How Far Is the Human Hand?
A Review on Anthropomorphic Robotic End-effectors

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Abstract

In this paper, some considerations about the state of the art and the current trends in the design and control of "robot hands" are reported and discussed. The authors, on the basis of a long research activity for the development of robotic end-effectors and related technologies, address what they consider key-points for the development of "dextrous hands", being related this term not only to kinematics properties or aesthetic appearance, but also to sensory system, control strategies, integration with the carrying arm and so on... . In particular, some indices are defined as an attempt to present a clear comparison of the different "robot hands" presented in the literature. The indices refer to the degree of anthropomorphism, that is the resemblance with the human hand concerning aspect and mechanical structure, and to the level of dexterity, resultant from the kinematic configuration, the sensory apparatus and the control system.

1 Introduction

With the growth of interest towards humanoid robots, anthropomorphism of robotic hands becomes a necessary design goal, that has been purposely addressed by most recent research projects, e.g. the Robonaut hand by NASA (Lovchik and Diftler 1999, Ambrose, Aldridge, Askew, Burridge, Bluethmann, Diftler, Lovchik, Magruder and Rehnmark 2000), the DLR hands (J.Butterfass, G.Hirzinger, S.Knoch and H.Liu 1999, Butterfass, Grebenstein, Liu and Hirzinger 2001), the University of Tokyo hand (Lee and Shimoyama 1999), the Karlsruhe University ultra-light hand (Schulz, Pylatiuk and Bretthauer 2001), the GIFU hand (Kawasaki, Shimomura and Shimizu 2001), and others. Consistent levels of anthropomorphism were present, however, in many previous design proposals, e.g. the Utah hand (Jacobsen, Iversen, Knutti, Johnson and Biggers 1986), the Stanford/JPL hand (Salisbury and B.Roth 1983), the UB hand (Melchiorri and Vassura 1992, Melchiorri and Vassura 1993)and many others.
The reason of such a tendency is easily understandable considering that the human hand is the most dexterous "device" created by the nature during a millenary evolution. Therefore it has became a model for the majority of the researchers in the field of robotic manipulation, even if the projects, in which they are involved, do not explicitly require anthropomorphism as design specification.
Despite such a trend towards the development of human-like robotic hands, the results so far achieved are not yet comparable with the performances of our hand. In this paper we try to define a "quantitative" measure of the distance of a generic robotic end-effector from this ideal target. Such a distance is the result of several aspects, which jointly contribute to the "real" dexterity of a robotic device. Therefore, this measure has been expressed by means of some indices, which refer to the degree of anthropomorphism, that is the resemblance with the human hand concerning aspect and mechanical structure, and to the level of dexterity, resultant from the kinematic configuration, the sensory apparatus and the control system. These indices allow to evaluate the features of the different "robot hands" available in the literature, and make a clear comparison between them. In this way it has been possible to outline trends and open problems in robot hand design, in an integrated perspective, which considers mechanical aspects, sensing capabilities and control issues.

2 Basic concepts: anthropomorphism, functional capabilities, dexterity

With the term "anthropomorphism" we intend the capability of a robotic end-effector to mimic the human hand, partly or totally, as far as shape, size, consistency, and general aspect (including color, temperature, and so on) are considered. As the word itself suggests, anthropomorphism is related to external perceivable properties, and is not, itself, a measure of what the hand can do. On the contrary, "dexterity" is related to actual functionality and not to shape or aesthetic factors.
As a matter of fact we can find in the literature anthropomorphic end-effectors with very poor dexterity level, even if they are called hands, as the tasks they perform are limited to very rough grasping procedures (Fukaya, Toyama, Asfour and Dillmann 2000). Similarly, we can find smart end-effectors, capable of sophisticated manipulation procedures, without any level of anthropomorphism, e.g the DxGrip-II (Bicchi and Sorrentino 1995a). Anthropomorphism itself is neither necessary nor sufficient to achieve dexterity, even if it is quite evident that the human hand achieves a very high level of dexterity and can be considered a valid model for dexterous robotic hands.
Anthropomorphism is a desirable goal in the design of robotic end-effectors mainly for the following reasons:

- the end-effector can operate on a man-oriented environment, where tasks may be executed by the robot or by man as well, acting on items, objects or tools that have been sized and shaped according to human manipulation requirements;
- the end-effector can be tele-operated by man, with the aid of special-purpose interface devices (e.g. a data-glove), directly reproducing the operator's hand behavior;
- it may be specifically required that the robot has a human-like aspect and behavior, like for humanoid robots for purposes of entertainment, assistance, and so on.

2.1 Functional capabilities of a (robotic) hand

Besides the geometrical reproduction of the human hand, the main research target remains the emulation of those functionalities which make it such a versatile end-effector.
Two are the main skills of a human hand:

- *prehension*, i.e. the hand's ability to grasp and hold objects of different size and shape;
- *apprehension*, or the hand's ability to understand through active touch.

In this sense, the human hand is both an *output* and *input* device(see (Iberall and MacKenzie 1990)). As output device, it can apply forces in order to obtain stable grasps or perform some procedures of manipulation while, as input device, besides providing information about the state of the interaction with the object during the task, it is capable to explore an unknown environment. The same characteristics should be desirable in advanced robot hands. As a matter of fact, the application of robotic systems in unknown servicing environments requires dexterous manipulation abilities and facilities to execute complex operations in a flexible way.

2.2 The meaning of dexterity

Generally speaking, with the term "dexterity" we intend the capability of the end-effector, operated by a suitable robotic system, to autonomously perform tasks with a certain level of complexity. An exhaustive review of scientific work done so far about robotic hands dexterity, with a complete list of references, can be found in (Bicchi 2000).
Even if the word dexterity itself has a highly positive meaning, it is useful to consider different levels of dexterity, associated with growing complexity and criticality of performable tasks. The dexterity domain for robotic hands can be roughly divided in two main areas, that are *grasping* and *internal manipulation*.
Grasping is intended as constraining objects inside the end-effector with a constraint configuration that is substantially invariant with time (the object is fixed with respect to the hand workspace), while internal manipulation means controlled motion of the grasped object inside the hand workspace, with constraint configuration changing with time. Further subdivisions of these two domains have been widely discussed in the literature (different grasp topologies on one side (Cutkosky 1989), different internal manipulation modes based on internal mobility and/or contact sliding or rolling on the other side (Bicchi 2000)).

