CHAPTER 13

Mechanical Design and Performance Analysis of Articulated Mechanical Hands: A Review

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Introduction

Since the development of the first industrial robots in the early 1960s, robotics has frequently replaced humans in many arduous and repetitive activities. The ambition of using robots in more versatile tasks began in the early 1980s, and led to equip them with multi-purpose capabilities robotic hands sparking the research into the development of the faculty of grasping. Hence, the ability to grasp and manipulate objects of diverse weights and shapes became a challenging issue central to the advancement of robots. Numerous robotic hands have been developed over the last four decades of research into dexterous manipulation (Birglen & Schlicht, 2018), (Zhang et al., 2020), (Hughes et al., 2020), (Samadikhoshkho et al., 2019), (Yoon & Choi, 2021). However, the improvement of such robotic hands remain a key challenge and far from human hand capabilities as grasp is very developed in the human being. The grasp may be soft or develop the necessary force to be firm (Yoon & Choi, 2021), (Chen et al., 2018). A robotic gripper, usually made of hard material, does not naturally possess this ability. The example of the handling of a fruit is demonstrative of such a dilemma.

The human-like dexterous manipulation is represented by the development of flexible multi-fingered grippers with both adaptive grasping and in-hand manipulation capabilities. The ability to grasp is generally seen as a set of kinematic strings connected to a base and closed on an object in areas of contact that should be modeled (C. Reboulet, 1988). There are essentially two types of grasps: (1) the power grasp also known as ‘full-hand’ that uses the principle of stability and safety, and (2) the delicate-gentle or precision grasp that may be performed by a child therefore needing dexterity.

Various traditional gripper designs that have been developed over the years have two or three rigid-material fingers that allow them to perform pick-and-place tasks but fail to accomplish activities requiring more complex actions (Bicchi & Kumar, 2000). Such complex manipulation activities are made possible when the thumb faces the remaining hand fingers (Seguna & Saiba, 2001).

The human hand acts as an articulated mechanical system similar to a complex

kinematic chain with a tree structure (Osswald & Wörn, 2001). Indeed, its skeleton is formed by the complex assembly of the bones of the carpus, the metacarpus, and the phalanges. The articulations between these bones vary according to the number of DOF they possess. The long fingers represented by the forefinger, middle finger, ring finger, and little finger have the same structure while that of the thumb is more complex (Brown & Vardy, 1998). The design of the mechanical hands is often inspired by the morphology of the human hand. They have been developed to interact with the human environment.

In particular, the robotic capabilities of sensing and manipulating unfamiliar objects spawn more applications and enormous economic benefits. For instance, robots used in restaurants improve the efficiency of food delivery and reduce labor costs (Thanh et al., 2019). Moreover, the successful applications of domestic robots help people handle some housework to save people's time (Yamazaki et al., 2012), and robots in factories perform repetitive tasks quickly for a long time and reduce the loss caused by the worker's fatigue (Dogar et al., 2019).

Nowadays, the majority of these are made up of a mobile base equipped with one or two articulated anthropomorphic manipulator arms, the end of which is equipped with a gripper capable of capturing objects of various geometries.

The articulated mechanical hands of today have become analogous to human hands. They can capture objects of arbitrary shape and offered as equipment to the mobile manipulators with a versatile dexterity such as that achieved by a hand with multiple fingers capable of performing a variety of different entries thus enabling the reduction of the terminals.

The present paper provides a comprehensive review of mechanical and dextral hands. It presents eight of the more currently operated articulated mechanical hands, and includes those having three fingers as well as those integrating a thumb opposite to three or four fingers that can handle objects safely applying both arbitrary forces and movements to manipulate objects (Murray et al., 1994). It furthermore identifies their benefits and drawbacks and compares their respective designs to their diverse object-grasping capabilities and applications.

