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A comprehensive study of actuation, perception and control technologies for dexterous hands

Haoyang Liu[1, *]

[1]Brunel London School, North China University of Technology, Beijing, China

*Corresponding author: 2161258@brunel.ac.uk

Abstract:

Humanoid five-fingered dexterous hands, known for their agility and versatility, have extensive applications in industrial automation and healthcare fields. This paper reviews advancements in actuation, perception, and control technologies for dexterous hands. Electric, hydraulic, and pneumatic actuators are compared regarding power density, precision, and efficiency. The review also covers internal and external perception technologies, including position sensing and force feedback, which are critical for ensuring accurate and stable manipulation. Control methods such as position, force, and hybrid control are analyzed for their effectiveness in handling multi-degree-of-freedom tasks. Despite significant progress, challenges remain in improving precision, energy efficiency, and real-time response. This review highlights these challenges and suggests future directions, including developing adaptive control algorithms and advanced materials. The findings provide a reference for researchers and engineers, contributing to the development of more advanced dexterous hands.

Keywords: Bionic Dexterous Hands, Drive technology, Sensory technology, Control technology

1. Introduction

Humanoid five-fingered dexterous hand, as one of the important branches of modern robotics, has a wide range of applications covering a variety of fields such as industrial automation, healthcare, and service. Humanoid five-fingered dexterous hand, as a mechanical imitation of the human hand, has a high degree of agility and adaptability, especially for complex tasks in unstructured environments.

Over the past few decades, many different types of Humanoid five-fingered dexterous hands have been developed, some with advanced haptic perception and others with precise control systems. For example, the pneumatically driven ZJUT hand, with its flexible pneumatic actuator, is particularly suitable for use in scenarios such as agricultural harvesting where fragile objects need to be handled [1]. In addition, the Stamford-JPL hand, which combines position control and force control, allowing the manipulator to apply force in a precise manner when gripping an object, is widely used in industry [2].

This study systematically reviews actuation, perception, and control technologies for dexterous hands and identifies current challenges and opportunities for future improvements. The three core components of actuation, sensing and control are interdependent and key to determining the performance of a dexterous hand. For example, when grasping an object, the actuator provides the necessary motion force, the sensors are responsible for real-time monitoring of force and object position data during contact, and the control system adjusts the actuator based on the feedback.

Despite some advances in electric, hydraulic and pneumatic drive technologies, challenges remain in performance, efficiency and integration. While moving towards multimodal systems, perception technologies still face difficulties in achieving high accuracy and real-time response. Moreover, for multi-degree-of-freedom dexterous hand control techniques, current technology still requires further optimization of algorithms and more profound development of hybrid control for more complex tasks. Currently, there are no articles that systematically study and review these issues.

This study aims to fill this gap by summarising the current techniques, identifying research gaps and highlighting the importance of further developments in this area.

2. Actuation Technologies

2.1 Electric Actuators

Electric drives are critical to the bionic dexterous hand, which relies on efficient servo-motor systems to control multi-degree-of-freedom motion precisely. The basic principle is to generate joint torque by controlling the rotation of a motor with an electric current. These motors are often integrated with force sensors, position sensors and control modules to ensure high-precision operation. The Shadow Dexterous Hand, for example, uses an intelligent motor drive system that uses EtherCAT bus technology for real-time data transmission and operates at up to 1 kHz for precise force and position control [3], while the HIT/DLR hand optimizes power output and compactness by combining brushless DC motors with harmonic drives [4]. Each finger has sensors that maintain joint motion accuracy within ±0.2 degrees and generate an output force of 30N at the fingertips [4]. Its actuator utilizes a differential helical gearing system that allows for synchronized or reversed motor movement, further increasing efficiency [4]. However, electric actuation may be limited in high-load applications, which can be addressed by hydraulic actuation through higher power density and force output. The next section explores the role of hydraulic actuation in handling complex force-intensive tasks.

