Literature Review and Proposed Research

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1 Introduction

The purpose of this document is to compile the references of existing work in the area of the prosthetic hand project broadly related to kinematics, robotics and mechanism design. This information is used to present and justify the approach chosen in our research.

The kinematics, robotics and mechanism design are relevant in two separate areas of this project:

1. **Identification of the hand motion**. This is necessary as input data for the system identification of the myoelectric signals, in order to relate the electrical impulse to a certain motion. The signals will differ, besides physiological variables (environment, history,..), mainly by the motion to perform and the exerted force implied in the action. These two are always coupled, and a system to identify and separate the effects of each of them is needed. This implies the need of a system to track hand motion and another sensory system to track contact and maybe also internal forces, to account for the fact that the same motion can be performed with “relaxed” or with “tense” muscles.

2. **Development of an artificial prosthetic hand**. The final hand prosthesis has a strong mechanical component, in which the advances of robotic artificial hands need to be paired with the results of the signal identification and constrained by desired user specifications: similarity to the real human hand (weight, size, complexity, surface), comfortable body interface, human-like performance and adequate sensory feedback. The design of the prosthetic hand is mechatronic and multidisciplinary in nature.

In the following sections, both areas of the project are analyzed separately, reviewing the existing research, and explaining and justifying the adopted research plan.

2 Identification of Hand Motion

2.1 Literature review

There is a great amount of work done in identifying the motion of the human body and, in particular, of the human hand. The fields of interest are also diverse; much of the work has been done in the area of computer graphics, in order to create realistic virtual motion for avatar animation, for automatic hand language identification, for automatic sketching [102], etc.; also in the areas of humanoid robotics, in order to program human-like motion in the robots, and in the area of biomechanics. This diversity of goals led to many different techniques being developed. Here we will try to compile the most successful ones and also adpt some general classification scheme.

The extraction of motion and posture information has been categorized by Varga et al. [102] according to three aspects, that we reproduce here as a good framework to classify the previous and actual research. The extraction of motion information can be categorized according to the sensing device used as *contact* (in which the device is mounted on, or touches the hand) or *non-contact* (in which the information is extracted at a distance). Regarding whether the whole hand or only some characteristic points are tracked, the information is classified as *complete* or *incomplete*. This information can be transferred directly to some geometric modeling system (*direct transfer*) or the information can be fed to an intermediate hand model that adjusts the raw information before sending it to the geometric modeler (*indirect transfer*, also called *model-based*). Figure 1 shows a graphic depicting those options. Notice that any combination may give valid data; in the Figure, we have highlighted the options that may be used in our research.