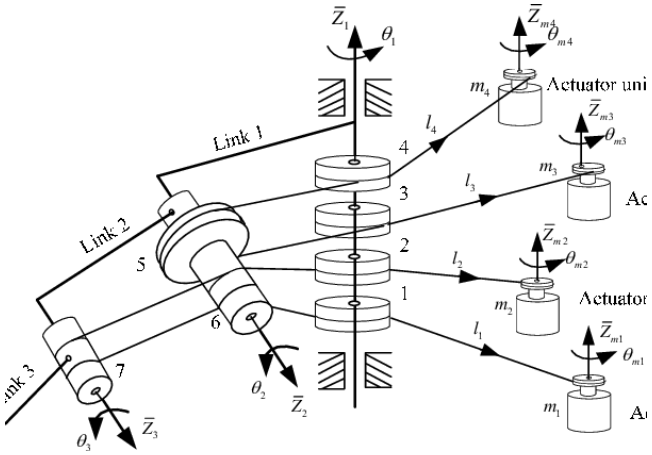
Articulated Mechanical Hands

Articulated mechanical hands are becoming more and more analogous to human hands. They are capable of grasping objects of arbitrary shape. They further offer solutions to equip mobile manipulators with versatile dexterity such as that achieved by a multi-fingered hand capable of performing a variety of different grips thus enabling the reduction of terminals.

The Hand of Stanford-JPL

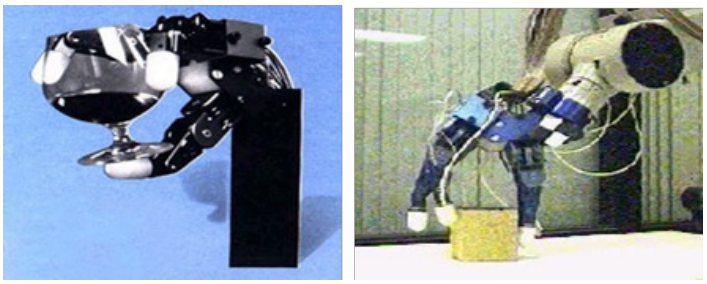
The Stanford hand illustrated in Figure 1 has not been initially designed to reproduce the human hand but rather to investigate the phenomena of handling along with the necessary conditions associated with it (Salisbury & Roth, 1983). The study led him to the conclusion that a minimum of three fingers are necessary for carrying out effective handling, a fourth finger would significantly increase its complexity (Loucks et al., 1987).

Figure 1.
Functional Representation of the Stanford/JPL Finger (Sang et al., 2016)



The Stanford hand comprises a mechanism articulated around three modular fingers, each one displaying three degrees of mobility. Both the first and second articulations show a 90° deflection while the third may be deflected through 135°. It uses a design of four tendons and offers three DOF. Its modular transmission system is made of four Teflon-coated steel cables protected by ducts. A direct current motor is used to actuate and control each joint (Pollard & Gilbert, 2002) while a cable tensioning mechanism located at the entrance of each finger controls the effort. This system positioning was dictated by the appearance of stresses that were exerted on the guide pulley. Incremental optical encoders located directly on the motors allow the obtaining of the positions and speeds of the hand joints. A sensor determines the location, amplitude, and direction of the force exerted at a distal phalanx contact point (Loucks et al., 1987). On this hand, the modularity of the fingers is realized to simplify the design while its dexterity is sacrificed because of the non-competition of the axes of the joints (Figure 3).

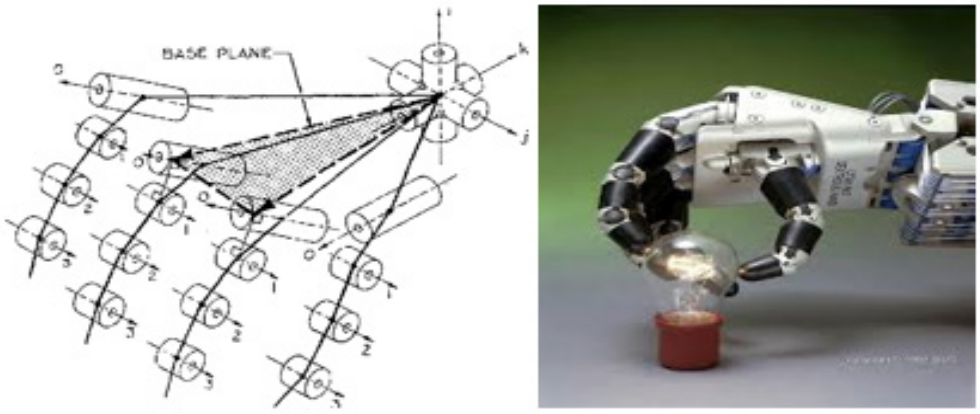
Figure 2.
The Stanford/JPL dexterous hand performing haptically-guided closed-loop grasp synthesis (Piater & Grupen, 2002)