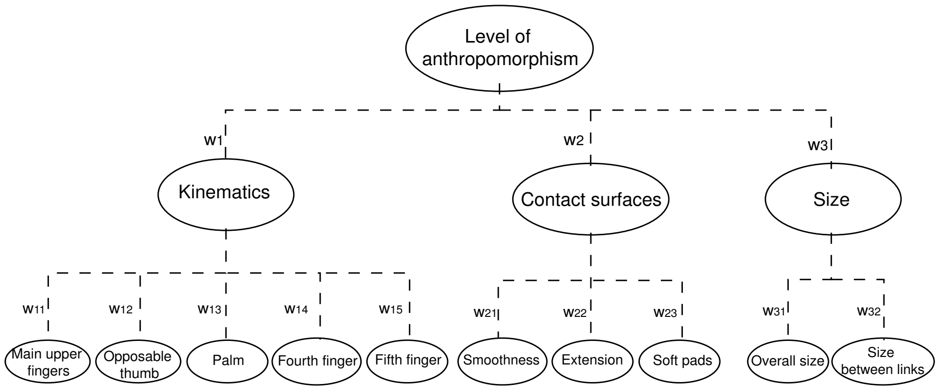


Figure 1: Evaluation graph of the anthropomorphism level of a robotic hand.

3 An anthropomorphism index

From the observation of the many robotic end-effectors inspired by the human hand, we can conclude that the level of achieved resemblance with a human hand is greatly variable from case to case, although all of them are defined as anthropomorphic hands.
An interesting problem arises: *what are the components of anthropomorphism and how the achieved level of anthropomorphism can be quantified?* Is it more anthropomorphic a hand with five fingers but sharp rigid edges or one with three fingers well shaped and covered with a compliant layer? With the only aim of trying a comparison between different design proposals presented in the literature, the authors have defined an anthropomorphism index (in the following denoted as α_x), that is determined considering the following aspects:

- *Kinematics.* This aspect considers the presence of the main morphological elements (principal upper fingers, secondary upper fingers, opposable thumb, palm). Each of them, whose value ranges between 0 and 1 (according to the number of articulations inside each finger, in comparison with the human case), gives a different contribution to the kinematic evaluation score, weighted by the factor w_{1i};
- *Contact surfaces*: extension and smoothness of the contact surfaces, that means the capability to locate contacts with objects all over the surface of the available links, and availability of external compliant pads;
- *Size.* This contribution takes into account the actual size of the robotic hand compared with the medium size of a human hand and the "correct" size ratio between all the links.

The index α_x is calculated as the weighted sum of these three aspects, as shown in Fig. 1. If we consider the structure of the human hand the final value for α_x will be obviously equal to 1, therefore the index associated to a given design (e.g. $\alpha_x = 0.75$) provides an immediate idea of how far from the human shape and aesthetics it places. For example, in Tab. 1 the index α_x relative to the UB-Hand, shown in figure Fig. 2, is presented (Melchiorri and Vassura 1992, Melchiorri and Vassura 1993).

4 A measure of dexterity

If the notion of dexterity is well settled, the way to achieve it remains debated. The factors affecting the actual capabilities of a robotic end-effector are so many, that often the analysis and above all the synthesis of dexterous hands do not take in the right consideration some of these elements, namely:

- morphological features;
- sensory equipment;
- control algorithms;
- task planning strategies;
- ...

As a matter of fact, a very simple end-effector like a rigid stick can be used for very sophisticated object-pushing tasks if used by a robot with visual and force feedback, while a complex articulated hand without adequate control can limit its dexterity to trivial self-adapting encompassing grasps. Evaluating the design

Evaluated Elements and Related Weights		Value	Result
Kinematics ($w_1 = 0.6$)	Main Upper Fingers ($w_{11} = 0.3$)	1	0.18
	Opposable Thumb ($w_{12} = 0.3$)	0.8	0.144
	Palm ($w_{13} = 0.2$)	0.8	0.096
	Fourth Finger ($w_{14} = 0.1$)	0	0
	Fifth Finger ($w_{15} = 0.1$)	0	0
Contact Surfaces ($w_2 = 0.2$)	Smoothness ($w_{21} = 0.33$)	0.9	0.0594
	Extension ($w_{22} = 0.33$)	0.9	0.0594
	Soft Pads ($w_{23} = 0.33$)	0.3	0.0198
Size ($w_3 = 0.2$)	Overall Size ($w_{31} = 0.5$)	1	0.1
	Size Between Links ($w_{32} = 0.5$)	0.9	0.09
Total			0.745

Table 1: Evaluation of the anthropomorphism level (index α_x) of the UB Hand II.

of a robotic hand, for example examining its kinematical configuration or its sensory equipment, we can define a *potential dexterity* intrinsically related to its structure.

4.1 Potential dexterity of a given mechanical structure

It is quite evident that the potential dexterity of an articulated five-finger hand is better than that of a rigid stick, but it is obvious at the same time that much of the potential dexterity of such a complex structure can be wasted if proper actuation or sensory system are not adopted and suitable control procedures are not implemented. The evaluation of potential dexterity of an articulated hand depending on its kinematical configurations (e.g. evaluation of manipulation ellipsoid) has been widely discussed in the literature, as reported in (Bicchi 2000).
This kind of analysis requires the knowledge of some mechanical details and parameters, which are often unavailable. Therefore in the following, the potential dexterity of a robotic hand will be roughly quantified considering its functional capabilities (allowed by the features of its mechanical structure, such as number of degrees of freedom, smoothness of the contact surfaces,...). In particular two main areas can be recognized:

- hands with capability limited to grasping (simplified kinematical configuration or complex kinematical configuration but reduced number of controlled degrees of freedom)
- hands that are capable of some kind of internal manipulation.

Each of these two areas can be further subdivided in two parts, distinguishing if the capability is limited to fingertip operation or is extended to the other active elements of the hand (whole hand grasp and manipulation). It is a rough subdivision, but can help to distinguish between projects that may look aesthetically similar but in practice achieve quite different levels of operating capabilities. In order to make this comparison easier, an index of the kinematic dexterity can be constructed, by tacking into account the contribution of the different abilities (as shown in figure 3).

4.2 Potential dexterity related to the sensory apparatus

Dexterous manipulation, besides suitable mechanical configurations, requires an adequate sensory system. In fact, the manipulation of an object needs precise information about the configuration of the hand and the state of the interaction with the environment (typically the grasped object), and often the success (or simply the completion time) of the task depends on the level of this information. Since the human hand can be considered as the best known example of dexterous end-effector, not only its structure but also its sensory system has become a paradigm for the researchers. As a matter of fact, many of them tend to adopt similar sensory configurations even in devices quite simple from the mechanical point of view and not anthropomorphic at all. This is the case of the ROTEX Gripper (see Fig. 4) (Hirzinger, Brunner, Dietrich and Heindl 1993), whose equipment includes position, force and tactile sensors.

The internal state of the human hand (position, velocity and force) is known by means of receptors collocated in muscles, tendons, and joint capsules (for a complete overview see (Grupen, Henderson and McCammon 1989, McCloskey 1978)). But the key point of human dexterity is the richness of cutaneous information (high-frequencies vibrations, small scale shape or pressure distribution, accelerations and dynamic forces, thermal properties). As a matter of fact, it has been shown that the lack of touch sensation, due for example to thick gloves (e.g. in space) degrades the human ability and prolongs the task completion time up to 80%, (Shimoga 1993).