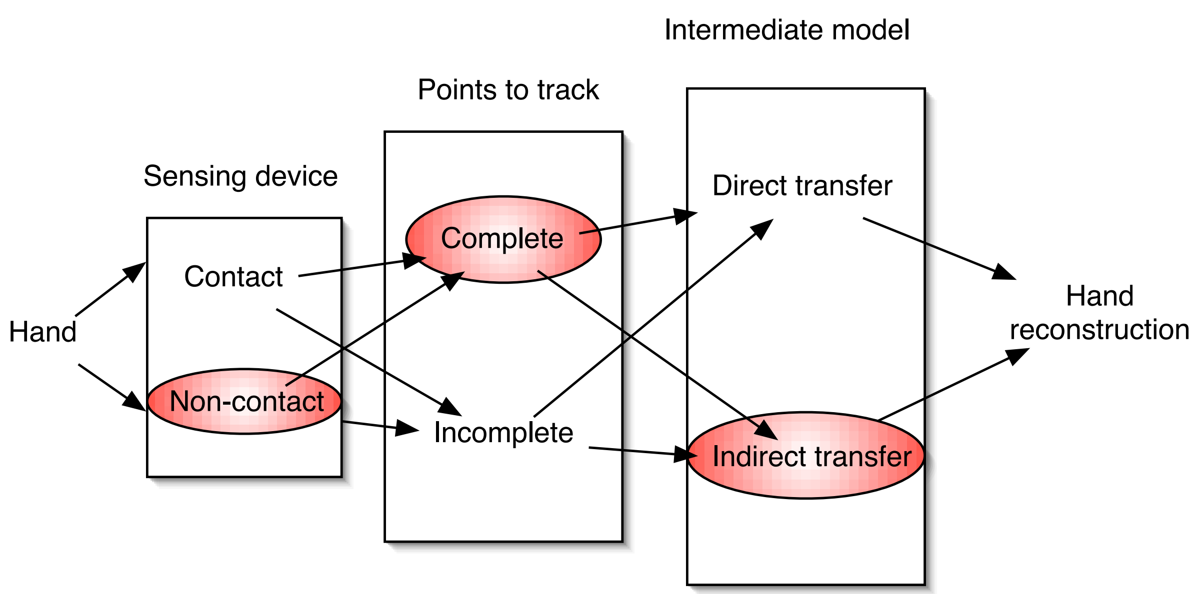

Figure 1: Classification of hand reconstruction techniques according to [102]

Several articles have been published that contain a survey of hand motion detection and processing technologies; among them, we highlight Varga et al. [102] and Ong and Ranganath [81], oriented towards hand trajectory and hand gesture recognition.

2.1.1 Contact technologies

Contact devices can be classified as data gloves (with different sensing technologies), electromagnetic emitter/receiver tracking systems, and exoskeletons.

Among the contact systems, the data glove, combined with visual feedback for the position of a point in the hand, seems to yield good results. Data gloves sense relative motion between adjacent movable links of the hand.

Commerical data gloves contain around 20 sensors and measure flexion and abduction of the fingers, and palm-arching motion. Gloves developed for research purposes (SIGMA Glove, University of Sheffield, Sensor Glove from University of Berlin, etc.) may have up to 30 degrees of freedom [27]. Actual glove designs perform incomplete tracking, according to the classification above. Sensor resolution can be good in theory, about 0.5 degrees and raw sensor data rate can be very fast, with typical values of 150 records/s.

A couple of negative aspects of the data gloves are the following: if hand positions need to be detected, the system needs to assume or measure a priori the distances between finger joints. If that is not done, using the same glove for individuals with different hand dimensions leads to a significant increase in the error of the measurements. In addition, the implicit model of the hand considers the joints as parallel and perpendicular; in any case, no information can be extracted about the real directions of the joints of the human hand. In many applications, a different sensing device needs to be used in order to identify the motion of the wrist and the location and orientation of the hand in space.

The list below contains a summary of commercial glove contact devices, shown also in Figure 2.

- Optical (VPL Dataglove) - Sensitive to hand size. Neoprene-fabric glove with two fiber optic loops on each finger; each loop goes up to one knuckle. That is the problem with the hand size. When hand is bent, light escapes through small cuts of the fiber. Needs recalibration for each user. DOF: 5 metacarpo-phalangeal joints, interphalangeal joint of the thumb, 4 proximal interphalangeal joints of the other fingers. Resolution: ¡ 1 degree (in good conditions), rate: up to 160 Hz. Price $ 11000 approx. It seems that the dataglove is not being manufactured anymore.

- Resistor-based (Virtex Cyberglove). Versions of 18 or 22 sensors(3 per finger 4 abduction sensors, palm arch sensor, and sensors for flexion and abduction, resolution 0.5 degrees, data rate 90 records/s. Wireless version. Price from $ 9800 approx.

- Magnetic (TUB-SensorGlove). Developed at the Technical University of Berlin around 1995, it has both pressure and position sensors. These are located in the back, ten sensors to measure finger flexion and two for thumb rotation. Only two joints of each finger are measured. Weighs 150 g, angular resolution from 0.1 to 1 degrees.
- Accelerometers (AcceleGlove). Developed by the George Washington University, consists of a leather glove with five accelerometers, one per finger, mounted on the nail of the thumb and on the mid phalanx of each other finger. Last version includes a two-link arm skeleton.
- Electromagnetic (Polhemus 3Space Fastrak). Manufactured by VRLogic, it is not exactly a glove but a tiny electromagnetic emitter and receiver that measures position and orientation of the point attached to it. Range up to 10 feet, resolution of 0.025 degrees and 0.0002 in, update rate 120 updates/s.
- Ultrasonic (Mattel's PowerGlove) - Very cheap (about $ 100), with a very bad resolution. Lowest model reports wrist roll in 30-degree increments. Basically used in video games.

