Robotic Dexterous Hands' Structure Design and Drive-Transmission System

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Abstract. The robotic dexterous hand is one of the most important components of robots. As a new type of end-effector, it can help the robot to interact with the environment, enabling the function of grasping and dexterous operation to objects in various situations such as daily life, medical treatment and industry. This paper investigates the development history and current situation of the robotic dexterous hand in the world, conducts the research and comparative analysis focusing on the characteristics of the existing robotic dexterous hands' mechanical transmission and drive system, comprehensively obtains its development trend, and finally draws the conclusion and makes the prospect of the future development of the robotic dexterous hand.

Keywords: Robotic dexterous hand, mechanical transmission, robot system.

1. Introduction

As an advanced end-effector of the robot, the fundamental purpose of the robotic dexterous hand is to help the robot interact with the objects in the real environment. The key distinction between the robot hand and its clip claw is the robot's low degree of freedom, which allows it to maintain high flexibility and accuracy while mimicking the function of the hand. This allows the robot to perform a variety of complex capture operations in a variety of industrial, medical, and service fields. In addition to realizing the function of gripping and grasping, the robot is also capable of certain hand dexterous operations and can flexibly change gestures [1].

Strictly speaking, since the opening of the new era of microcomputers in the 1970s and the initial formation of the concept of robotic dexterous hands, a large number of extensive researches on robotic dexterous hands have been carried out in the world. Since the 21st century, the dexterous hand of a robot has grown increasingly complete, flexible, anthropomorphic in structure, and sophisticated in terms of its drive and transmission system, sensor system, and control system. Therefore, in recent years, "how to make the robot dexterous hand maintain high flexibility and functionality while making the mechanical structure more streamlined, the drive and transmission system and the sensing and control system more integrated, and the robot dexterous hand as a whole more lightweight and low-cost" has become the core problem in the field of robot dexterous hand. This paper summarizes and organizes the development history of the robotic dexterous hand in the world, analyzes the research on robotic dexterous hand from the aspects of configuration, degrees of freedom and number of joints as well as drive and transmission system, and then outlines and predicts the possible development direction of robotic dexterous hand in the future.

2. Development Process and Current Situation of Robotic Dexterous Hand

The earliest robotic hand was the MH-1, developed by Heinrich A. Ernst at the San Jose Research Laboratory of International Business Machines Corporation (IBM). It was officially launched in 1962 [2].

The development of robotic dexterous hands went through an important initial phase in the 1970s and 1980s as the need for industrial automation increased and the concept of dexterous hands evolved. Research and development during this period laid the foundation for the later development of more advanced robotic dexterous hand technologies.

In 1979, T. Okada, a researcher at the Japanese government's Electrotechnical Laboratory, developed the three-fingered Okada hand, which has a total of 11 joints and 11 degrees of freedom [3]. It can perform not only simple movements such as bending and stretching, but also lateral flexion movements such as adduction and abduction, and it has a high degree of dexterity to realize high-precision movements [3].

The years 1980-1990 were characterized by the rapid development of drive and transmission strategies for dexterous hands. Increasingly flexible robotic dexterous hands with more fingers and more degrees of freedom began to appear.

In 1983, K. Salisbury developed the motor-driven, tendon actuated 9-degree-of-freedom three-finger Salisbury hand. it has nine joints and uses an n+1 tendon design. Such design provided a new way to coordinate the three fingers, allowing the robotic hand to behave similarly to a human assembling an object, improving finger dexterity and precision [4].

In 1986, the University of Utah and the Massachusetts Institute of Technology (MIT) collaborated to develop the highly anthropomorphic four-fingered Utah/MIT Hand, whose drive method innovatively uses pneumatic drive; its transmission method uses a pulley-based tendon drive, and its tendons are configured in a 2n configuration, i.e., each joint of each finger is controlled by two tendons, which provides excellent dynamics and high load-bearing capacity, facilitating more flexible and fine control [5].

From 1990-2000, dexterous hands began to seek more anthropomorphic designs, while the number of fingers and degrees of freedom increased further, and smaller, more integrated, precise and complete designs were sought. At the same time, in 1989, G. Vassura and A. Bicchi introduced the concept of whole-hand manipulation, which led to a focus on the design of the phalanges, the palm and even the wrist beyond the fingertips during this period [6].

In 1992, the Jau-JPL Hand. robotic hand system, designed by B.M. Jau, introduced compliance mechanisms and Active Electromechanical Compliance, which mimic the function of human muscles in joint positioning and alteration of stiffness, which is more anthropomorphic and easier to perform grasping and manipulation [7].