If the sensing system of the human hand is the desired target, unfortunately current technologies are still far from their biological models, in particular considering transducers of touch sensations. As a matter of fact, tactile sensors are object of great research efforts and the sensors currently available still present some important problems and functional limitations: basically they can detect the contact point and the magnitude of applied forces (while acceleration or vibration sensors are current under development (Howe and Cutkosky 1993) but not yet available for their integration in advanced robot hands) but they are generally characterized by low reliability, non-linear (hysteresis) phenomena and a large number of electrical connections.

A synthesis of sensing technologies for manipulation
The standard equipment of an advanced robotic end-effector includes, besides sensors directly collocated in the actuators (e.g. encoders), a number of additional sensing elements; in particular three main classes can be identified:

- **Joint position sensors**
  Although position sensors on motor shaft are a solution simple, reliable and with a relatively high resolution (considering that the rotor motion is 'reduced' several times by the mechanical transmission), back-lashes and deformations of the motions transmissions can render the measure quite

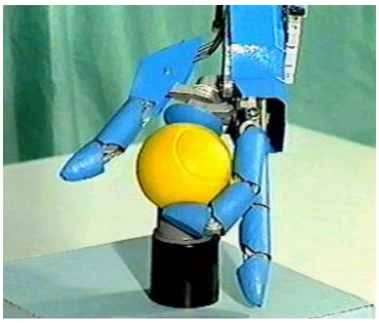


Figure 2: The University of Bologna Hand II.

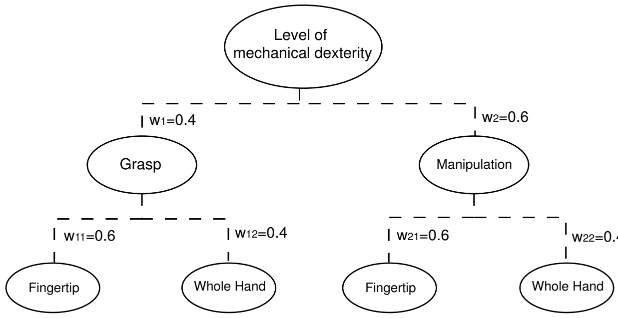


Figure 3: Evaluation graph of the kinematic dexterity level of a robotic hand.

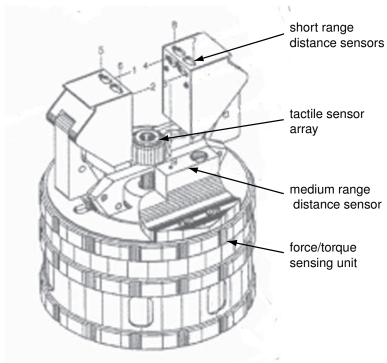
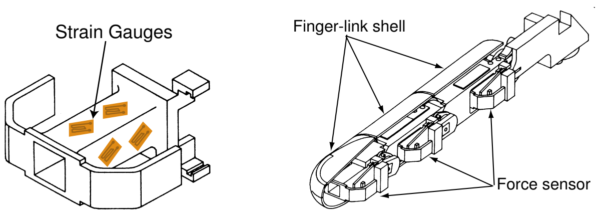


Figure 4: Sensory equipment of ROTEX gripper.

  rough. Besides, the use of non-rigidly coupled joints or under-actuated systems makes the *minimal* solution of motor encoders not applicable, since a well-defined relation between the rotor positions and the joint configuration does not exist: in general it depends also on external conditions (e.g. contact with the grasped object). In any case, when a single motor is used to drive more than one joint, and, in general, in order to improve the position measurements, additional position sensors must be added directly (or as close as possible) to the joints in the kinematic chain. Position sensors are based on different physical principles and methods: Hall effect sensors (e.g. the position sensors on the gripper designed by the University of Bologna, (Biagiotti, Melchiorri and Vassura 2000)), potentiometer, optical sensors (e.g. in the DLR hand I,(Butterfass, Hirzinger, Knoch and Liu 1998)), and so on.

- **Interaction sensors**
  If the sense of touch (and in general force information) is the main reason of human hand dexterity, a robot hand, which will physically interact

with the environment, can not leave aside force sensing. The measure of the interaction can be done in different way, but schematically it is possible to find three alternative methods (complete overview are available in (Nicholls and Lee 1989, Nicholls and Lee 1999, Melchiorri 2001)); on one hand the force exchanged with the external environment can be known by means of force/torque sensors collocated within the kinematic chain of the end-effector, on the other hand tactile sensors, directly placed on external surface, can provide information on the contact area and force magnitude when the interaction occurs. In the middle, Intrinsic Tactile (IT) can be considered.
Force/torque sensors measure the efforts exerted by fingers, at different levels and in different way: it is possible to detect the torques on finger joints, or consider the tension of tendons (which often are used to transmit the motion in robot hands), or if the mechanical chain is back-drivable measure the force/toruqe provided by the actuators. Other kind of force/torque sensors are able to detect all the components of the applied wrench; basically, the major part of these devices are transducers which measure forces/torques by means of the induced mechanical strains on flexible parts of their mechanical structure. The mechanical strains are in turns measured by elastomers (strain gauges), properly glued on the structure, that change their resistance according to local deformations. Based on a force/torque sensor with known external shape and connected to a link of a manipulator (see Fig. 5), the *IT sensor* has the possibility to determine, when a contact is established between the link and an object, both the applied wrench and the position of the contact centroid on the surface of the link. For this reason, the IT sensor can be considered an intermediate solution between force sensors and tactile ones, even if one of the main drawbacks of this technology is the fact that they can not detect the difference between one contact and multiple contacts in the same structure (producing in the second case wrong estimations) and measure the shape/extent of the contact area. For this purposes, that is to determine the exact shape and position of contact (possibly not-punctual) area, *tactile sensors* are used. Usually, they consist in a matrix (array) of sensing elements. Each sensing element is referred to as a *taxel* (from "tactile element"), and the whole set of information is called a *tactile image*. Main goal of this class of sensors is to measure the map of pressures over the sensing area, allowing to get geometrical information (position and shape of contacts), as well as knowledge about mechanical properties (e.g. friction coefficient), and to detect when a slip condition occurs. In order to realize this kind of transducers several technologies have been developed, ranging from piezoresistive to magnetic, to optical effects (Nicholls and Lee 1989, Nicholls and Lee 1999).



(a) (b)

Figure 5: An IT sensor (a) within a finger of the UB-Hand II (b).

- **Additional sensors**
  Additional sensors can be added for particular applications or to obtain specific capabilities; for example end-effectors for space activities are often equipped with proximity sensors and/or cameras directly installed within the hand (Butterfass et al. 1998). Other classes of sensors, which can increase the dexterity of a robot hand, include accelerations or vibrations sensors (Howe and Cutkosky 1993), but their development is still in progress.