Figure 2: Different data-glove images, obtained from the manufacturer's web pages. From left to right: upper row, VPL dataglove and Virtex cyberglove. Lower row, TUB SGlove and GWU AcceleGlove

Exoskeletons are rigid structures designed to follow, up to certain extent, the motion of the hand. They are in fact less used than gloves for applications in hand tracking. One of the reasons is that it is difficult to create an exoskeleton that can adapt to the hand deformation and still keep the accuracy in measuring certain joint motions; they are mostly used to identify and track the motion of a few degrees of freedom. Nakagawara et al. [77] present a hand exoskeleton used as a master to control a slave hand, see Figure 3. In this paper, some of the common problems of exoskeletons are also identified. Kim et al. [54] present a wearable device called SCURRY which has characteristics of both exoskeletons and data gloves.

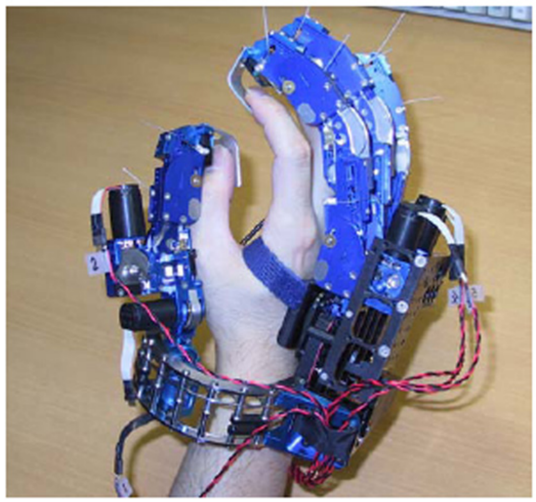

Figure 3: Exoskeleton used as a master to control artificial hand [77]

Magnetic tracking follows the position and orientation of an emitter attached to a point of the hand. Iseems to yield a very good resolution and it is a promising technology to be applied to hand tracking; for application of magnetic tracking systems to characterize human motion, see [73] and [94]. One of the disadvantages of electromagnetic tracking systems is interference: metallic objects near the transmitter or receiver may affect the performance; this may be a problem if other sensors need to be used to characterize a human task, for instance force sensors. Magnetic trackers are also incomplete tracking systems; for a more rich motion identifications, more sensors need to be placed in different points of the hand.

In general, contact systems are more intrusive, expensive, have cable connections, are not portable (subject-dependent in many cases), and require expertise to set up. Depending on the sensing system, they may be affected by environmental noise. Some of the systems have very poor accuracy, as specified in the list above, while others may have a better accuracy than the non-contact (vision-based) systems.

2.1.2 Non-contact technologies

Non-contact technologies refer almost exclusively to vision systems. Vision-based systems can use a single camera, stereo cameras or orthogonally-placed cameras. Advantages of vision-based systems are that they are less intrusive than any of the contact technologies; however, small motions, certain views and occlusions may present problems in order to identify the motion. This is partially overcome with the recovery of 3D position and orientation information, but this in turn is difficult and computationally expensive.

One of the main problems of the vision-based systems is that of the automatic identification of the hand and the hand posture from the image. In order to distinguish the interesting features in the hand, strategies such as using color, motion or edge information have been implemented. Among other strategies, there are the following: skin-color detection (in which the subject must wear long-sleeved clothes of a different color), color cues, motion cues (when the hand is the only moving object), or shape detection.

Much work has been done in this area, see for instance [71] for an application using a single camera. Typical systems nowadays consist of the combination of the different techniques that have been proved to be useful. Background supression is a first step to pinpoint the subject. Then, particle filters may be applied to identify different areas of the image of interest, based on its shape and geometry (for instance, the tip of the fingers, the wrist, etc.), or sometimes on the skin tone [98]. Those selected areas are used to build a 3-D or 2-D model of the image. When using a single camera, occlusion becomes a bigger challenge. To overcome this, some researchers use colored gloves. Others locate the hands in a non-occlusive view first and relay on tracking the motion from the previously known location, assuming that the displacements between frames is small; these systems aim to the global motion of the subject (hand) by considering the motion of each pixel, and not to its articulation; see [19] and also [112], which uses neural networks to identify the motion and contains also a summary of different approaches.

In order to recognize hand gestures or hand configuration from the interesting data, there are two basic approaches: appearance-based approaches and model-based approaches.