The second generation of the UB Hand, the UB Hand II, developed by the University of Bologna, was first introduced in 1998 with the introduction of a wrist joint possessing two degrees of freedom in bending and rotation [8]. At the same time, it innovatively introduced the concept of full hand manipulation, which was oriented to increase the kinematic redundancy appropriately, resulting in the enhancement of the geometrical consistency of the neighboring links [6]. A symmetrical palm is also designed for grasping objects.

At the beginning of the twenty-first century, the main goals for the development of the field of robotic dexterous hands were higher system integration and richer sensing capabilities, more efficient means of actuation and transmission, and more anthropomorphic mechanical designs. For the post-2010 period, where complex systems lead to high manufacturing and maintenance costs, a major goal is to simplify the robotic dexterous hand system and to increase its robustness. More and more underdriven dexterous hands have been created.

In 2001, the DLR Hand II, developed by the DLR, was launched with four fingers, 17 joints and 13 degrees of freedom. It achieves full integration of electronic components, reduces the weight and the number of cables, and improves the reliability of the hand and the dexterity of its operation. Overall, it brings it closer to the functionality of a human hand [9].

The Anatomically Correct Testbed Hand (ACT Hand), developed by A.D. Deshpande et al. in 2004, is an extremely highly anthropomorphic robotic dexterous hand with 21 degrees of freedom. It simulates the structure and function of the bones, joints and muscles of the human hand, allowing the fingers to perform hyperextension and complex hand movements. Overall, the ACT hand is the first rigorous anatomical design of an extremely highly anthropomorphic robotic dexterous hand, with the rigorous bionic design of the mechanical structure, drive train, and control strategy [10].

In 2004, the upgraded version of UB Hand II, UB Hand III, was launched. Its driving mode is based on a brushless Direct-Current motor and roller screw drive system. Meanwhile, in its structure, UB Hand III innovatively adopts the endoskeleton structure of the human hand instead of the traditional exoskeleton design, so that the fingers can be wrapped with thicker compliant materials around the fingers, which mimics the role of the human hand's soft tissues, improves the compliance and reliability of the hand, and reduces the mechanical complexity [11].

In 2011, Columbia University developed Columbia Hand, a highly underdriven three-fingered robotic dexterous hand, which is motor-driven with a Tendon-Pin Underactuated (TP-UA) transmission, which makes the movements more detailed and easier to control, and improves the compliance of the robotic hand. It demonstrates the great potential of an underdriven robotic dexterous hand for future development [12].

In 2012, following the UB Hand III, designers from the University of Bologna created the UB Hand IV, also known as the DEXMART Hand, within the DEXMART project. It is driven by tendons made of Dynema Fast-Flight high-performance synthetic fibers, which increase its strength, durability, and stability; its drive system innovatively uses a torsion rope drive system, which simplifies the mechanical structure of the device, reduces most of the friction with the mechanism, and improves the compatibility and durability of the robotic hand. At the same time, it reduces assembly complexity by directly integrating flexible joints and transmission elements using 3D printing technology [13].

In 2012, the University of Pisa developed the Pisa/IIT SoftHand, a humanoid five-finger dexterous hand. It has five fingers with a total of 19 joints and a total of 19 degrees of freedom of the fingers, and all joints can be controlled by differential mechanics (pulleys) through only one single drive source. With reference to soft synergies, it additionally uses elastic elements (springs) on the tendons connecting the pulleys to allow a certain amount of independent movement of each joint, but still maintaining a certain amount of coordination within a predefined synergy pattern, which makes the joints more flexible and has excellent compliance, and greatly simplifies the actuation system, making it a very classical underdriven hand model [14]. In 2015, C. Della Santina et al. improved it by developing a new generation of Pisa/IIT SoftHand+. Its introduction of a second DOA allows the manipulator to perform more fine-grained force adjustments and postural control during gripping, which is helpful for performing more complex manipulation tasks [15].

In 2016, the University of Washington developed the highly bionic Washington Hand. With five fingers and 15 joints totaling 21 degrees of freedom, it is almost identical to a human hand in terms of degrees of freedom and joint configurations and is extremely highly bionic. It utilizes artificial joint capsules, braided ligaments and tendons, laser-cut stretch caps, and elastic pulley mechanisms to closely mimic the structure of the human hand. Modern rapid prototyping techniques such as 3D printing and laser scanning are also integrated to create replicas of bones and soft tissues, by which the biomechanical properties of the human hand can be more accurately replicated for more complex hand manipulations [16].