A comparative index
In order to give an immediate idea of the complexity of the adopted solutions in some noticeable examples of robot hands, we have defined an index σ_x which takes into account the sensory equipment. In Table 2 the sensory apparatus of the UB Hand II has been considered: the index is the result of evaluation of the three classes defined in the previous section, considered with different weights according the level of dexterity they can, in authors' opinion, allow.
Sensors that detect the status of the interaction (force/torque and tactile sensors) are considered as preeminent to achieve dexterity. Moreover, it is worth to notice that tactile "array" sensors and intrinsic tactile sensors are treated as alternative: the information they provide are quite different and normally used for different aims (planning the former, control the latter). Tactile capabilities are further specialized con-

sidering their peculiar features:

- distribution on the robotic devices (fingertips/phalanges/palm) and number of detectable force/torque components for IT sensors;

- distribution, covering (partial/total of the finger link surfaces), and spatial resolution for tactile array sensors.

The index σ_x can be very useful to compare different designs and to have an immediate idea of how different researchers have faced the problem of dexterity.
Moreover, it provides a measure of the gap with the human hand, whose index is not far from one (not exactly one, because of the lack of some sensors, such as proximity sensors)

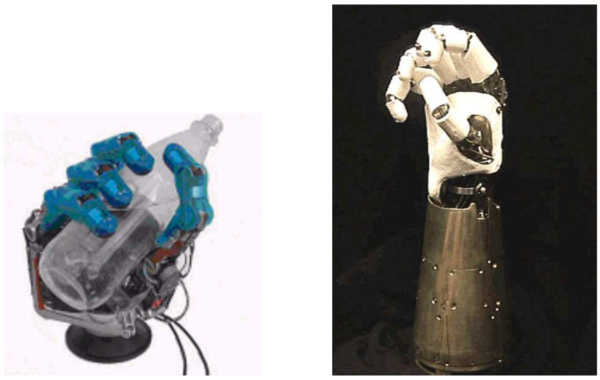
5 Integration

Besides the dexterity or the anthropomorphism, in authors' opinion a key point in the design of a robotic end-effector is the *integration*. This term has several meanings, but all of them are fundamental in robot hands design.
As a matter of fact, a right integration between mechanical parts, sensors and electronics systems and control algorithms is one of the most stressed concepts in the design of robotic devices and automatic systems in order to achieve structural simplification, increase of reliability, and drop of costs. In particular this is true for a dexterous robot hands, which usually are extremely complex devices with quite small dimensions. Moreover, as shown in Sec. 4, the dexterity and the functional capabilities of robot hands are the result of several contributions, which must balanced as much as possible. Therefore, as stated in Sec. 4.2, it is very important to properly match mechanical structure and sensory apparatus and also a medium-complexity hand can be dexterous and effective if an adequate mix has been done.
But, considering a robotic end-effector, *integration* concerns also the relation between the hand to be designed and the rest of the robotic system, considering both the physical parts of the system (*structural integration*) and the way they interact or cooperate in order to accomplish manipulation tasks (*functional integration*). Structural integration directly determines mechanical design guidelines, while functional integration is mainly a conditioning goal as far as control strategies and task planning procedures are concerned.

5.1 Structural integration

Two different concepts about the structural integration of robotic hands are described in the literature, which can be summarized with the following formula:

- Modular Hands (MH), Fig. 6.a;
- Integrated design Hands (IH), Fig. 6.b.



(a) (b)

Figure 6: Example of modular hand (DLR Hand II) (a) and of hand-arm structural integration (Robonaut Hand) (b).

In the former case, the hand is considered like an independent device to be applied at the end of an arm: the same hand can be applied to any kind of arm because it has been designed independently of it (examples of this approach are the DLR Hands (J.Butterfass et al. 1999, Butterfass et al. 2001), the Barret Hand (Townsend 2000), the Salisbury's hand (Salisbury and B.Roth 1983),...).
In the latter case, reproducing the biological model, the hand is considered a non-separable part of the arm, deeply integrated with it: the hand and the arm are jointly designed and cannot be conceived as separate subsystems (as examples of this approach we can remember the Robonaut hand (Lovchik and Diftler 1999, Ambrose et al. 2000), the UB Hand (Melchiorri and Vassura 1992, Melchiorri and Vassura 1993)).
The main difference between these two approaches is that a modular hand must contain all its functional components (actuators, sensors, electronics, etc:), while an integrated system (hand + arm) can distribute these components in the whole structure, placing them where room is available. The different design approaches have the most evident implications in the placement of the actuators, necessary to move

Evaluated Elements and Related Weights				Value	Result
Position ($w_1 = 0.2$)	Joint Position Sensors ($w_{11} = 1$)			1	0.2
Interaction ($w_2 = 0.6$)	Force/Torque Sensors ($w_{21} = 0.3$)			0.4	0.072
	Tactile Sensors ($w_{22} = 0.7$)	Intrinsic ($w_{221} = 0.6$)	# Axis ($w_{2211} = 0.5$)	1	0.126
			Placement ($w_{2212} = 0.5$)	1	0.126
		Array ($w_{222} = 0.4$)	Spatial Resolution ($w_{2221} = 0.3$)	0	0
			Covering ($w_{2222} = 0.2$)	0	0
			Placement ($w_{2223} = 0.5$)	0	0
Additional ($w_3 = 0.2$)	Proximity,Vision, Dynamic Force Sensors ($w_{31} = 1$)			0	0
Total					0.524

Table 2: Evaluation of the sensory equipment of the UB Hand II.

the hand joints.
In the first case all the needed actuators have to be placed in the hand, while in the second case the hand design is developed considering the possibility to put the actuator in the forearm. Each of these two modalities has advantages and drawbacks. At present, bulk and performance of available actuators make very difficult to host the required number of actuators inside the hand. As a matter of fact, the size of the proposed modular hands is larger with respect to the human hand, the grasping forces are weaker and the overall design seems complex and not enough reliable.
On the other side, the choice of integrating the hand and the arm with simultaneous design allows the placement of actuators for example in the forearm. The size and bulk of stronger actuators is no longer a problem, but many other problems arise due to the need of transmitting the motion through the wrist joints. There are pros and cons on both sides, but it is in authors' opinion that an integrated hand can reach more easily a high level of anthropomorphism, at least with the technical resources available so far.

6 A review of robotic hands with some degree of anthropomorphism

Several robotic hands, more or less anthropomorphic, have been developed over the past two decades. The goals of each project were most times rather different, and the results are not easily comparable to the purpose of declaring one project better than another. Anyway, in order to point out the effectiveness of each contribution and to trace the historical evolution of this sector of robotics, a classification of the potential dexterity and level of achieved anthropomorphism of each design can help to outline results, tendencies, open problems and goals for future evolution of research.
In Tab. 3-10 a survey of some noticeable examples of robotic hands is reported, considering the the main features of the mechanical design, as well as of the adopted sensory system. The review is limited to those projects that clearly addressed the achievement, at a significant level, of both dexterity and anthropomorphism.