Appearance-based, or shape detection, considers only a handful of gestures that are quite different among them, fitting the actual gesture to the closest in the database; see for instance Ong and Bowden [80] Similarly, Hoshino and Tanimoto [42] identify the hand posture by searching a similar image from a vast database, optimized for quick searching.

Model-based approaches construct a 3-D model of the hand in order to gather all the positional information. Model-based approaches are very common in the literature, the main difference being the degree of complexity and accuracy of the model used. Almost all models consist of rigid links connected by joints. In the simplest cases, the joint is just a point allowed to perform any rotation. A different model is studied in Bray et al. [11], who use a stochastic meta-descent algorithm and a deformable hand model to track hand motion.

A hybrid of the two approaches consists on considering a 3-D articulated model that is compared to the image for a set different values of the joint angles [72]. The main inconvenient is that the searching process becomes very long.

Only the model-based approach can yield the actual quantitative information about the hand motion required for our research, and it is the focus of the literature review below.

The 3-D identification and tracking with indirect transfer (using a model) may rely on stick figures representing the skeleton, which gives the rigidity and articulation to the body, 2-D contours, or 3-D volumes such as cylinders, ellipses or blobls, which are fitted to the subject. The pose of the model is predicted from the data and compared to the image. See [61] for an early reference in a model-based approach. Holden and Owens [40] use a 21-dof hand model consisting of 15 dof for the hand plus a 6-dof wrist base that locates the hand arbitrarily in space. In order to sense the motion they use a color-coded glove, where each link has a different color, and a single camera. The 3-D models consist of 3-D shapes connected by joints with different degrees of freedom, see [45]. Hidden Markov models, coupled with the knowledge of the geometry of the segments, are used in [105] in order to recognize and track hand gestures from three-dimensional vision data. To identify the body parts, they fit shapes to a controlled set of motions. Nolker and Ritter [79] use neural networks to locate the positions of the fingertips and to estimate the three-dimensional pose of the hand, based on an articulated hand model with 20 joint angles, some of which are considered coupled to simplify the problem.

The amount of work in this area has been considerable. See also [117] , [108], [69], [13], [55], [103], [51], [8], and [33] for a review of available technologies.

However, in all models developed so far except [104], the joints have pre-assigned location and direction, hampering the fitting to the real data, or, in the other extreme, are loosely defined as able to have much more freedom than real human hand joints do. Also the kinematics description is not optimized for the problem. The fitting of the configuration of the model to the image is performed by defining a configuration for the model and using heuristic methods like silhouette matching, instead of using kinematic synthesis theory. In addition, most of the systems require a first pre-defined pose in order to better identify the object.

2.2 Proposed Research

In order to identify the motion of the hand, we propose the use of non-contact technology, consisting on several cameras to capture the motion of the hand. The different hand links are then identified from the hand image and fed to our model of the human hand. This model consists of links and joints, as do some of the works cited above ([61], [79], [11], [108], [51], [103], [33]); however, while many of the models are vague in defining the specific type and direction of the joints, in our model the joints have specified locations and orientations (see [35] for a similar approach, used to define the kinematics of the arm). These joint locations and orientations can be adapted to the actual geometry of the subject by using kinematic synthesis, yielding a much more accurate model and motion angles.

In order to both adapt the hand model to the geometry of the captured hand, and to track the angle at each joint, our procedure follows that of [104], adapted to the more precise identification of motion of the hand. It consists on applying kinematic synthesis theory expressing the motion as elements of a Clifford algebra [70], [3]; this seems to yield a very good behavior for the numerical solution. The equations are solved hierarchically using a Levenberg-Marquardt solver. See our preliminary results in [32]; the synthesis has been proved to recover the hand geometry and hand motion accurately from synthetic hand data.

Actual research is focused in the setting of the camera system and the development of a good calibration algorithm. Future research will be oriented towards the automatic identification of the different hand limbs, and to test the robustness of the algorithm with real data.

The main advantages of this system are the following: the non-intrusiveness allows for more natural motion of the hand, and also allows for the addition of new sensors (for instance force or tactile sensing) without altering the motion sensing system. The system is immediately adaptable to different hand sizes and geometries. Once the system is working properly, it can be easily adapted to capture the motion of any other body part; only a new kinematic model of that part (for instance, the complete arm) needs to be defined and used in the solver. As disadvantages, we can cite that we don't know yet what will be the accuracy of the system, which we expect to be heavily dependent on the quality of the cameras used. Other issues, such as the correct identification of each hand limb, are still pending.

