using PRISMA. Mechanism and Machine Theory, 2025, 206: 105900.

[8] Le H G, Ho N L, Dao T P. Design synthesis, modeling, control strategies, and fabrication methods of compliant grippers for micromanipulation and micromanipulator: A comprehensive review. Robotics and Computer-Integrated Manufacturing, 2025, 92: 102893.

[9] Gao Y, Huang X, Mann I S, et al. A novel variable stiffness compliant robotic gripper based on layer jamming. Journal of Mechanisms and Robotics, 2020, 12(5): 051013.

[10] Lee J, Kim J, Park S, et al. Soft robotic palm with tunable stiffness using dual-layered particle jamming mechanism. IEEE/ASME Transactions on Mechatronics, 2021, 26(4): 1820-1827.