In 2019, H. Liu et al. developed the five-finger dexterous hand PRISMA Hand II, which has 19 joints and 19 degrees of freedom. It adopts an underdrive design, using three motors to drive all the joints through elastic tendons. The most innovative feature of the hand is the drive method, which uses elastic tendons to drive the compliant finger movements through rolling contact joints, allowing the joints to automatically adapt to the shape and size of the object to be grasped without a complex control system. At the same time, it possesses compliance in multiple directions such as lateral bending, twisting and back bending [17].

In 2020, Ningbin Zhang et al. from Shanghai Jiaotong University developed a 3D-printed multi-module pneumatic soft dexterous hand. With five fingers and 11 degrees of freedom, it has excellent dexterity, robustness and impact resistance, and it achieves high bionic under pneumatic drive mode. It is also highly lightweight with only 138 grams [18].

In 2021, U. Kim et al. at Asia University developed the ILDA Hand, which is a linkage-driven five-finger hand. It has 20 joints and 15 degrees of freedom. Its highly integrated and modular design integrates all actuators and sensors within the hand while maintaining a compact size and lightweight construction. Its maximum length is 218mm and its weight is only 1.1kg [19].

3. Research on Robotic Dexterous Hand Characteristics

3.1. Dexterous Hand Configuration

The difference between the robotic dexterous hand and the commonly used robot claw (two fingers, three fingers, suction cup) is that it not only realizes the function of grasping, but also can carry out certain in-hand dexterous operations, and can realize the switch between a variety of gestures. Usually, the robotic hand with a number of fingers greater than or equal to 3 and a degree of freedom greater than 9 is called the robotic dexterous hand. The configuration of the robotic dexterous hand is usually divided into three fingers, four fingers, and five fingers dexterous hand.

3.2. Drive and Transmission System

3.2.1 Degree of freedom and number of joints

The degrees of freedom and the number of joints of a robotic dexterous hand are mainly designed with reference to the human hand. According to Grant's Atlas of Anatomy, the thumb of a human hand contains three joints, the Interphalangeal joint of thumb (IP), Metacarpophalangeal joint (MCP) and Carpometacarpal joint of thumb (CMC) [19]. The other four fingers contain Distal interphalangeal joint (DIP), Proximal interphalangeal joint (PIP), MCP and CMC. Among these joints, the DIP, PIP, and IP joints of the thumb have one degree of freedom, while the MCP joint has two degrees of freedom: flexion, extension, and abduction, and cannot rotate autonomously around the root of the finger. When calculating the degrees of freedom of the human hand, the CMC joint of the thumb is considered to have two degrees of freedom, but whether the degrees of freedom of the CMC joints of the four fingers other than the thumb are included has been controversial. Gray's Anatomy suggests that the CMC joints of the four fingers can be included, while Grant's Atlas of Anatomy argues that the CMC joints of the ring and little fingers can be included [19, 20]. However, the purpose of robotic dexterous hand researchers to focus on human hand degrees of freedom in dexterous hand design is to create more bionic and practical robotic hands. So some joints with small movement angles will be directly ignored in the design. Therefore, it can be compromised that the range of motion of the CMC joints of the four fingers except the thumb gradually increases from the index finger to the little finger, the index finger CMC joint has no obvious angle of motion, the middle finger and ring finger CMC joints each have one degree of freedom, and the little finger CMC joint has two degrees of freedom. And comprehensively, among the CMC joints of the four fingers, only the CMC joint of the little finger has an obvious moving angle. So in the design of the robot dexterous hand, almost only the CMC joint of the little finger needs to be considered as having one degree of freedom. It is therefore concluded that the degrees of freedom of a simulated human hand are between 23 and 29, often seen as around 25 degrees of freedom.

The most flexible dexterous hand that has been widely commercialized today is the Shadow Dexterous Hand, which has 24 joints and 20 degrees of freedom of actuation including the wrist, as well as 4 degrees of freedom of underactuation provided by the DIP joints of all four fingers except the thumb [21]. It includes the design of the pinky CMC joints, which are otherwise similar in design concept to the human hand and are highly bionic.

At the World Robot Conference 2023, the Casia Hand, developed by the research group of Peng Wang at the Institute of Automation of the Chinese Academy of Sciences, was focused for the first time. The dexterous hand has 25 joint degrees of freedom and 21 drive degrees of freedom, compared to the Shadow Dexterous Hand, the CMC joints of the pinky thumb were designed to have two degrees of freedom, one more degree of freedom than the Shadow Dexterous Hand, setting a new record for degrees of freedom in robotic dexterity hand design.