3 Artificial Hands

Much work has been done in the area of artificial hands. Previous theoretical work in the areas of kinematics, dynamics, grasping, sensing and actuation of artificial hands has been developed since the early 1980's; for one of the first studies of kinematics and force control issues for artificial hands, see Salisbury and Craig [89]. The last five years have seen a big development in the practical implementation of these systems. This section contains a review of the work done on theoretical issues as well as on practical applications to both robotic and prosthetic hands.

3.1 Grasping

From a functional point of view, there are two main requirements that an artificial (and natural) hand is supposed to accomplish: dexterous manipulation and grasping. Dexterity may be defined in robotics as the capability of changing the position and orientation of a manipulated object from any point to any other point within the workspace [4]. Dexterity can be accomplished by means of the mechanical design of the system only, even though that has to be balanced with other requirements such as avoiding interference and singularities within the workspace and implementing a simplified control and actuation.

Grasping is a complex task that involves kinematic motion planning, force control (static and dynamic), and heavily depends on the geometry, strength, stiffness and surface finish of the object being grasped, as well as properties of the fingertips. In addition, it is desirable for the grasping to be robust, that is, being insensitive to disturbances.

Most of the designs and research efforts in developing artificial hands for grasping purposes follow the direction established by Cutkosky [23]. In his paper, he classified the grasping constraints as task, object and gripper constraints, and developed the taxonomy of grasps shown in Figure 4. See also [82] for an overview on grasping and dexterous manipulation issues, [10] for a study on the grasp quality measure, [48] for a study of the grip force distribution in the natural hand, and [29] for a study of underactuated grippers for grasping diverse objects.

The study of grasping from the geometric and static point of view has been extensively studied; see [76], [65] and recently [43]. Bicchi [4] presents a survey of the different trends in hand design based on three types of requirements: dexterity in manipulation, grasping capabilities and human operability. See also [5], [2]. For dynamic grasping, see [34]. For a study of the two-finger pinching motion, see [97].

3.2 Sensing

Both proprioceptive and exteroceptive sensing seems to be needed for the accurate grasping (and in general, control) of the hand. However, the sensing system of the human hand is difficult to replicate due to its great redundancy, the need for some sensors to be placed in the surface of the prostheses, and the still unresolved issue of providing the appropriate feedback. In this line of research we can distinguish two main topics: that research being directed to create new sensors, and the research directed to incorporate and integrate the different sensing capabilities in the hand tasks. Embedded sensors [28] seem to be a good option for hand prostheses.

Zecca et al. [113] present an underactuated hand equipped with proprioceptive and exteroceptive sensors. Proprioceptive sensors include position of the tendon, joint angular position and tendon force. Exteroceptive sensors include skin force sensors. See also also Vacalebri et al. [101].

Dubey and Crowder [31] present a slip sensor that could be applied to hand prostheses to obtain grasping information. They also have a good literature review of this topic.

Another area of research is that of transmitting sensory feedback to the prosthetic hand user. See