From the data collected in the tables, the indices mentioned in Sec. 3, 4 have been computed for each hand and graphically displayed in order to give a synthetic idea of the main characteristics of each project and to compare the different designs. In order to give an historical perspective of the considered aspects (anthropomorphism, dexterity,...), the robot hands are presented according to a chronological order.
Firstly, in Fig. 7 the anthropomorphism level has been considered: it is clear that in last years (in particular in the last 5-6 years) the interest towards fully anthropomorphic devices has been growing. As a matter of fact the kinematic structure of robotic hands becomes more and more close to the human model and the dissimilarity with our hand mainly concern the size and the "skin". If the former difference is above all due to technological problems (in particular, to the lack of miniaturized actuators), the latter strongly depends on a traditional way of designing robotic devices. Despite it has been recognized that suitable contact surfaces (in particular soft pads) can greatly enhance (besides their appearances) the dexterity of robot hands (Shimoga and Goldenberg 1992), only in the last years this issue has been explicitly faced and the first endoskeletal structures, apt to be integrated with soft layers, have been presented (Schulz et al. 2001, Lotti and Vassura 2002).

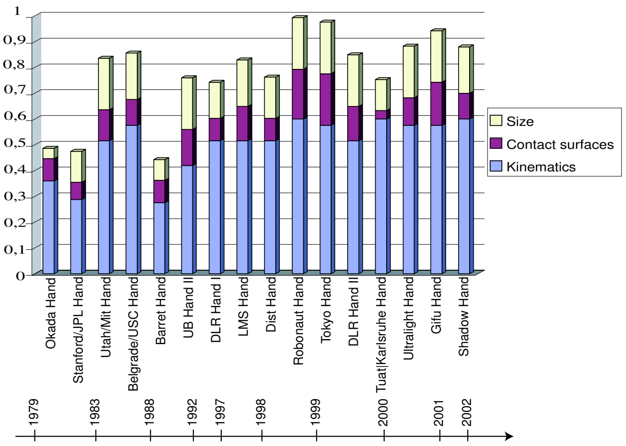


Figure 7: Anthropomorphic level of the reviewed robotic hands.

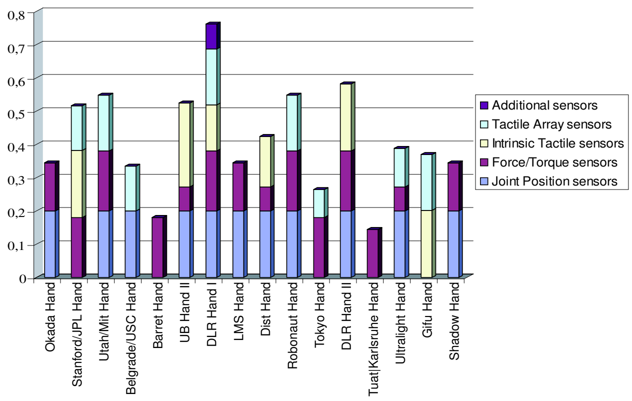


Figure 9: Potential dexterity related to the sensory system of the reviewed robotic hands.

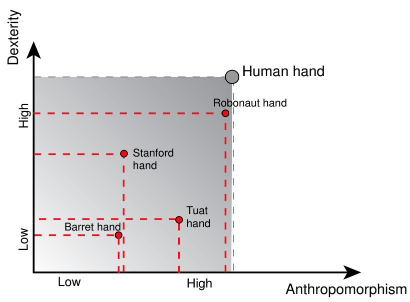


Figure 10: Relation between anthropomorphism and dexterity.

As mentioned in Sec.3 anthropomorphism and dexterity are orthogonal concepts; this is evident if we consider the other two defined index, that is the degree of dexterity related to the mechanical structure and to the sensory equipment, respectively reported in Fig. 8 and 9. Tacking into account the mechanical structure, it can not be observed the trend, which characterizes the anthropomorphism level, towards an increase of dexterity. There are examples in the scale of evolution, from very anthropomorphic but low dexterity designs (it is the case of hands simply oriented to adaptable grasp applications, e.g. the Tuat/Karlsruhe Hand (Fukaya et al. 2000) and the Laval Hand (Underactuated robotic hands webpage)) to fairly dexterous but less anthropomorphic ones. In Fig. 10 possible relations between anthropomorphism and dexterity are displayed, considering some notable examples of robotic hands. These designs are usually associated to very restricted and limiting specifications and precise purposes:

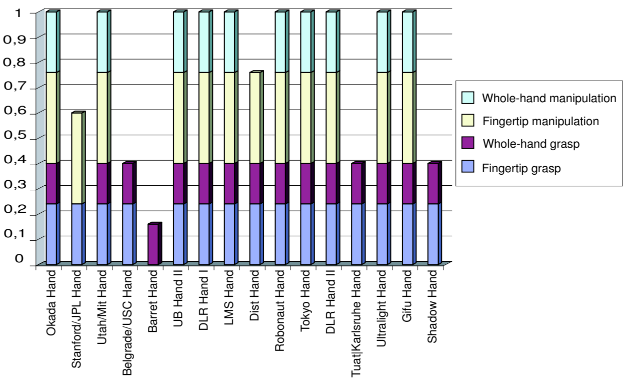


Figure 8: Potential dexterity related to the mechanical structure of the reviewed robotic hands.

- Salisbury, designing the Stanford/JPL hand, explicitly focus the problem of dexterity, but no considerations about resemblance with the human hand have been done;

- the target of the Tuat/Karlsruhe hand is to exploit the structure of the human hand in order to achieve good grasp capabilities with a very low complexity (only one actuator has been used);

- Robonaut hand aims to substitute the human hand concerning both functional capabilities and shape/structure;

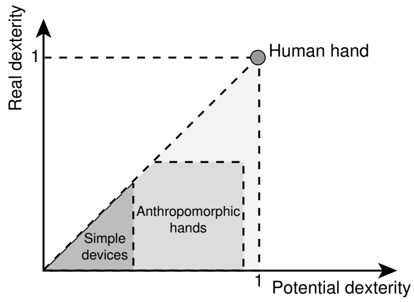
- Barret hand is, according the definition of its designer, a grasper and therefore neither anthropomorphism nor high-level of dexterity has been specifically addressed.

