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Multidimensional Performance Comparison and Evolutionary Trends of Typical Transmission Systems for Underactuated Robotic Hands

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Abstract

This review focuses on the transmission systems of underactuated robotic hands. It aims to compare the dynamic characteristics of three mainstream approaches—linkage, tendon-driven, and flexible structures—to reveal their performance bottlenecks and provide guidance for design optimization. Based on relevant theoretical and experimental data, the study comparatively analyzes key indicators such as force transmission efficiency, degrees of freedom, and environmental adaptability. The findings indicate that linkage transmission offers high stiffness and superior precision, making it suitable for heavy-load scenarios and widely used in aerospace applications. However, its bulky structure affects dynamic response speed. Tendon-driven transmission is lightweight and compliant, producing almost no rigid impact, which makes it ideal for biomimetic grasping and widely applied in medical rehabilitation due to its high safety. Nevertheless, it has insufficient lateral stiffness. Flexible structures exhibit strong adaptability to complex environments and are advantageous for handling fragile objects, such as in agricultural picking tasks, but suffer from low control precision and response lag. In summary, no universal solution exists. Future development should involve task-specific trade-offs in selection, exploration of hybrid mechanisms, or the integration of rigid-flexible coupled hybrid actuation systems.

Keywords

underactuated robotic hand, transmission system, rigid-flexible coupling, nonlinear control

1. Introduction

Underactuated robotic hands have become a highly dynamic research direction in robotics due to their unique advantages in lightweight design, biomimetic principles, and cost control. Their application prospects continue to expand, ranging from medical rehabilitation devices requiring compliant interaction to industrial collaborative scenarios pursuing human-robot coexistence. Reviewing their development, early research focused on the optimization of rigid linkage mechanisms. However, inherent issues such as friction losses and difficulty in achieving lightweight design have remained hard to overcome. In the 21st century, the combination of intelligent control algorithms and flexible structures has given rise to a new generation of products integrating distributed sensing and real-time feedback. The current frontier is moving toward integrated innovation, which not only enables precise torque control but also performs dynamic compensation, aiming to unlock greater potential for underactuated robotic hands in fields with demanding performance requirements [1].

The transmission system is the core of underactuated robotic hand research. It essentially serves as the critical hub determining overall performance and directly decides whether the system can realize the underactuated logic of achieving more degrees of freedom with fewer actuators. From a dynamics perspective, the transmission system acts as a force/impedance regulator, which directly affects the safety and stability of the hand during contact transients [2]. Furthermore, the topological structure of the transmission system (e.g., designs based on metamorphic mechanisms) directly shapes the workspace of the robotic hand [3]. Therefore, transmission system design is central to the hand's adaptability and robustness when facing complex, unstructured tasks, serving as the key bridge from theoretical models to practical applications. Accordingly, this paper reviews typical transmission system structures of underactuated robotic hands from previous years, aiming to provide theoretical support and selection guidance for transmission system optimization.

2. Main Types of Transmission Systems for Underactuated Robotic Hands

2.1 Linkage-Based Transmission Systems

In underactuated robotic hand transmission systems, linkage-based mechanisms transmit force and convert motion through rigid link assemblies. The core lies in utilizing the geometric constraints of linkages to transform the linear or rotary motion of actuators into complex motion trajectories at the joints.

This type of system exhibits high rigidity in kinematic analysis, ensuring precise force transmission. For example, Zhu et al. developed an underactuated robotic finger based on a crank-slider mechanism in series with a four-bar linkage, which solved the motion dead-point problem and enabled precise large-angle curling of the finger through minimal slider movement [4].

Another advantage of linkage-based underactuated robotic hands is their ability to withstand large loads and output high torques, resulting in superior grasping weight capacity compared to other transmission systems. A Korean research team developed a robotic hand with integrated linkage actuation [5]. During operation, the linkages experience almost no elastic deformation and thus minimal energy loss. By leveraging the lever amplification effect and optimizing link lengths, the team achieved a fingertip force of 34 N.