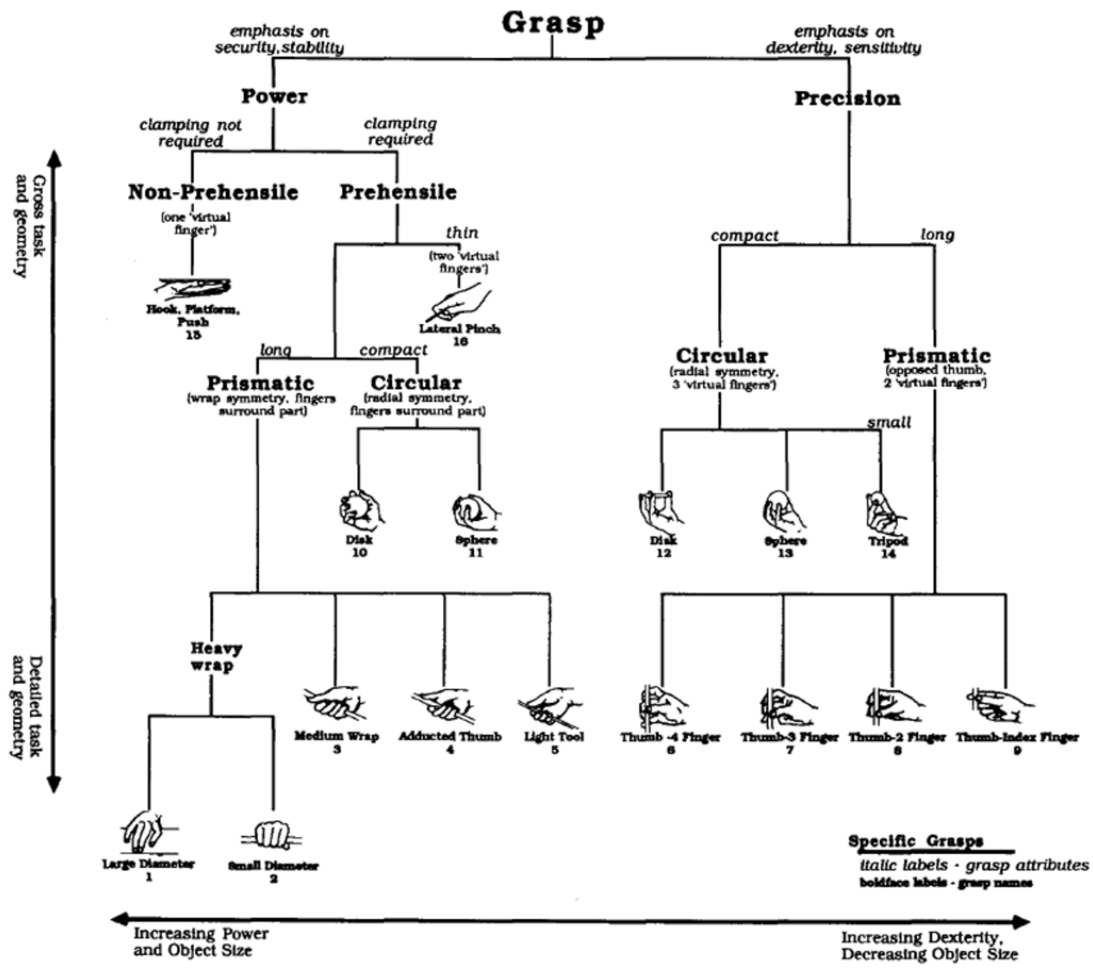

Figure 4: Taxonomy of grasps presented by Cutkosky [23]

[53] for an example of the research in this area.

3.3 Actuation

Both for prosthetic hands and for modular robotic hands, it is desirable that the actuators can be placed within the hand or occupying the least space possible. The two solutions more widely used are tendons driven by DC motors and minimotors coupled with gear reductions.

Tendons allow for a very compact design but present problems of friction, compliance, etc. See [83] for a static study of the tendon actuation, and [12] for an implementation of anthropomorphic tendon actuation on a finger. Gialias and Mastuoka [37] present a muscle actuator design that follows Hill's muscle model but is is made with conventional DC motors and a cable tendon transmission. Even though the most common actuation consist of DC motors driving tendons or using gear reductions, other solutions are being developed.

Cho and Asada [20] describe an array of shape memory alloy actuators, inspired by biological muscles, to be used to drive a five-fingered hand; see their most recent results in [21]. Also using shape memory alloy actuators, Loh, Yokoi and Arai [67] present SMA wire actuators applied to control a hand prosthesis; two actuators are used to control a single degree of freedom. Lee and Simoyama [63] present a miniature pneumatic McKibben artificial muscle applied to actuate a robotic hand.

Lee et al. [62] present an artificial muscle based on ionic polymer metal composite (IPMC), to be actuated by EMG signals. The IPMC is used to create contraction and extension similar to those of human muscles. In order to increase the output force, the IPMC can be made thicker or arranged in parallel, but that reduces the flexion of the material. The application of this technology is still limited to the force and displacement output.

3.4 Implementation of Artificial Hands

From the point of view of the construction of artificial hands, we can distinguish two lines of work:

- Robotic hands, which tend to be similar to human hands in topology and number of degrees of freedom, they are able of rich and complex motion but are quite complicated in their control and actuation. Robotic hands are now being research for fine grasping, with force and contact feedback.
- Prosthetic hands, which are simplified in their structure but present a very simple control and human characteristics of weight and external aspect, as well as adaptability to the human arm. Some key areas of research is human-signal control, and skinning.