2.2 Hydraulic Actuators

Hydraulic drive technology transmits power through fluid pressure, relying on the incompressibility of the fluid to generate force. Components such as pumps, pipework and hydraulic actuators enable the system to deliver high power output in a compact form, which is ideal for applications requiring high force density—for example, the Integrated Electro-Hydraulic Actuator (IEHA) presented by Alfayad et al. The main principle is that a fluid is pressurized to provide power to a hydraulic pump, which drives a hydraulic cylinder or motor, allowing the system to produce a high power output from a relatively small volume. With a load capacity of up to 38 kg and an operating pressure of 100 bar, the IEHA is suitable for humanoid robotics and industrial use [5]. Alternatively, the underwater hydraulic soft hand can withstand up to 300 kPa pressures, allowing precise handling of objects in complex environments [6]. However, due to the complexity of the hydraulic system, complex pipework, pumps and valves are required, which increases the risk of leakage and pressure loss. In addition, inefficient energy conversion, such as heat generation, reduces the long-term energy efficiency of hydraulic systems. To address these issues, compressed air pneumatic drives offer a simpler, more energy-efficient alternative, as discussed in the next section.

2.3 Pneumatic Actuators

Pneumatic actuators produce mechanical movement by controlling compressed air and are usually made of flexible materials such as silicone or rubber. These materials, combined with built-in air chambers, allow the actuator to passively bend, rotate or deform when it encounters an external object, making it ideal for adapting to differently shaped targets. Compared to motor-driven and hydraulic systems, pneumatic actuators have a simple design, low friction, and low vibration due to the absence of complex gears. The ZJUT hand, for example (Fig. 1), utilizes a Flexible Pneumatic Actuator (FPA), which consists of a rubber hose and helical steel wire that allows the finger joints to bend or swing sideways with minimal friction [1]. A pneumatic pressure regulator adjusts the angle and torque of each joint and the air pressure feedback is fed back to the main control system via a pressure sensor, ensuring efficient movement and low wear [1].

The RBO Hand 3 utilizes a PneuFlex actuator to achieve finger flexion using silicone airbags that flex the actuator when inflated and a helical harness constraints. Its thumb is actuated using a combination of PneuFlex and bellows actuators [7]. This pneumatic system passively adapts to the shape of the object without the need for precise control algorithms [7]. However, the pneumatic system is less energy efficient and requires a constant supply of compressed air, leading to increased energy consumption and a less precise response when performing high-precision tasks due to air pressure fluctuations.

Fig. 1 The ZJUT hand's pneumatic actuators [1]

In summary, electric, hydraulic and pneumatic drive technologies have their advantages and disadvantages for dexterous hand applications. Electric drives excel in multi-degree-of-freedom systems due to their high accuracy and fast response, hydraulic drives excel where high power density and stable force output are required, and pneumatic drives are suitable for adaptive maneuvering of different shaped targets due to their flexibility and lightweight design. Table 1 compares the differences between the above three drive technologies in dexterous hand applications and their applicable scenarios to demonstrate each drive technology's characteristics more clearly.

Table 1. The Compares of Three Different Technologies [8]

Aspect	Electric Actuation	Pneumatic Actuation	Hydraulic Actuation
Description	Commonly used in artificial hands with various motor types like stepper, servo, AC, DC, and BLDC motors.	Uses compressed air to generate force, suitable for lightweight and quick-response applications.	Relies on fluid pressure to transfer force, commonly used in tasks requiring high power and stable force output.
Advantages	High precision, quick response, suitable for tasks requiring precise control and dynamic adjustment.	Lightweight, fast response, simple structure, low cost, and easy maintenance.	High power density, excellent load capacity, provides stable performance in complex operations.
Challenges	Lower efficiency in high-load, high-frequency operations, increased complexity in multi-degree-of-freedom systems, issues with heat management.	Limited precision control, instability in multi-degree-of-freedom tasks, potential issues with air leaks and noise.	Large size, complex system, risk of fluid leakage, slow response speed, and high maintenance requirements.

3. Perception Technologies

3.1 Position Sensing Technology

In dexterity, the core function of position-sensing technology is to provide feedback on the relative positions of robotic parts by detecting information such as joint angles and finger curvature to enable precise motion control. The following types of sensors can help implement position-sensing technology:

Joint angle sensors are important position sensors used in dexterous hands to measure the angle of rotation of joints and the position of fingers and mainly contain Hall effect sensors and optical angle sensors.