The UTAH/MIT or Jacobsen Hand

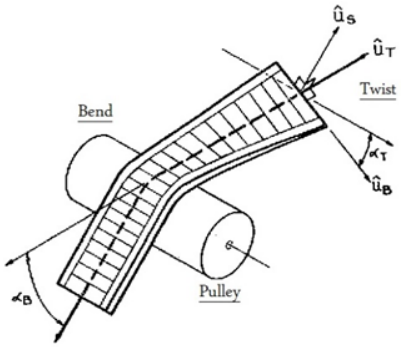
The UTAH/MIT hand was developed at the 'Center of Engineering Innovation' of the University of Utah in collaboration with the 'Computer Science and Artificial Intelligence Laboratory' of the Massachusetts Institute of Technology (MIT). The aim was to make available a robotic terminal device for carrying out studies in the field of dexterity. This collaboration has brought out the most sophisticated hand on the market that possesses four modular fingers with a thumb-shaped opposing the three long fingers, the little finger having been considered unnecessary to facilitate the manipulation. Each of the four fingers had four DOF. Figure 3-a shows the kinematic pattern of Jocobson's hand which consists essentially of a motor block, an actuator, and an analog controller that acts on the joints. A tactile sensor system is integrated at the fingertips and in the palm. Figure 3-b shows the hand performing a guided closed-loop precision grasp.

Figure 3.
The Utah/M.I.T Dexterous Hand. (a) Kinematics of the Hand (b) The Hand Performing a Haptically-Guided Closed-Loop Grasp Synthesis (Jacobsen et al., 1986), (Amirouche, 2004)



The joints noted '0' and '1' of each finger are separated to allow for the conveyance of the tendons. The friction exerted on the tendons leads to a limited lifespan, they have been replaced by flat belts generating stress separated by axial torsions (Figure 4). The axis of the proximal joints '0' is parallel to the palm plane with an inclination of 30° while for the human hand, the first joints of the fingers are perpendicular to it. This alteration allows the fingers to perform a movement in the lateral direction and therefore improves their mobility. When the fingers oppose the thumb, the joints noted '0' show zero displacement while those indexed '1' allow a displacement of 90°. The geometric adjustments incorporated into the design of the UTAH/MIT hand to grant it an anthropomorphic appearance also include the positioning of the thumb in the section of the palm between the first and second fingers. The wrist joints provide an additional space for the installation of 32 independent tendons as well as pneumatic actuators.

Figure 4.
Flat Belt of the Utah/M.I.T Dexterous Hand (Jacobsen et al., 1986)

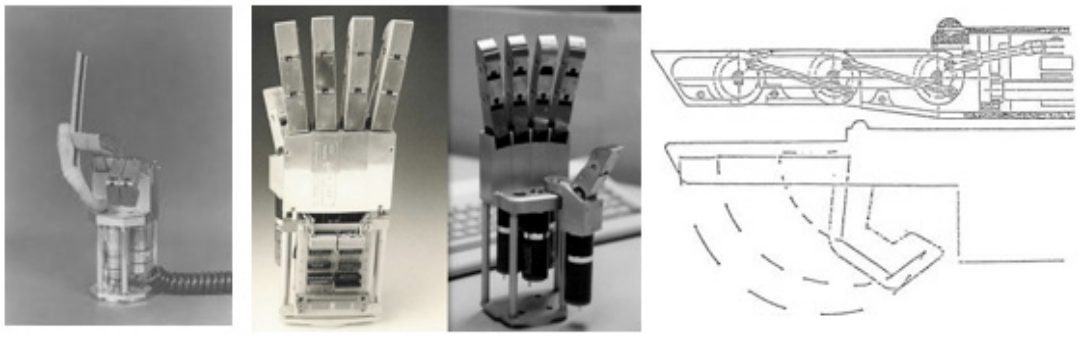


This hand is available in many American universities and is the subject of various research tasks, particularly in the field of remote operation (J.L. Banks, 2001). It resembles the Stanford model presented previously but differs in the number of fingers as well as in the design. While Salisbury and Roth were developing a non-anthropomorphic hand with some dexterity, the UTAH researchers in collaboration with MIT engineers were trying to replicate the human hand (Bekey et al., 1990).