However, the inherent limitations of rigid linkages cannot be ignored. They increase system weight and affect dynamic response speed. The bulky nature of linkage structures limits their use in compact designs. In wearable exoskeleton devices, uneven mass distribution of linkages may reduce comfort and safety. In high-speed motion of lightweight parallel-linkage robots, elastic vibrations inevitably occur, affecting trajectory tracking and positioning accuracy [6]. To address these issues, Song used mechanism simulation software for dynamic analysis, quantified output torque, and optimized topology and mass distribution. As shown in Tables 1 and 2, under nearly unchanged maximum stress and displacement, the mass was reduced by 28% while the first-order natural frequency of the structure was improved [7]. Linkage transmission systems offer clear advantages in precision and rigidity, but lightweight design and dynamic performance remain frontier challenges.

Table 1: Natural frequencies of the beam before and after optimization [7]

Order	1st	2nd	3rd	4th	5th	6th
Before	234.32	304.34	361.1	398.39	529.21	598.31
After	278.51	284.64	405.7	408.17	547.12	577.6

Table 2: Comparison of maximum structural stress, displacement, and mass before and after beam optimization [7]

	Max. Displacement (mm)	Max. Stress (MPa)	Mass (Kg)	Mass Reduced (Kg)	Reduction Ratio (%)
Before	15.86	0.29	159.74	0	0
After	16.89	0.41	114.98	44.76	28

2.2 Tendon/Cable-Based Transmission Systems

Tendon-driven transmission systems use flexible connectors to simulate biological tendons, transmitting actuator motion to the joints of underactuated robotic hands. The core mechanism relies on tension transmission and deformation characteristics of the tendons [8]. High-strength polymers (e.g., Kevlar fibers) or metal alloys (such as shape memory alloys, SMA) are used as transmission media, with pretension maintaining stable torque transmission.

Tendon-driven systems offer excellent flexibility in dynamic response, absorbing impact loads and suppressing vibrations. They are significantly lighter than traditional linkage systems and provide greater dexterity, giving them unique advantages in biomimetic robotic hands. For instance, Huang et al. simulated human hand skeletal structure, optimized low-friction tendon routing channels, and employed bidirectional actuation principles to develop a highly dexterous tendon-driven anthropomorphic robotic hand [9].

In certain industries, tendon-driven hands are favored for their lightweight and stable operation with almost no rigid impact. A high-adaptability massage robotic hand developed by the China Academy of Chinese Medical Sciences adopted underactuated tendon transmission combined with a differential pulley mechanism to absorb impact energy and avoid rigid shocks. When massaging a subject, the overall massage force ranged between 22 and 33 N, enhancing comfort and safety while enabling multiple massage postures [10]. However, tendon-driven underactuated hands generally suffer from insufficient lateral stiffness, which is often addressed through composite structure designs.

2.3 Flexible/Soft Structure-Based Transmission Systems

Flexible structure transmission systems primarily rely on pneumatic, hydraulic, or soft materials to transmit force and control motion. The key is utilizing the nonlinear deformation characteristics of materials to achieve underactuated operation. Rather than discrete joint rotations, this system accomplishes underactuation through continuous body deformation.

A classic example is the compliant robotic hand developed by Sofla et al., which used Festo fluidic muscles to control axial motion and spherical hinges as auxiliary drives, enabling the continuous body structure to produce complex bending deformations [11]. This structure endows the hand with extremely high energy density and inherent safety, allowing it to naturally absorb impact energy during contact transients and effectively prevent rigid collisions with fragile objects.

Flexible robotic hands also demonstrate strong performance in adaptability to complex environments. Inspired by octopus tentacles, Kang et al. developed a multi-continuum-arm flexible robotic hand and robot [12]. The design mimicked the muscular hydrostat structure of octopus arms using a skeleton-free approach. Hydrodynamic modeling was performed to optimize the structure, enabling the hand to use fluid dynamics for propulsion or stable grasping in underwater complex terrains without being disrupted by water currents.