Hall effect sensors (Fig. 2(a)) measure a joint's rotation angle by detecting changes in the magnetic field. The principle is that a small magnet is mounted on the joint's axis of rotation, and the sensor is placed in the vicinity of the joint so that as the joint rotates, the magnetic field changes to determine its position. The CyberHand, for example, is

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equipped with eight Hall effect sensors in each joint. The Hall effect sensors not only measure the angle of the finger joints but can also be used to monitor the position of the motors [9].

Optical angle sensors (Fig.2(b)), on the other hand, measure the angle of the joint by measuring the reflection or interference of light. It enables measurements in tight spaces and provides non-contact angle measurements with reduced mechanical wear. Because of its high accuracy and flexibility, it can provide timely angular feedback to the finger [10].


(a) Hall Effect Sensors (b)Optical Encoders

Fig. 2 The sensors used for position-sensing

3.2 Force Sensing Technology

Force sensing technology is critical to robot dexterity, providing real-time feedback on external contact forces to ensure the safety and accuracy of dexterous hands. Force sensors are typically classified as triaxial or multi-axial and can detect forces and moments from multiple directions. In an underactuated adaptive manipulator, customised three-axis force sensors at the root and tip of each finger detect forces, indicating whether an object is being grasped and how hard it is being grasped [11]. The force sensors are based on the Hall effect and consist of four Hall effect devices and a small neodymium magnet located in the centre to measure the change in force as the finger deforms [11]. When the finger comes into contact with an object, the base deforms, causing a change in the position of the magnets relative to the sensor, which in turn causes a change in the magnetic field, leading to a change in the sensor's output voltage, which in turn enables the sensor to detect the force exerted on the object. An optoelectronics-based force sensor uses LEDs and phototransistor arrays to detect force by measuring the change in reflected light as an elastic surface deforms [12]. This sensor can accurately measure force in the ±4N range and torque in the ±20Nmm range.

These force sensors can be used in a variety of applications. For example, in the medical field, a rehabilitation robot uses a multi-axis force sensor. The sensors have a cantilever beam structure with strain gauges to measure forces in different directions [13]. Shear strain gauges are used to measure the Z-axis and the bent beam structure is used to measure the X- and Y-axis. Once the data is collected, the sensor converts it into electrical signals to provide real-time force feedback.

3.3 Tactile Sensing Technology

Many types of tactile sensors exist, including piezoresistive, piezoelectric, capacitive, and optical sensors. Piezoresistive sensors detect externally applied force through the piezoresistive effect of the material. When an external force is applied to the sensor, the deformation of the material causes a change in the resistance, and the magnitude of the external force is inferred by detecting the amount of change in the resistance [14]. Sensors are typically made of flexible conductive materials that can be fitted to complex curved surfaces. There is also a new type of high-resolution, soft, circular tactile sensor based on GelSight technology, which uses a circular design to maintain a large contact area when grasping an object so that even if the finger is moved at different angles and directions, the contact area remains relatively consistent [15]. The sensor uses light pipe illumination technology to achieve uniform illumination through a semi-mirrored sensing surface and a thin plastic shell, where light is propagated through total reflection within the medium to provide consistent illumination across the curved sensor surface, enabling the sensor to capture accurate contact force and surface information [15]. The sensor is also capable of real-time 3D reconstruction at 40Hz, which allows the robot to continuously receive haptic feedback as it performs grasping or moves objects and adjusts to the feedback, ensuring stability and accuracy [15]. The sensor was subjected to experiments on controlling the rolling of objects after being mounted on the Allegro Hand [15]. The results showed that the sensor successfully performed 99 per cent of rolling tasks and switched precisely between different object surfaces and contact zones [15].

In summary, tactile sensing technologies such as piezoresistive, piezoelectric, capacitive, and optical sensors play a key role in detecting and interpreting external forces, enabling dexterous hands to interact effectively with objects. Advances in high-resolution sensors based on GelSight technology have significantly improved the accuracy and consistency of force detection at different angles and surfaces. These developments have improved the stability and precision of robotic maneuvers, paving the way for more reliable and responsive haptic feedback systems in complex tasks.