High dexterity is usually synonym of complexity. In this sense the designs of the reported robotic hands ap-

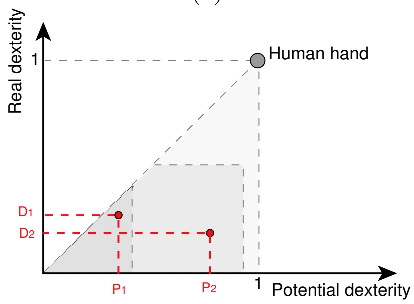
pear very coherent, according to the criterion of integration between mechanical and electronic parts mentioned in Sec. 5. As a matter of fact hands showing the highest degrees of structural dexterity, and therefore the largest number of controlled degrees of freedom and actuators, are characterized by an extremely complex sensing apparatus. Conversely commercial hands (like Barret hand or Shadow hand), that must be particularly reliable and consequently not too complex have only a basic set of sensors.
In any case, if we observe the potential dexterity related to the sensory system, all the projects show high-level equipments (compared with traditional robot manipulators), including positions and force/torque sensors. Moreover the design of such an equipment is somehow incremental, and often additional sensors are employed afterwards. In particular, this is true for tactile sensing: despite the contribution of tactile sensors to the dexterity of robotic hands is widely recognized, their use is not settled yet. From the Fig. 9 it is clear that a "final decision" between intrinsic tactile sensors, tactile array sensors, or both has not been definitely made and it is currently an important research topic in the field of robot manipulation.

7 Potential or real dexterity? The role of control

As stated by Bicchi (Bicchi 2000), citing the Greek philosopher Aristoteles, one of the (old) theories regarding the relationship between human hands and mind claims that "because of his intelligence he (man) has hands". Despite, researches of paleoanthropologists have shown that the converse opinion, which considers the development of the brain of human beings as a result of the structural dexterity of their hands, is preferable, the former theory gives an insight into the importance of the "intelligence"(in a broad sense) in order too obtain the dexterity of an (artificial) hand.
As shown in previous sections, the dexterity of a robot hand is the result of its mechanical structure as well as of its sensory equipment. Adding up the contributions sketched in Fig. 8 and Fig. 9 it is possible to quantify the overall degree of dexterity of the reviewed hands. At this point, a first consideration is that some of the devices taken into account are not distant (considering their structure and their features) from the human hand but the tasks they can autonomously perform are still simple and quite far from the human capabilities. Therefore, in order to estimate the real dexterity of a robot hand, the "intelligence", that is control algorithms and task planning strategies, can not be neglected. Indeed, the control is a key element, which puts potential dexterity into real one and is the main reason of the success of the human hand.
Because of its "control system", the human hand can fully exploit its complex structure. The same does not happen for robot hands: as qualitatively shown in Fig. 11.a their actual dexterity is considerably lower than the dexterity given by their structure and paradoxically some simple devices with suitable control strategies may be more dexterous than a complex robot hand (see Fig.11.b). A tangible example of such a smart device is given by Dx-Grip II, a 2-jaw gripper developed by Bicchi et al. (Bicchi and Marigo 2002), able to arbitrarily change the position/orientation of quite general objects, by means of rolling.
A number of theoretical works show that *rolling* and *sliding* can greatly enhance the robot dexterity (Brock 1988, Howe and Cutkosky 1996, Payandeh 1997, Bicchi and Sorrentino 1995b) but, despite the effectiveness of manipulation by rolling or sliding can be observed also in human beings, these results are not applied to complex robot hands. In the same way, the use of tactile sensors for direct servoing have been the subject of several recent works (Okamura and Cutkosky 1999, Moll and Erdmann 2002), but prac-



(a)



(b)

Figure 11: Potential versus real dexterity: general case (a) and an example (b).

tical demonstrations of the achieved results has been done only by means of special purpose robotic devices. The challenge for the future is to take the results mentioned above to robot hands, exploiting the complexity of the available devices (which are potentially very dexterous) and fill the gap between theoretical speculations and practical applications.

8 Conclusions

This paper presents an attempt to classify robotic hands, proposed so far by research institutions or industries, focusing on their anthropomorphism and dexterity. In particular, the human hand has been taken as paradigm, and the "distance" of the reviewed robot hands from this ideal target has been estimate by taking into account the degree of anthropomorphism as well as the level of dexterity. In this way it has been possible to outline trends and open problems in robot hand design, in an integrated perspective, which considers mechanical aspects, sensing capabilities and control issues.

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Table 3: Main features of Okada and Stanford/JPL Hands.

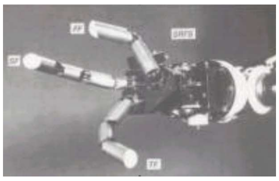
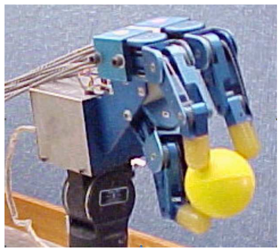
Project identification	Project denomination	**Okada Hand**	**Stanford/JPL Hand**
	Reference author(s)	T. Okada	Salisbury
	Research institute	Electrotechnical laboratory, Japan	Stanford University
	Year of presentation	1979	1983
	Reference	(Okada 1986)	(Salisbury and B.Roth 1983, Chase and Luo 1997, Fearing 1987)
Picture			
Mechanical structure:	Arm/hand Integration	MH	IH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	-	-
	Fifth finger	-	-
	Palm	-	-
	Number of links	12	10
	Number of joints	11	9
	Number of controlled degrees of freedom	11	9
Morphological features:	Size w. r. to a human hand	$>$	$=$
	Surfaces apt to contact with objects	Fingertips/Phalanges	Fingertips
	Contact surface smoothness and continuity	Fair	Poor
Mechanical details	Structural design concept	Exoskeletal	Exoskeletal
	Actuator location	Remote	Remote
	Actuation type	Electrical revolute motor	Electrical revolute motor (DC)
	Act. joints back-drivability	Not Found (NF)	✓
	Kind of not-actuated joints	-	-
	Type of transmission	Tendons	Tendons
	Transmission routing	Pulleys/sheaths	Pulleys/sheaths
Sensors:			
Position	Motor position sensors	✓	✓
	Joint position sensors	Potentiometers	-
Force/Torque sensors	Joint torque sensors	-	-
	Tendon tension sensors	-	✓
	Motor effort sensors	✓	-
Contact sensors	Intrinsic tactile sensors	-	Fingertip force sensors
	Tactile array sensors	-	8×8 tactile sensors array with complete coverage of the cylindrical fingertip
Additional Sensors			

Table 4: Main features of Utah/Mit And Belgrade/USC Hands.