The Belgrade/USC Hand

The first model of the Belgrade/USC hand was equipped with a rigid thumb and four articulated fingers (Figure 5-a), the motors being placed in the lower part of the wrist. The second model developed (Figure 5-b) has approximately the size of the human hand. It comprises five aluminum-made fingers. Its mechanical structure allows for the joints separation between the long fingers and the thumb. A control rods transmission system is used to ensure the movements of the fingers.

Figure 5.
The Belgrade/USC Hand. (a) Model-I, (b) Model-II, (c) Control Architecture for a Long Finger (Bekey et al., 1990)



The thumb is essentially constituted by two joints that rotate around an axis parallel to the wrist, allowing it to perform a movement of 120◦thus allowing an opposition movement with the four long fingers. The four fingers are identical in size having three joints each. All finger rotations are handled by miniature ball bearings powered by DC servo motors located in the structure of the wrist (Soto-Martell & Gini, 2007). The movement of the phalanges is ensured by the reduction mechanisms that allow direct transmission of the bending movement to the wrist using rods (Figure 5-c). Moreover, to imitate the movements of the human hand during a grasp, the motions of each finger phalanx are coupled using connecting rods. The trajectories of the phalanges during the phase of "bending" are shown in Figure 5-c. The design of the Belgrade/USC hand is different from that of both UTH/MIT and Stanford/JPL hands (Bekey et al., 1990).

The particularity of this hand lies in its mode of actuation. Four motors are placed in the wrist. Two operate the thumb while the two others operate the long fingers. Consequently, it seems to be more suitable for control grasp functions and lacks the dexterity needed for applications that require a large number of externally controllable DOF.
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The Multiple Actuator Hand (DLR)

The DLR-I hand (Deutshe Luft-Reederei) was developed at the German aerospace center and is a robotic hand articulated around four fingers (Butterfass et al., 1990). It has an anthropomorphic architecture and is represented in Figures 6-a and Figure 6-c. All the fingers are the same, possessing three phalanges made up of three joints.

Figure 6.
The DLR Hand. (a) DLR-I, (b) 2-dof Joint Unit With Actuator, (c) DLR-II (Butterfass et al., 1990)