4. Control Technologies

4.1 Position Control

In the operation of a multi-fingered dexterous robotic hand, position control refers to realizing a predetermined posture or grasping action of the hand by controlling the movements of individual joints and fingers, which is mainly used to ensure that the fingers can be accurately placed on the surface of the target object and to avoid possible collisions or sliding during the grasping process [16]. Position control has an important application in grasp preshaping (enabling the hand to better adapt to the shape and size of an object during grasping by adjusting the position and posture of the fingers prior to grasping the object) because, in a multi-fingered dexterous hand, the high degree of freedom of the joints makes it virtually impossible to determine the position of the contact using simple geometric descriptions, and thus requires the use of a grasping presets to simplify this process [17].

4.2 Force Control

Traditional grasping tasks can be categorised into static grasping (grasping) and dynamic grasping (manipulation). Force control is mainly used to ensure that the appropriate force is applied to the object during the grasping process and that it is stabilized by feedback control. There are two main types of force-controlled grasping. One is compliance control, which allows the robotic hand to adjust its grasping effort according to the applied force to avoid slipping or over-applying force to damage the object. The other is stiffness control, which is relatively more stringent and aims to maintain a certain level of grasping force and attitude stability during the grasping process [18]. Two common force control techniques are explicit force control and impedance control. Explicit force control is a control method that directly regulates the applied force and is particularly suited to scenarios where the applied force needs to be controlled to ensure stable operation in a particular task [19]. Its core lies in detecting the force when the robot's fingers are in contact with an object and generating a corresponding control signal to regulate the action of the actuator to ensure force stability. Implementing explicit force control relies on force feedback loops that use sensors (e.g., force-sensitive resistors) to measure the actual applied force and generate control signals to adjust the actuators at each joint to ensure that the force and position of the robot's hand are operated within safe limits. On the other hand, impedance control indirectly controls force by regulating the relationship between force and displacement, and is commonly used for tasks that require adaptation to complex or flexible environments, such as grasping elastic objects [20]. The advantage of impedance control over explicit force control is that it allows the system to respond to different operating scenarios by adjusting parameters such as finger stiffness and damping rather than relying solely on direct force feedback.

4.3 Hybrid Control

Hybrid control is a strategy that achieves higher accuracy and robustness by combining multiple control methods. By simultaneously regulating the end-effector's position and the force's interaction with the environment, it ensures flexible operational capabilities. It ensures that the system is able to meet the demands of the task in uncertain environments while ensuring operational stability and safety. A common hybrid is a force/position hybrid control, where there is a force/position control system with bounded actions that incorporate generalized saturation functions, a structure that employs generalized saturation functions to ensure that the control signal does not exceed the actuator's physical limits of the actuator [21]. The control balances force and position-tracking performance while maintaining torque limits, ensuring a stable finger grip. As shown in Fig. 3, the hybrid control framework integrates sensor input, control algorithms, and actuator systems, allowing for real-time adjustments to achieve both position and force control.