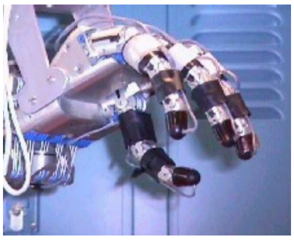
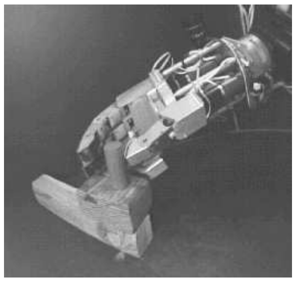
Project identification	Project denomination	**Utah/Mit Hand**	**Belgrade/USC Hand**
	Reference author(s)	Jacobsen	G.A. Bekey/R. Tomovic/I. Zeljkovic
	Research institute	Utah University	University of Belgrade
	Year of presentation	1983	1988
	Reference	(Jacobsen et al. 1986, McCammon and Jacobsen 1990, Johnston et al. 1996)	(Bekey et al. 1990)
Picture			
Mechanical structure:	Arm/hand Integration	IH	MH
Kinematical scheme:	Main upper fingers	✓	
	Opposable thumb	✓	✓
	Fourth finger	✓	✓
	Fifth finger	-	✓
	Palm	✓	✓
	Number of links	17	16
	Number of joints	16	18
	Number of controlled degrees of freedom	16	4 (2 thumb+2 fingers)
Morphological features:	Size w. r. to a human hand	=	=
	Surfaces apt to contact with objects	Fingertips/Phalanges/Palm	Fingertips/Phalanges/Palm
	Contact surface smoothness and continuity	Good	Fair
Mechanical details	Structural design concept	Exoskeletal	Exoskeletal
	Actuator location	Remote	Remote
	Actuation type	Pneumatic actuator	DC Motors
	Act. joints backdrivability	✓	-
	Kind of not-actuated joints	-	Rigid passive-driven joints
	Type of transmission	Tendons	Linkages
	Transmission routing	Pulleys	-
Sensors:			
Position	Motor position sensors	✓	✓
	Joint position sensors	Rotary Hall effect	Rotary potentiometers
Force/Torque sensors	Joint torque sensors	-	-
	Tendon tension sensors	✓	-
	Motor effort sensors	-	-
Contact sensors	Intrinsic tactile sensors	-	-
	Tactile array sensors	Capacitive tactile sensors covering finger segments and palm	Touch-pressure sensors (Force sensing resistor) on fingertips
Additional Sensors			

Table 5: Main features of Barret and UB (II) Hands.

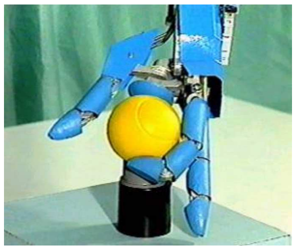
Project identification	Project denomination	**Barret Hand**	**UB Hand II**
	Reference author(s)	W.T.Townsend	Bonivento/Melchiorri/Vassura
	Research institute	Barret Technology, Inc	Bologna University
	Year of presentation	1988	1992
	Reference	(Townsend 2000, Barret hand webpage)	(Melchiorri and Vassura 1992, Melchiorri and Vassura 1993, Bonivento and Melchiorri 1993)
Picture			
Mechanical structure:	Arm/hand Integration	MH	IH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	-	-
	Fifth finger	-	-
	Palm	✓	✓
	Number of links	9	14
	Number of joints	8	13
	Number of controlled degrees of freedom	4	13 (2 wrist+11 hand)
Morphological features:	Size w. r. to a human hand	=	=
	Surfaces apt to contact with objects	Fingertips/Phalanges/Palm	Fingertips/Phalanges/Palm
	Contact surface smoothness and continuity	Fair	Good
Mechanical details	Structural design concept	Exoskeletal	Endoskeletal
	Actuator location	Inside the fingers	Remote
	Actuation type	Electrical revolute motors (Brushless)	Electrical revolute motors
	Act. joints back-drivability	✓	✓
	Kind of not-actuated joints	Underactuated	-
	Type of transmission	Spur and worm gear	Tendons
	Transmission routing	-	Pulleys/sheaths
Sensors:			
Position	Motor position sensors	Optical encoders	✓
	Joint position sensors	-	Hall-effect based
Force/Torque sensors	Joint torque sensors	Strain-gauges based	-
	Tendon tension sensors	-	-
	Motor effort sensors	Implicit (by means of break-away clutches)	-
Contact sensors	Intrinsic tactile sensors	-	6-axis IT-sensors in the phalanges and the palm
	Tactile array sensors	-	-
Additional Sensors			

Table 6: Main features of DLR (I) and LMS Hands.

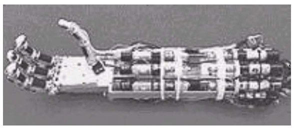
Project identification	Project denomination	**DLR Hand I**	**LMS Hand**
	Reference author(s)	Butterfass/Hirzinger/Knoch/Liu	Gazeau/Zeghloul/Arsicualt
	Research institute	DLR-German Aerospace Center	Université de Poities
	Year of presentation	1997	1998
	Reference	(J.Butterfass et al. 1999, Liu et al. 1999)	(Gazeau et al. 2001)
Picture			
Mechanical structure:	Arm/hand Integration	MH	IH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	✓	✓
	Fifth finger	-	-
	Palm	✓	✓
	Number of links	17	17
	Number of joints	16	17
	Number of controlled degrees of freedom	12	16
Morphological features:	Size w. r. to a human hand	$\gg$	=
	Surfaces apt to contact with objects	Fingertips/Phalanges/Palm	Fingertips/Phalanges
	Contact surface smoothness and continuity	Good	Good
Mechanical details	Structural design concept	Exoskeletal	Exoskeletal
	Actuator location	Inside the finger	Remote
	Actuation type	Electrical revolute motors	Electrical revolute motors
	Act. joints back-drivability	✓	NF
	Kind of not-actuated joints	Adaptive passive-driven joint	-
	Type of transmission	Tendons	Tendons
	Transmission routing	Pulleys	Pulleys/Sheaths
Sensors:			
Position	Motor position sensors	✓	✓
	Joint position sensors	Optical based	Potentiometers
Force/Torque sensors	Joint torque sensors	✓	-
	Tendon tension sensors	-	Implicit (tendon elongation)
	Motor effort sensors	-	-
Contact sensors	Intrinsic tactile sensors	x-y force sensor on fingertips	-
	Tactile array sensors	Tactile sensors(Force sensing resistor)in each finger link	-
Additional Sensors		Stereo-camera in the palm and light projection diodes in the fingertip to simplify image processing	

Table 7: Main features of DIST and Robonaut Hands.