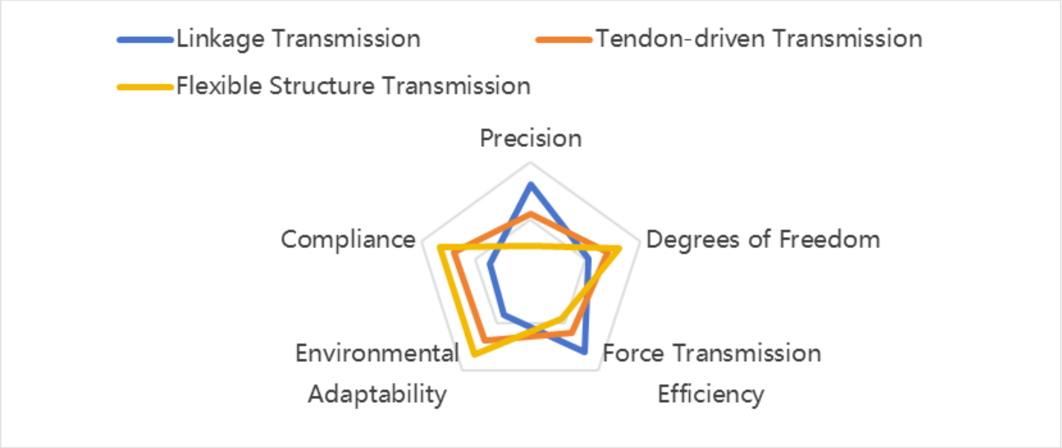
However, such systems face inherent challenges in control precision and response speed. Suppressing vibration and achieving accurate control remains difficult. In a typical case, scholars from Moulay Ismail University used a Kalman filter to provide state feedback for an adaptive model predictive control system, effectively suppressing tip vibration. The method can adaptively tune the process noise covariance $Q=10^{-4}$ and measurement noise covariance $R=2.5\times\mathrm{Diag}\,(0,10^{-3},0,0)$ under external disturbances, thereby significantly improving the system's robustness and control accuracy [13]. Nevertheless, dynamic response remains a bottleneck. Future research should focus on multi-material composite structures to balance compliance and dynamic performance.

3. Performance Comparison and Application Scenarios of the Three Transmission Methods

3.1 Comparative Performance Analysis of Different Transmission Systems

In the field of underactuated robotic hands, the transmission system serves as the core link connecting the actuator and the end-effector. Its performance parameters directly determine the hand's grasping capability, environmental adaptability, and operational precision. As shown in Figure 1, linkage-based transmission systems achieve force transmission and motion conversion through rigid link mechanisms, offering significant advantages such as high stiffness, large output torque, and precise position control [14]. However, their relatively high self-weight and structural complexity limit their application in lightweight scenarios. In contrast, tendon-driven systems simulate the biological structure of human tendons, using ultra-high molecular weight polyethylene or steel cables for long-distance power transmission. They provide high compliance, compact structure, and excellent adaptive enveloping capability [15]. Flexible structure transmission systems utilize elastic materials and underactuated mechanisms to achieve adaptive grasping through deformation, making them particularly suitable for handling fragile objects and irregularly shaped items [16]. The three transmission schemes exhibit significant differences in degrees of freedom, force transmission efficiency, and environmental adaptability. There is no universal solution; optimal selection must be made according to specific application scenarios.

Figure 1: Radar Chart of Performance Comparison of the Three Transmission Methods



3.2 Application Scenarios and Applicability Analysis

In the aerospace field, linkage transmission systems, with their kinematic precision and stiffness characteristics, can achieve sub-millimeter positioning accuracy, making them suitable for fine manipulation tasks. The linkage-driven dexterous hand jointly developed by the German Aerospace Center (DLR) and Harbin Institute of Technology (HIT) integrates physics-informed neural networks (PINN) with linkage coupling design, combining physical models with data-driven approaches to enable tool operation in microgravity environments [17].

In medical rehabilitation applications, optimized tendon-driven structures offer high load-bearing capacity and meet the requirements for high dynamic response with minimal rigid impact during finger rehabilitation training. The cable-driven finger motion rehabilitation training system developed by Southeast University uses steel cables to simulate human tendons. It dynamically adjusts the PWM duty cycle of MR dampers based on the deviation between set force and feedback force, achieving precise force tracking [18].

In the food and agricultural product processing sector, flexible structures employing underactuated degrees of freedom reduce the inertia of the end-effector, demonstrating superior safety and compliance. The flexible grasping-suction picking robotic hand developed by Nanjing Agricultural University adopts a multi-level compliance design, ensuring gentle grasping of apples through coordinated optimization of materials, structure, and actuation [19].

Based on the above case analyses, linkage transmission excels in scenarios requiring rigid constraints, tendon-driven transmission performs well in balancing lightweight design and precision, while flexible structures hold unique advantages in dynamic contact force control.