Based on the quantitative relationship between the number of actuators of a dexterous hand and its DOAs, a dexterous hand can be categorized into a full-drive dexterous hand and an underdrive dexterous hand.

The number of actuators in a fully actuated dexterous hand is roughly equal to the number of degrees of freedom of actuation. Each finger joint of a fully actuated dexterous hand can be actively controlled, which can theoretically accomplish more delicate operations, and a fully actuated dexterous hand with a high degree of freedom can mimic almost all human hand shapes and even accomplish more delicate movements. However, there are still shortcomings that need to be improved. the full-drive dexterous hand has more actuators, the volume is relatively larger, and the installation process is more complicated. It is more difficult to be controlled, and the control system is more complicated. It has a high failure rate compared with the underdriven dexterous hand because the joints that are frequently active and often in contact and collision with the objects during grasping and manipulation, such as DIP joints, are more likely to break down. At the same time, all these factors point to the problem of design complexity and high cost.

In order to solve the problem of full-drive dexterous hands, more full-drive robotic dexterous hand designs nowadays use partial joint underdrive handling. For example, the Shadow Dexterous Hand is considered as a fully actuated dexterous hand in its entirety [21]. the DIP joints of the four fingers are partially underdriven, while the other joints use a micro-motor actuation scheme [21]. This design avoids the problem of the high failure rate of the DIP joints and increases the adaptability to the shape of the object during grasping and manipulation, as well as reduces the workload of the control system.

The number of actuators in underdriven dexterous hands is smaller than their DOAs, and the extra degrees of freedom are generally generated by the coupled adaptive motions of actuator-driven parts driving parts without actuator-driven parts [22]. It is highly integrated and the overall system is highly simple and easy to control. It is able to adapt to the shape of the object and has good flexibility against external shocks. The disadvantage is that compared with the fully driven dexterous hand, it is unable to mimic some of the high-precision grasping and manipulation motions that can be made by human hands, and so on.

3.2.2 Drive system

Nowadays, the driving methods of robotic dexterous hands are mostly fluid drive, electric drive, shape memory alloy drive and hybrid drive, of which the fluid drive includes hydraulic drive and pneumatic drive, the electric drive includes motor drive and EAP drive, etc., and the hybrid drive includes gas-electric hybrid drive and liquid-electric hybrid drive, etc.

Hydraulically driven manipulator is characterized by greater power, force and moment and inertia, fast response, and easier-to-achieve direct drive, so it is often used in industrial manipulators, suitable for large-scale gripping operations. At the same time, it has high stability and reliability, and its structure is simple. With strong anti-interference ability, the application value of the hydraulic drive system is particularly significant in specific fields such as disaster rescue and field exploration [23].

The advantage of a pneumatic drive is that the system is lightweight, simple in structure, inexpensive, and quick in response and action. The disadvantage is that it is not easy to be finely controlled, so the trajectory accuracy is relatively low. At the same time, the limitation of pneumatic pressure makes its load capacity low [1].

The motor drive is the most common drive method in robotic dexterity. Generally, robotic hands use small motors, which are fast responding and very efficient in information transfer, detection and processing, while their output is stable, accurate and energy efficient. It provides high-precision position control, allowing the robotic hand to move with millimeter-level accuracy [24].

The Electroactive Polymer (EAP) represents a novel material with distinctive electrical and mechanical characteristics. This polymer produces small deformations when electrically stimulated. The use of dielectric EAP as a driving material offers numerous advantages. Primarily, it can directly interact with the external environment without needing a transmission mechanism, which simplifies the system structure, reduces its size, and allows for high integration. Secondly, it exhibits a rapid response speed, large deformation, and the ability to produce significant displacement. Its excellent flexibility facilitates the structural arrangement and integration of joints and drives. Its operational characteristics are analogous to those of biological muscle, exhibiting high bionic performance. Consequently, it has promising developmental potential [25].

Similar to dielectric EAP, Shape Memory Alloys (SMA) are innovative materials that show potential for driving robotic dexterity due to their unique shape memory effect, which has a wider range of applications than dielectric EAP. The main advantage is the ability to realize more complex movements while providing softer interaction forces. Among them, the most frequently used is Nickel-Titanium alloy (NiTi), which has a rapid shape change capability and good reversibility for high-speed operating scenarios [26]. SMA actuation is suitable for application in small robots with fast response and large deformation for large displacements, but it is not able to work for a long time and has low fatigue strength. However, despite the potential of SMA for dexterous hand actuation, they present some challenges in terms of responsiveness and control difficulty. The actuation speed is limited because shape memory alloys require energy conversion through an external heat source during deformation [26].