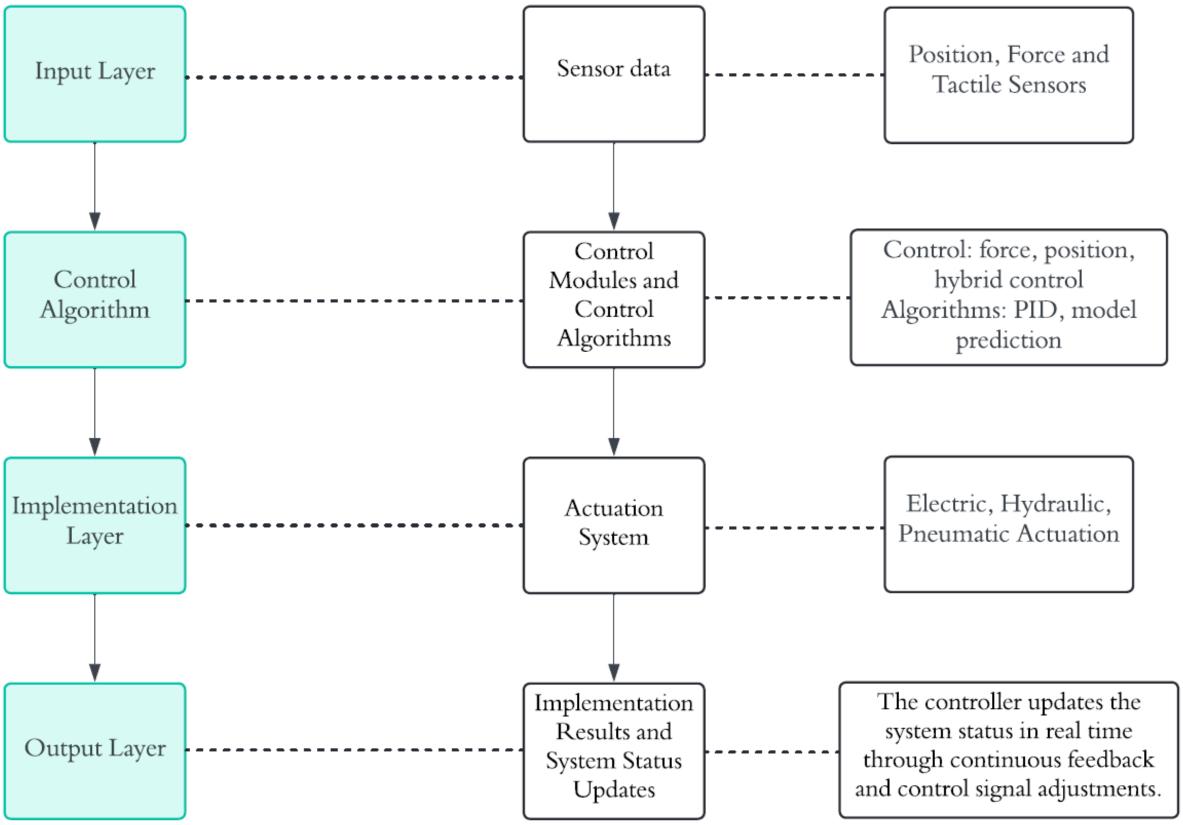

Fig. 3 Flow Chart

The other combines continuous dynamics control and discrete event switching control to handle the manipulator's multiple contact modes (e.g., rolling and sliding) in complex operational tasks [22]. This control formalizes the problem of manipulating a multi-fingered dexterous hand as a Dynamic Complementarity (DC) system and solves it by converting the DC system into a Mixed Logical Dynamical (MLD) model [23]. Subsequently, a Mixed Integer Quadratic Programming (MIQP) algorithm is used to optimize the control process and achieve dexterous hand flexibility [23].

In summary, hybrid control strategies integrate multiple control techniques to enhance accuracy and adaptability in robotic systems. By balancing force and position tracking while considering the actuator's physical limitations, these strategies provide stable and flexible control, even in uncertain environments [21]. Advanced methods like Dynamic Complementarity systems and Mixed Integer Quadratic Programming further optimize dexterous hand movements, ensuring precise manipulation across various operational scenarios [23].

5. Current Research Status and Challenges

5.1 Challenges

5.1.1 Precision and Response Limitations

Achieving high precision control and fast response in real-time environments with complex tasks is a major challenge for dexterous manipulators. Current drive technologies, such as electric and hydraulic systems, struggle to provide the required accuracy, compromising the overall performance of multi-degree-of-freedom manipulators [5]. Moreover, for high-frequency operations, existing systems utilize energy inefficiently and have high energy losses, limiting the system's sustainability [7].

5.1.2 Sensor Resolution and Data Fusion Issues

Current perceptual technologies, including haptic and force feedback sensors, have significant problems with resolution and responsiveness when dealing with complex operational tasks. Although these sensors can provide valuable force feedback, they typically lack the speed and accuracy required for real-time control. In addition, multi-modal sensing integrates data from vision, force feedback, and haptics, resulting in delayed system response due to inefficient data fusion [10]. The durability of sensors during high-frequency operation is also a challenge; as sensors are used, the material wears out, reducing sensitivity.