3.3 Common Challenges and Evolutionary Trends of Underactuated Transmission Systems

Underactuated robotic hand transmission systems are mainly divided into three categories: linkage, tendon-driven, and flexible structures. Although their technical approaches and performance metrics differ significantly, they share common core challenges. Underactuated systems are inherently nonlinear. Linkage systems face difficulties in solving kinematic equations, with limited degrees of freedom and complex structures. Tendon-driven systems rely on high-strength fiber cables to simulate tendon functions but suffer from tension control lag. Flexible structures depend on elastic material deformation for motion transmission, exhibiting the most severe nonlinearity due to large-deformation geometric nonlinearity and material hyperelastic nonlinearity in their constitutive relationships.

To overcome these bottlenecks, transmission system design is shifting from purely rigid or purely flexible structures toward rigid-flexible coupling. By combining the high precision of rigid mechanisms with the compliance of flexible structures, the challenges of nonlinear systems can be effectively addressed. For example, the underactuated exoskeleton rehabilitation glove developed by Li Kun's team adapts well to the nonlinear motion of the human hand. This is primarily because the biological finger was simplified into a four-bar linkage model, and traditional rigid links were replaced with rigid-flexible hybrid structures based on elastic materials, successfully overcoming nonlinear control issues [20].

4. Conclusions

In summary, research on transmission systems for underactuated robotic hands has evolved from single rigid or flexible structures toward multidimensional performance trade-offs. A single transmission mode struggles to meet increasingly complex engineering demands. Current technological evolution shows a clear trend toward integration, using rigid-flexible coupling mechanisms to balance the contradictions between nonlinear control and system robustness.

Future development of transmission system technology will deeply integrate intelligent materials science, multi-modal actuation mechanisms, and adaptive control theory, forming interdisciplinary innovation paradigms. In the field of intelligent material integration, combinations of shape memory alloys and piezoelectric ceramics can enable dynamic stiffness adjustment of transmission systems. In multi-modal hybrid actuation, coordinated control of pneumatic artificial muscles can significantly expand the system's workspace and load capacity. In terms of control, the development of adaptive control algorithms will focus on combining reinforcement learning with model predictive control to address nonlinear coupling problems in underactuated systems.

Future research should further explore the application of bio-inspired materials in extreme environments and real-time monitoring systems based on digital twins, so as to achieve full-lifecycle optimization of transmission systems.

References

[1] Shang, D. Y., Wang, H. Z., Yin, M., & Li, X. P. (2026). Fuzzy rule-based uncertainty identification control for underactuated space flexible link manipulators: Compensation for payload perturbations during capture. *Engineering Applications of Artificial Intelligence*, 172, 114249. https://doi.org/10.1016/J.ENGAPPAI.2026.114249.

[2] Mamo, M. B. (2025). Control of flexible link manipulators using nonlinear feedback. *Results in Engineering*, 27, 106186. https://doi.org/10.1016/J.RINENG.2025.106186.

[3] Sun, M. J. (2019). Design and research of underactuated manipulator based on metamorphic principle [Master's thesis, Northeastern University]. https://doi.org/10.27007/d.cnki.gdbeu.2019.002164.

[4] Zhu, Y. (2016). Research on a new type of mechanical finger [Master's thesis, Hebei University]. https://kns.cnki.net/kcms2/article/abstract?v=7DtDJWciuTJwR85dh9N80jFWE0DYIrFL4SC_9R6IVmPj_6_yVBCGxb67_8xjQ3jbY2B-rX5vkW21j4dmBFulsKa8plCMO_mXU4XhkdwYGKWX_GlHSnGxhqwiLuge8KGbTz6XAIOYrreGmRtLRTTscbrQS88VYOaeSiJTFK0ZO3XOolonoWT-ig==&uniplatform=NZKPT&language=CHS.

[5] Kim, U. K., Jung, D. W., Jeong, H. Y., Park, J. W., Jung, H. M., Cheong, J. O., ... & Park, C. H. (2021). Integrated linkage-driven dexterous anthropomorphic robotic hand. *Nature Communications*, 12(1), 7177. https://doi.org/10.1038/S41467-021-27261-0.

[6] Dong, L., Cui, M. J., Li, S. Y., Chang, B. Y., Wang, Z., & Zhang, J. P. (2026). Rigid-flexible coupling dynamic modeling and adaptive intelligent composite control for a novel redundantly actuated flexible parallel robot. *Advances in Engineering Software*, 212, 104048. https://doi.org/10.1016/J.ADVENGSOFT.2025.104048.