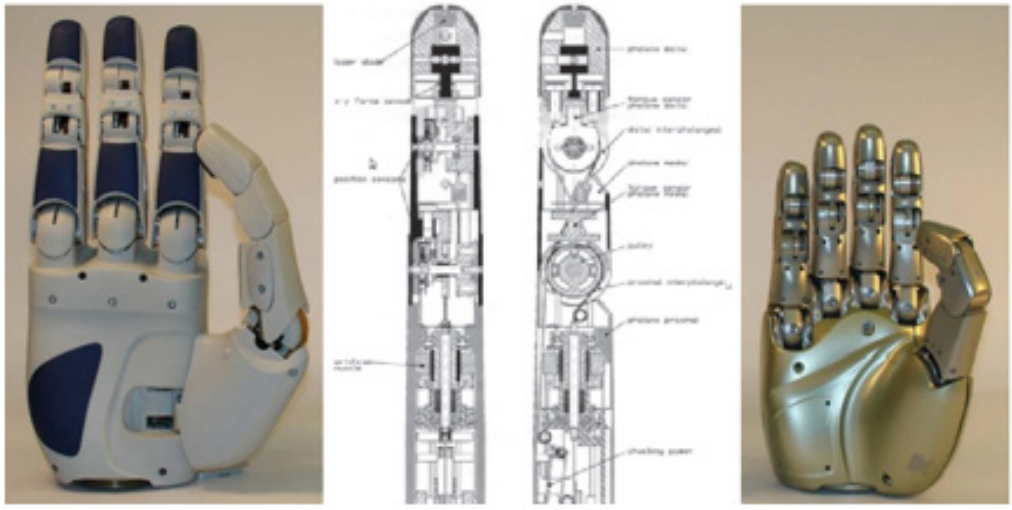


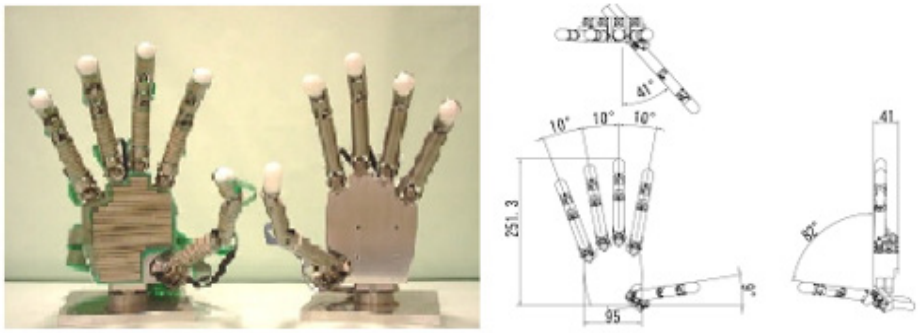
Figure 6-b shows a two-joint single-actuator finger unit. The first joint is situated between the proximal phalanx and the intermediate phalanx while the second lies between the middle phalanx and the distal phalanx. This last joint is coupled with the first one the same way it is accomplished within the kinematics of the human hand thus reducing this unit number of DOF to a single one. The transmission of the movement is ensured through cables and pulleys (Butterfass et al., 1990). The DRL hand has eighteen DOF, six of which refer to the movement of the wrist while three are independently controllable for each finger. This leads to an architecture that gives fingers modular design for of this hand.

Several versions of the DLR hand have been designed, all of them possessing four fingers except the one developed in collaboration with the Harbin Institute of Technology (HIT) which has five fingers (Figure 6-c). The development of a 5-fingered hand is very complex. To achieve a strength and size comparable to that of the human hand, the servomotors have been moved to the level of the forearm (Leblanc, 2011). The DLR-HIT collaboration enabled the development of a hand with 19 DOF using 'Dyneema' cords that are made of Ultra High Molecular Weight Polyethylene fibers. It integrates an independent palm and 5 identical modular fingers, the length and width of each having been altered by a proportion of two-thirds compared to previous versions. The use of a wire coupling mechanism achieved a unit ratio of transmission from the distal phalanx during all movements, and the type of conditioning used for the fingers and palm allowed the size of the hand to be reduced and made it anthropomorphic. Innovative force, torque, and position sensors have been integrated to increase its multi-sensory capacity (Shaowei et al., 1990). Each finger had 3 DOF and 4 joints. Electric actuators have been integrated in the body of the finger and also in the palm.

The Anthropomorphic Gifu Hand

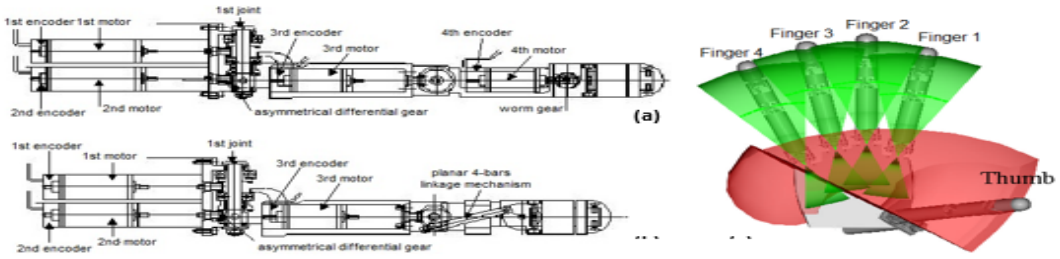
The GIFU hand versions I and II have been developed at GIFU University, Yanagido in Japan (Kawasaki et al., 2002). The GIFU hand comprises five fingers, has twenty joints with sixteen DOF, and is driven by built-in servo motors. The improved version of this hand has been called the "GIFU III" hand and has been designed to reduce the clearance that appeared in the gear transmission of the previous versions as a result of long operation time.