Each drive mode has its advantages and limitations. In recent years, hybrid drive soft robots have become a new direction for scientists to explore. By combining electric, hydraulic (or pneumatic), and shape memory alloy actuation methods, dexterous hands can be created that can exhibit excellent performance in different application scenarios. The hybrid drive approach helps the robotic hand to achieve a better balance between strength, speed, precision, and adaptability [27].

The most common hybrid drive methods are air-electric hybrid and liquid-electric hybrid. An example is the Shadow Dexterous Hand, which is driven by 40 pneumatic muscles and 20 micro DC motors [21].

The drive placement mode of the robotic dexterous hand is divided into drive built-in mode and drive external mode. Built-in driver means that the driver of the dexterous hand is placed inside the hand. The advantages are: firstly, the proximal drive allows the sensors inside the dexterous hand to measure the relevant data directly, with higher measurement accuracy; secondly, the built-in driver makes it easier to replace the various modules of the hand, and the later maintenance is relatively easy. However, the disadvantages are also quite obvious: first, the built-in driver will make the dexterous hand too large, and second, it will make the choice of internal drivers, sensors, and controllers more stringent because of the limitation of the hand's size, which makes the arrangement more complicated and makes it more difficult to control.

External driver means that the driver of the dexterous hand is placed outside of the hand, and its advantages are: firstly, it is usually combined with a tendon drive system for remote actuation, which means that it can make full use of the space with a flexible arrangement, and can limit the size of the dexterous hand to a certain extent, making it more anthropomorphic. Secondly, it allows the dexterous hand to choose from a wider variety of larger actuators, allowing for a stronger finger grip and more dexterous operation. The disadvantage is that remote actuators may not accurately reflect the state of the dexterous hand in the sensor measurements, which reduces the accuracy and poses sensing and control problems.

3.2.3 Transmission system

The mechanical transmission mode of the dexterous hand is related to the transmission efficiency and precision of the dexterous hand, which is an important part of dexterous hand structure design. Nowadays, the commonly used transmission methods of the dexterous hand are tendon transmission, linkage transmission and gear transmission.

Tendon transmission is the most widely used transmission mode today. The reason is that the cables are highly anthropomorphic, just like human muscles, and allow for remote actuation of the dexterous hand as mentioned above. However, one of its drawbacks is the coupling problem, which may lead to an overly complex control system in a multi-tendon control system. At the same time, its load-carrying capacity needs to be improved, and as the load increases, the tensile strength of the cable is tested while the support structure is also affected accordingly.

Correspondingly, there will be problems related to load capacity, service life, and maintenance costs. Today's robotic dexterous hands use a variety of tendon drive strategies, such as tendon-pulley drive, tendon direct drive, tendon-pin drive, etc. [12].

The linkage transmission is one of the commonly used dexterous hand transmission modes in industry. Its advantages are high stiffness and relatively high transmission efficiency, and its disadvantage is that it is generally heavier, while relatively less flexible and less compliant.

Gear transmissions are also commonly used in dexterous hands for industrial robots. Its advantage is that it has a stable transmission ratio and high transmission efficiency, but its disadvantage is that the structure is complex, with high maintenance costs.

4. Conclusion

In summary, with the rapid development of robotic systems and market demand, the robot dexterous hand industry has shown a rapid development trend in recent years. The development direction of the dexterous hand is getting closer and closer to the route of higher integration, higher bionic degree, higher robustness and higher cost-effectiveness. In the future, with the development of sensing and control system, the degree of freedom of dexterous hand will gradually increase, then make more dexterous movements than human beings. At the same time, its appearance and structural design will be more anthropomorphic. Its transmission system will be developed in the direction of higher transmission efficiency, higher loading capacity, higher flexibility, higher life expectancy, and simpler structure. At the same time, the drive system will expand the development direction, and continue to develop the electric drive to make it more integrated and explore more new types of drive methods to improve reliability, accuracy, response speed, energy efficiency, and integration.

With the rapid development of the robotics field, the need for interaction with the external environment is becoming more and more frequent. Robot dexterous hand, as its end-effector, has an excellent development prospect in the future. At the same time, the design of its structure and drive transmission system, as an important part of the robot dexterous hand, will continue to become a research hotspot in the field of robot dexterous hands in the future.

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