[7] Song, H. C. (2021). Research on dynamic analysis and optimization design of five-degree-of-freedom linkage mechanism manipulator [Master's thesis, China University of Mining and Technology]. https://doi.org/10.27623/d.cnki.gzkyu.2021.000567.

[8] Duan, J. Y., Hao, J. X., Du, P. Y., Zhang, B., Zhang, Z. Q., & Shi, C. Y. (2025). A high-precision and robust geometric relationships-inspired neural network for the inverse kinematic modeling of the tendon-actuated continuum manipulator. *Advanced Intelligent Systems*, 8(1), 2401027. https://doi.org/10.1002/AISY.202401027.

[9] Huang, G. W., Chen, H. H., Zhao, T. C., & Zhang, P. F. (2020). Development of cable-driven anthropomorphic robotic hand. *Electromechanical Engineering Technology*, 49(12), 76-77, 132.

[10] Deng, K., Meng, C. L., Liu, G. W., Zhan, J. W., & Zhang, Q. (2025). Structural design and analysis of high adaptability massage manipulator. *Journal of Mechanical Transmission*, 49(12), 89-97. https://doi.org/10.16578/j.issn.1004.2539.2025.12.011.

[11] Sofla, M. S., Sadigh, M. J., & Zareinejad, M. (2021). Design and dynamic modeling of a continuum and compliant manipulator with large workspace. *Mechanism and Machine Theory*, 164, 104413. https://doi.org/10.1016/J.MECHMACHTHEORY.2021.104413.

[12] Kang, R. J., Branson, D. T., Guglielmino, E., & Caldwell, D. G. (2012). Dynamic modeling and control of an octopus inspired multiple continuum arm robot. *Computers and Mathematics with Applications*, 64(5), 1004-1016. https://doi.org/10.1016/j.camwa.2012.03.018.

[13] Hannane, A., Bakhti, M., & Idrissi, B. B. (2022). Extended Kalman filter based adaptive model predictive control of a flexible manipulator. IFAC-PapersOnLine, 55(12), 707-712. https://doi.org/10.1016/J.IFACOL.2022.07.395.

[14] Niu, Y. X., Bai, Z. F., & Wang, H. (2025). Design and kinematic analysis of cable-driven underactuated manipulator on spacecraft. *Mechanics Based Design of Structures and Machines*, 53(5), 3887-3903. https://doi.org/10.1080/15397734.2024.2440523.

[15] Cao, X. G., Xiang, J. F., Wang, P., Wu, X. D., & Zang, J. S. (2025). Design and contact mechanics analysis of a dual-path transmission underactuated manipulator with mixed working modes. *Journal of Mechanical Transmission*, 49(02), 62-69. https://doi.org/10.16578/j.issn.1004.2539.2025.02.008.

[16] Mouazé, N., & Birglen, L. (2022). Bistable compliant underactuated gripper for the gentle grasp of soft objects. *Mechanism and Machine Theory*, 170, 104676. https://doi.org/10.1016/J.MECHMACHTHEORY.2021.104676.

[17] Al-Shahrabi, A., Javid, M. J., Fahmy, A. A., Griffiths, C. A., & Li, C. (2025). Torque tracking position control of DLR-HIT II robotic hand using a real-time physics-informed neural network. *Applied Mathematical Modelling*, 145, 116110. https://doi.org/10.1016/j.apm.2025.116110.

[18] Ouyang, Y. X. (2021). Finger motor function rehabilitation training system based on cable-driven [Master's thesis, Southeast University]. https://doi.org/10.27014/d.cnki.gdnau.2021.000394.

[19] Yi, B. Y. (2022). Design and experiment of flexible suction picking manipulator [Master's thesis, Nanjing Agricultural University]. https://doi.org/10.27244/d.cnki.gnjnu.2022.001284.

[20] Zhao, L., Guo, F. H., Yang, F., Li, C., Zhao, Y. F., Qu, J., ... & Bu, L. G. (2025). A novel underactuated exoskeleton rehabilitation glove for hand flexion and extension training. *Biomimetic Intelligence and Robotics*, 5(4), 100248. https://doi.org/10.1016/J.BIROB.2025.100248.

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