Figure 7.
The Anthropomorphic Gifu Hand-III. (a) Left and Right Hands, (b) Hand Structure (Cerruti, 2016)



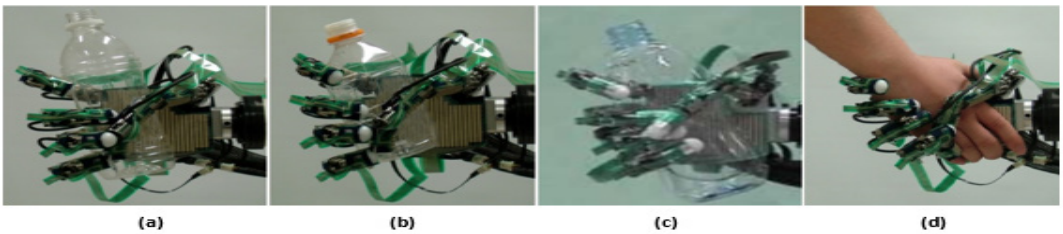
Both left and right hands have been designed symmetrically. They each have a thumb and four long fingers. Each long finger has 4 joints and 3 DOF while the thumb has 4 joints and 4 DOF. The movement of the first joint of both the thumb and the long fingers allows the adduction-abduction while the second and the fourth joint allow the ante-flexion and retro-flexion. Each servo motor has a magnetic encoder with 16 pulses per revolution. The thumb and long finger design mechanisms are shown in Figure 8-a and Figure 8-b respectively while the mobility space of the long fingers is represented in Figure 8-c (Mouri et al., 2002).

Figure 8.
Gifu Hand-III. (a) Mechanism of the Thumb, (b) Mechanism of the Long Fingers, (c) Opposability of the Thumb and Mobility Space of the Fingers (Mouri et al., 2002)



The improvement made on this hand lies in the use of a new tactile sensor having 859 detection points distributed over the hand (313 on the palm, 126 on the thumb, and 105 on each long finger). The motors are equipped with position sensors, and force sensors may be found at the fingertips (6 axes). A control device of the hand is coupled with an operating system in real-time called 'ART-Linux'. All this makes the Gifu III hand the artificial hand that may be considered as the closest to the human hand from the point of view of instrumentation. Several object seizures have been performed following a grasping strategy that imitates the human grasping reflex (Mouri et al., 2007).

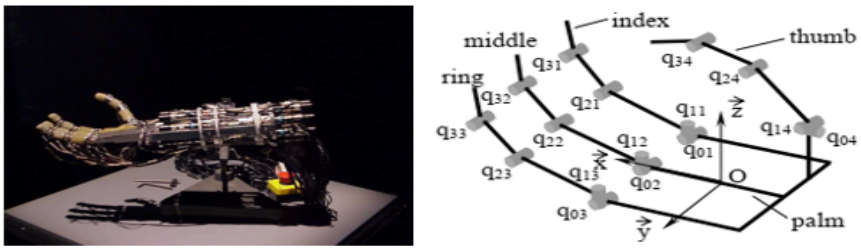
Figure 9.
Figure 9. Grasping force of the Gifu Hand-III (a) Cylindrical object (b) Rectangular object, (c) Curved Object, (d) Human hand (Mouri et al., 2007)



The L.M.S Four-Finger Articulated Mechanical Hand

The LMS hand, shown in Figure 10-a, has been developed within the 'Solid Mechanics Laboratory' of the University of Poitiers, France. It has three long fingers and a thumb in opposition. Each finger has four DOF. Three of the fingers enable the flexion-extension moves, while the fourth implements the abduction-adduction movements (J.P. Gazeau, 2000). For the long fingers, the axis of abduction-adduction movement is established by the connection to the proximal phalanx thus allowing it to maintain the amplitude of this operation regardless of the configuration of the finger. The range of the abduction-adduction movement is much greater in the thumb as it must allow the opposition arrangement of the thumb to the other fingers. Its axis is fixed relative to the palm.