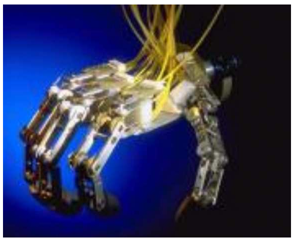
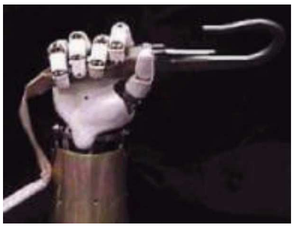
Project identification	Project denomination	**DIST Hand**	**Robonaut Hand**
	Reference author(s)	Cafés/Cannata/Casalino	C.S.Lovhik/M.A.Diftler
	Research institute	DIST-Universitá di Genova	NASA Johnson Space Center
	Year of presentation	1998	1999
	Reference	(Caffaz and Cannata 1998, Dist hand webpage)	(Lovchik and Diftler 1999, Ambrose et al. 2000, Robonaut webpage)
Picture			
Mechanical structure:	Arm/hand Integration	MH	IH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	✓	✓
	Fifth finger	✓	✓
	Palm	✓	✓
	Number of links	17	22
	Number of joints	16	22 (2 wrist + 20 hand)
	Number of controlled degrees of freedom	16	14 (2 wrist + 12 hand)
Morphological features:	Size w. r. to a human hand	>	=
	Surfaces apt to contact with objects	Fingertips	Fingertips/Phalanges/Palm
	Contact surface smoothness and continuity	Poor	Very Good
Mechanical details	Structural design concept	Exoskeletal	Endoskeletal
	Actuator location	Remote	Remote
	Actuation type	Electrical revolute motors	Electrical revolute motors (Brushless)
	Act. joints back-drivability	NF	✓
	Kind of not-actuated joints	-	Adaptive Passive-driven joints
	Type of transmission	Tendons	Flex-shaft + lead screw
	Transmission routing	Pulleys/Sheaths	-
Sensors:			
Position	Motor position sensors	✓	✓
	Joint position sensors	Hall-effect based	✓
Force/Torque sensors	Joint torque sensors	-	
	Tendon tension sensors		✓
	Motor effort sensors	-	
Contact sensors	Intrinsic tactile sensors	3-axis fingertip force sensors	-
	Tactile array sensors	-	FSR (Under development)
Additional Sensors			

Table 8: Main features of Tokyo and DLR (II) Hands.

Project identification	Project denomination	**Tokyo Hand**	**DLR Hand II**
	Reference author(s)	Y.K.Lee/I.Simoyama	Butterfass/Grebestein/ Hirzinger/Liu
	Research institute	Univ.of Tokio,bunkyo-ku,J	DLR-German Aeropsace Center
	Year of presentation	1999	2000
	Reference	(Lee and Shimoyama 1999)	(Butterfass et al. 2001)
Picture			
Mechanical structure:	Arm/hand Integration	IH	MH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	✓	✓
	Fifth finger	✓	-
	Palm	✓	✓
	Number of links	17	18
	Number of joints	16	17
	Number of controlled degrees of freedom	12(1 wrist + 11 hand)	13
Morphological features:	Size w. r. to a human hand	=	≫
	Surfaces apt to contact with objects	Fingertips/Phalanges/Palm	Fingertips/Phalanges/Palm
	Contact surface smoothness and continuity	Very good	Good
Mechanical details	Structural design concept	Endoskeletal	Endoskeletal
	Actuator location	Remote	Inside the fingers
	Actuation type	Pneumatic Mckibben artificial muscles	Electrical revolute motors
	Act. joints backdrivability	✓	✓
	Kind of not-actuated joints	Rigid passive-driven joints	Rigid passive-driven joints
	Type of transmission	NF	Harmonic drives/gears
	Transmission routing	NF	-
Sensors:			
Position	Motor position sensors	✓	✓
	Joint position sensors	-	Potentiometers
Force/Torque sensors	Joint torque sensors	-	Strain-gauges based
	Tendon tension sensors	-	-
	Motor effort sensors	✓	-
Contact sensors	Intrinsic tactile sensors	-	6-axis force sensors in the fingertips
	Tactile array sensors	Pressure sensors foreseen	-
Additional Sensors			

Table 9: Main features of Tuat/Karlsruhe and Ultralight Hands.

Project identification	Project denomination	**Tuat/Karlsruhe Hand**	**Ultralight Hand**
	Reference author(s)	Fukuya/Toyama/Asflur/Dillman	Schultz/Pylatiuk/Bretthaue
	Research institute	Tokyo and Karlsruhe Universities	Research center of Karlsruhe
	Year of presentation	2000	2000
	Reference	(Fukaya et al. 2000)	(Kawasaki et al. 2001)
Picture			
Mechanical structure:	Arm/hand Integration	IH	IH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	✓	✓
	Fifth finger	✓	✓
	Palm	✓	✓
	Number of links	22	17
	Number of joints	24	18
	Number of controlled degrees of freedom	1	13 (3 wrist+ 10 fingers)
Morphological features:	Size w. r. to a human hand	=	≫
	Surfaces apt to contact with objects	Fingertips/Phalanges	Fingertips/Phalanges/Palm
	Contact surface smoothness and continuity	Poor	Good
Mechanical details	Structural design concept	Endoskletal	Exoskeletal
	Actuator location	Remote	Inside the fingers
	Actuation type	Electrical revolute motors	Pneumatic
	Act. joints backdrivability	NF	✓
	Kind of not-actuated joints	Adaptive passive-driven joints	Rigid passive-driven joints
	Type of transmission	Link mechanisms	Direct drive
	Transmission routing	-	-
Sensors:			
Position	Motor position sensors	✓	✓
	Joint position sensors	-	Bending sensors
Force/Torque sensors	Joint torque sensors	-	-
	Tendon tension sensors	-	-
	Motor effort sensors	Self-adapting mechanism	-
Contact sensors	Intrinsic tactile sensors	-	-
	Tactile array sensors	-	Pressure sensors in finger links
Additional Sensors			

Table 10: Main features of GIFU and Shadow Hands.

Project identification	Project denomination	**Gifu Hand**	**Shadow Hand**
	Reference author(s)	Kawasaki/Shimomura/Shimizu	
	Research institute	Gifu University	Shadow Robot Company Ltd
	Year of presentation	2001	2002
	Reference	(Jacobsen et al. 1986, Kawasaki et al. 1999)	(Shadow hand webpage)
Picture			
Mechanical structure:	Arm/hand Integration	MH	IH
Kinematical scheme:	Main upper fingers	✓	✓
	Opposable thumb	✓	✓
	Fourth finger	✓	✓
	Fifth finger	✓	✓
	Palm	✓	✓
	Number of links	21	24
	Number of joints	20	23
	Number of controlled degrees of freedom	16	23 (4×4 fingers + 5 thumb + 2 wrist)
Morphological features:	Size w. r. to a human hand	=	≥
	Surfaces apt to contact with objects	Fingertips/Phalanges/Palm	Fingertips/Phalanges/Palm
	Contact surface smoothness and continuity	Good	Fair
Mechanical details	Structural design concept	Exoskeletal	Exoskeletal
	Actuator location	Inside the fingers	Remote
	Actuation type	Built-in DC Maxon servomotors	Pneumatic
	Act. joints backdrivability	-	✓
	Kind of not-actuated joints	Rigid passive-driven Joints	-
	Type of transmission	Worm gear	Tendons
	Transmission routing	-	NF
Sensors:			
Position	Motor position sensors	✓	-
	Joint position sensors		Hall-effect based
Force/Torque sensors	Joint torque sensors		
	Tendon tension sensors		
	Motor effort sensors		✓
Contact sensors	Intrinsic tactile sensors	6-axis fingertip force sensors	
	Tactile array sensors	Distributed resistive tactile sensors	
Additional Sensors			