5.1.3 Control and Adaptability Challenges

Coordination of high degree-of-freedom systems remains a critical issue for dexterous hands. Conventional control algorithms have difficulty in providing dynamic feedback and generating precise commands in real-time processing, which affects the robustness of the system [16]. Seamless switching between different control modes (e.g., force control and position control) is also a challenge, limiting the adaptability of the dexterous hand in different operating scenarios [18].

5.2 Future trends

5.2.1 Innovative Actuation Materials and Designs

Future research should focus on developing new materials such as magnetorheological elastomers and shape memory alloys to enhance dexterity and agility in dexterous hands [21]. At the same time, attempts are made to go for lightweight and modular designs, which can reduce the complexity and energy consumption of multi-degree-of-freedom manipulators [5].

5.2.2 Advanced Sensor Technologies and Integration

The future should focus on developing high-resolution and faster haptic sensors using flexible electronic materials or bionic skin technology [14]. More effective integration of visual, force and haptic feedback through enhanced multimodal data fusion algorithms will be key to improving the synchronization and robustness of sensing systems in dynamic environments [14]. Low-power designs and durable sensor materials are key to improving long-term mission reliability.

5.2.3 Adaptive and Intelligent Control Systems

Exploring adaptive control methods and dynamic planning strategies will help to optimize control inputs, reduce unwanted motions and enable the system to quickly and accurately adjust forces according to object properties [16]. Meanwhile, combining deep reinforcement learning techniques and model-based predictive control (MPC) can further enhance the dexterous hand's ability to smooth transitions, prioritize control parameters, and handle non-linear interactions in real-world applications [17].

6. Conclusion

This review focuses on key technologies for actuation, perception and control of humanoid dexterous hands. By comparing electric, hydraulic and pneumatic actuators, it is evident that each has different advantages in terms of power density, precision and suitability for specific applications. Electric actuators provide precise control and are well suited to high-precision tasks, while hydraulic actuators favor tasks requiring high power density. Pneumatic actuators, while less energy efficient, offer flexibility in handling lightweight and precision objects. In addition, advances in sensing technology, such as position sensing using optical and Hall effect sensors and force feedback mechanisms, have greatly increased the dexterity and adaptability of robotic hands. Control methods, including position, force and hybrid control, are essential for managing multi-degree-of-freedom manipulation, allowing for more stable and efficient task execution. However, challenges remain in improving these systems' overall system integration, real-time responsiveness, and energy efficiency. Addressing these issues is critical to optimise the performance of dexterous hands further. This review's findings help clarify the direction for improving more functional robotic hands. Future research should focus on exploring advanced materials (e.g., smart materials) and adaptive control algorithms to improve the efficiency and functionality of dexterous hands.

References

[1] Wang Zhiheng, Bao Guanjun, Du Mingyu, Yang Qinghua. Grasping model identification for ZJUT hand. 2014 13th International Conference on Control, Automation, Robotics and Vision (ICARCV), 2014, 1159-1166.

[2] Salisbury J K, Craig J J. Articulated Hands: Force Control and Kinematic Issues. Proceedings of the 1981 ASME Computers Conference, 1981, 1-17.

[3] Shadow Robot Company. Shadow Dexterous Hand Technical Specification. 2021.

[4] Gao X H, Jin M H, Jiang L, Xie Z W, He P, Yang L, Liu Y W, Wei R, Cai H G, Liu H, Butterfass J, Grebenstein M, Seitz N, Hirzinger G. The HIT/DLR dexterous hand: work in progress. 2003 IEEE International Conference on Robotics and Automation (ICRA), 2003, 3164-3168.

[5] Alfayad S, Ouezdou F B, Namoun F, Cheng G. High performance integrated electro-hydraulic actuator for robotics – Part I: Principle, prototype design and first experiments. Sensors and Actuators A: Physical, 2011, 169: 115-123.

[6] Wang Haihang, Xu He, Yang Chen, Li Xin, Chen Siqing. Underwater Soft Robotic Hand with Multi-Source Coupling. 2021 Conference on Bio-Inspired Robotics, 2021.