Figure 10.
The LMS Mechanical Hand (a) LMS Hand, (b) Kinematics of LMS Exoskeleton (Arsicault et al., 2007)



The LMS hand uses a design similar to that of the UTAH/MIT hand i.e. an architecture based on the use of 32 cables allowing the control of 16 joints. The drive pulleys allow an independent tension of the two cables controlling a joint. Other guide pulleys ensure the passage of the cables at the level of the joints. The transmission of the movements to the phalanges requires the use of a return pulley using cables. The material used for the mechanical structure is aluminum alloy, and the moving parts are mounted on Torlon bearings. The behavior of the hand, using the exoskeleton trajectories represented in Figure 10-b, was found satisfactory.

The Shadow Hand

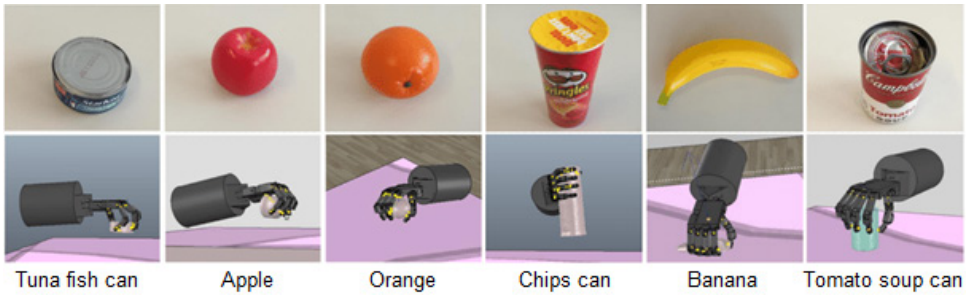
Through the Shadow hand illustrated in Figure 11, the anthropomorphic concepts are adapted to robotic handling (Rothling et al., 2007). With its twenty DOF, the shadow hand offers unique analogies with the human hand. Developed by Shadow and the University of Pierre et Marie Curie (UPMC), it has been equipped with force sensors, position sensors as well as sensitive ultra-tactile sensors at the fingertips. Moreover, it uses industry standard interfaces leading it to be easily used as a tele-operation tool. It can also be easily mounted on a range of arms as part of a robotic system and perform various grasps. (Figure 7-b-c-d-e).

Figure 11.
The Shadow Hand (a) The Shadow Hand Representations, (b) Shadow Hand dimensions (https://www.shadowrobot.com/)



The production of the Shadow hand constitutes a great achievement in the field of miniaturization, and its kinematics is very close to that of the human hand (Becket et al., 1990). With a total of 129 sensors (position sensors for each joint, force sensors for each actuator, contact sensors at fingertips, temperature sensors, and current loops on the motors) whose readings are processed via an 'EtherCaT' interface and a control board located in the palm, it can provide detailed telemetry that can be exploited to produce innovative manipulation control systems. This is particularly the case when wearing protective gloves needed for carrying out some specific tasks.

Figure 12.
Examples of Object Grasping by the Shadow Hand in the Simulator (https://www.roscomponents.com/en/robotic-hands/117-shadow-dexterous-robotic-hand.html)



The Shadow hand is fully accommodated to the Robot Operating System (ROS) that integrates various models of it along with its software. Moreover, its control along with its position command algorithms could be altered. For applications requiring detailed sensing capabilities, 'BioTac' touch sensors are available and can be added to each finger providing fine-tuned sensing of force, micro-vibrations, and temperature gradient.

Conclusions

Mechanical hands with four or five fingers facilitate the handling of objects as a result of the possibility of repositioning the fingers on the object. The mechanical design determines the fundamental dexterity of the hand i.e. the kind of handling that can be performed when grasping is performed. The size and arrangement of the fingers will drive the choice of approach. Anthropomorphic hands rely on the direct transfer of grasping strategies from the human hand while non-anthropomorphic hands consider the fingers to be identical and will therefore arrange them symmetrically.

The present review starts by introducing the anatomy of the human hand and the complex assembly of its bones, the joints that connect them, and the different movements achieved. This led the authors to present a range of mechanical hand structures made by the international scientific community as well as the latest developments in progress. Whatever structures are adopted, the goal of the designer is to obtain an artificial hand that exhibits dexterity as close as possible to that of the human hand with the concern of simplifying the design while choosing the appropriate control.

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