The challenge of future research in the area of prosthetics is to bring these two lines of research together, that is, to simplify and adapt the actual solutions for robotic hands so that they can be easily controlled using body signals without losing its richness of motion, as well as having human feeling and exteroceptive and proprioceptive feedback.

3.5 Robotic Hands

Robotic hands are being developed for many applications: for dexterous manipulation, for work in human environments and with human interaction, and also as a tool of research to study human cognition. Even for robotic hands, the challenge of controlling a human-like hand, with its more than 20 degrees of freedom, leads many of the actual research towards a mechanical solution that, without compromising grasping and gripping abilities, could reduce the complexity in the control. In order to overcome this problem, we can find both underactuated hands as well as different control strategies of more complicated hands. For underactuated hands, we cite the pioneer theoretical work of Gosselin, see for instance [60], [74] and [6], [7].

In this section we present a summary of robotic hands that have been recently developed.

Caffaz, Cannata et al. [14] developed the DIST hand, which appeared first in 1997. It is a four-fingered, tendon-driven hand with 16 degrees of freedom, see Figure 5. They later developed the MAC hand, with four fingers and 12 degrees of freedom, simplified in order to embed tactile and force sensors[15].

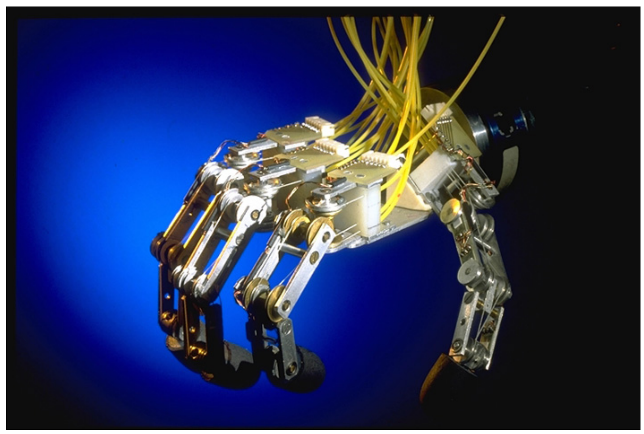

Figure 5: The DIST hand from University of Genova

Zhang et al. presented the BUAA hand [114], composed of four identical fingers with four degrees of freedom each, actuated by four DC servomotors, which are integrated within the hand structure. Each finger has eight position sensors, and a position control has also been implemented.

Kawasaki, Komatsu and Uchiyama [52] developed the Gifu-hand II, a five-fingered anthropomorphic hand, see Figure 6. The thumb has four dofs and the other fingers have three dofs, plus two perpendicular rotations at the wrist. Each joint is driven by a servomotor built into the fingers and the palm. The fingertips are equipped with force sensors and tactile sensors. On [75], a new hand model for different specifications is presented.

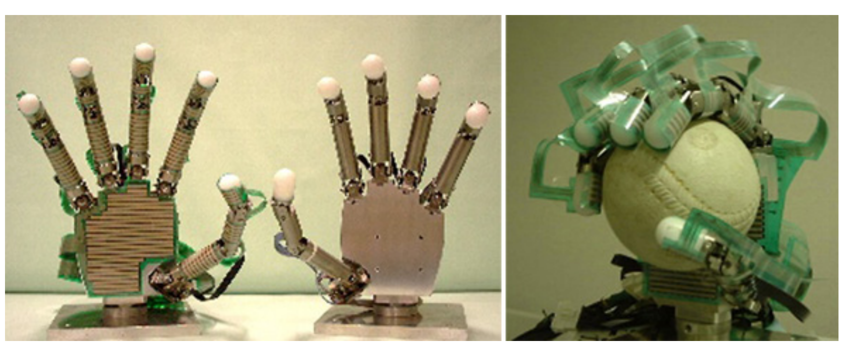

Figure 6: The latest version of the Gifu hand, developed at Gifu University, Japan [52]

Gazeau et al., from University of Poitiers, France, developed the LMS hand, a four-fingered hand in which each finger has four joints, see Figure 7. These joints are independently actuated using cables connected to DC motors. The authors developed position and force control algorithms for this hand in [36].