[7] Puhlmann S, Harris J, Brock O. RBO Hand 3: A Platform for Soft Dexterous Manipulation. IEEE Transactions on Robotics, 2022, 38(6): 3434-3447.

[8] Vertongen J, Kamper D G, Smit G, Vallery H. Mechanical Aspects of Robot Hands, Active Hand Orthoses, and Prostheses: A Comparative Review. IEEE/ASME Transactions on Mechatronics, 2021, 26(2): 955-973.

[9] Xia Ziwei, Deng Zhen, Fang Bin, Yang Yiyong, Sun Fuchun. A review on sensory perception for dexterous robotic manipulation. International Journal of Advanced Robotic Systems, 2022, 19(2): 1-18.

[10] Moosavi S K R, Zafar M H, Sanfilippo F. A review of the state-of-the-art of sensing and actuation technology for robotic grasping and haptic rendering. 2022 5th International Conference on Information and Computer Technologies (ICICT), 2022, 1-17.

[11] Savić S, Raković M, Penčić M, Nikolić M. Design of an underactuated adaptive robotic hand with force sensing. Proceedings of the 2016 International Conference on Robotics and Automation (ICRA), 2016.

[12] De Maria G, Natale C, Pirozzi S. Force/tactile sensor for robotic applications. Sensors and Actuators A: Physical, 2012, 175: 60-72.

[13] Grosu V, Grosu S, Vanderborght B, Lefeber D, Rodriguez-Guerrero C. Multi-axis force sensor for human–robot interaction sensing in a rehabilitation robotic device. Sensors, 2017, 17(6): 1294-1305.

[14] Kappassov Z, Corrales J A, Perdereau V. Tactile sensing in dexterous robot hands — Review. Robotics and Autonomous Systems, 2015, 74: 195-220.

[15] Romero B, Veiga F, Adelson E. Soft round high resolution tactile fingertip sensors for dexterous robotic manipulation. 2020 IEEE International Conference on Robotics and Automation (ICRA), 2020, 4796-4799.

[16] Rojas-García L N, Chávez-Olivares C A, Bonilla-Gutiérrez I, Mendoza-Gutiérrez M O, Ramírez-Cardona F. Force/position control with bounded actions on a dexterous robotic hand with two-degree-of-freedom fingers. Biocybernetics and Biomedical Engineering, 2022, 42(1): 233-246.

[17] Pons J L, Ceres R, Pfeiffer F. Multifingered dextrous robotics hand design and control: a review. Robotica, 1999, 17: 661-674.

[18] Yin Y, Luo Z, Svinin M, Hosoe S. Hybrid control of multi-fingered robot hand for dexterous manipulation. 2003 IEEE International Conference on Robotics and Automation, 2003, 3639-3644.

[19] Santos-Victor J, Moreno P. Force feedback control for dexterous robotic hands using conditional postural synergies. 2022 IEEE-RAS 21st International Conference on Humanoid Robots (Humanoids), 2022, 674-679.

[20] Ma Jide, Liu Mengjie, Hu Yongmei, Li Ke, Wei Na. Digit force control for dexterous manipulation: Effects of contact surface stiffness and object’s center of mass. 2020 IEEE 20th International Conference on Bioinformatics and Bioengineering (BIBE), 2020, 709-714.

[21] Cai Shibo, Tao Zhicheng, Wan Weiwei, Yu Haoyong, Bao Guanjun. Multi-fingered dexterous hands: From simplicity to complexity and simplifying complex applications. Journal of Mechanical Engineering, 2021, 57(15): 1-14.

[22] Liu Weihui, Li Xiaohui, Zhou Yuanzi, Lv Zhenhua, Zhang Meng. Cooperative motion control of humanoid robot arm system based on dexterity analysis. 2023 IEEE 18th Conference on Industrial Electronics and Applications (ICIEA), 2023, 349-355.

[23] Yu Chunmiao, Wang Peng. Dexterous manipulation for multi-fingered robotic hands with reinforcement learning: A review. Frontiers in Neurorobotics, 2022, 16(861825): 1-15.