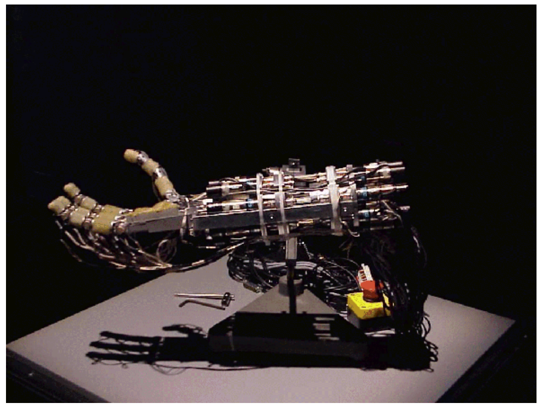

Figure 7: The LMS hand [36]

Hirzinger et al. [9] of DLR, Germany, present the last development of their anthropomorphic hands, generically called DLR hands (see Figure 8). The authors comment on some features of the hand that have proved useful along different experiments.

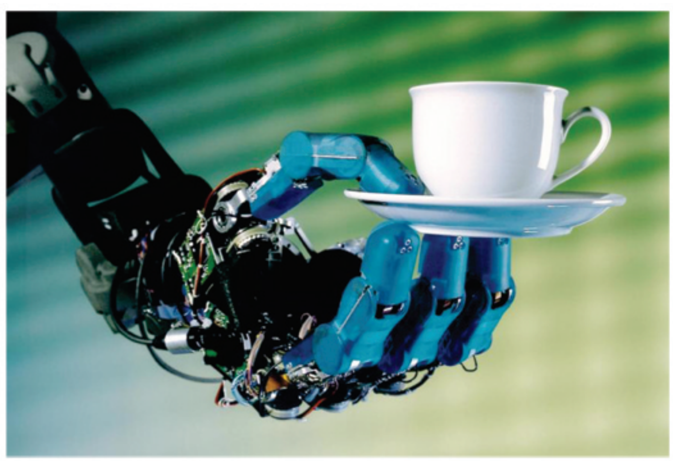

Figure 8: DLR hand from [10]

Ueda et al. [100] present the NAIST hand, a four-fingered hand, each of the fingers having three degrees of freedom. The hand is powered by small actuators that can be placed at the palm and in the fingers, thanks to the use of efficient gear transmissions. It seems that the cable-actuated systems require bigger actuators and that they have some problems with maintenance. However, also the size of the small actuators at the fingers limit the force at the fingertips. This hand is also equipped with vision-based tactile fingertip sensors (based on measuring the deformation of deformable fingertips) and a grip-force control. See Figure 9.

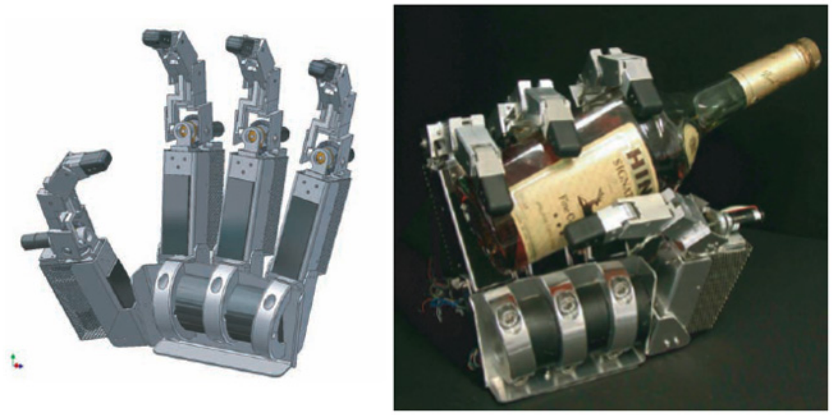

Figure 9: The NAIST hand from NAIST, Japan: concept (left) and implementation (right) [100]

Yamano and Maeno [109] developed a five-fingered robot hand with 20 degrees of freedom, composed of elastic elements that allow stable compliant grasping without power supply. Ultrasonic motors allow for their placement inside the hand. The size and shape of the hand are also similar to those of the human hand. The mechanical design was adjusted for the desired maximum force at the tip of the fingers. The hand has been tested for a variety of power and precision grasps. See Figure 10.

Figure 10: Hand developed at Keio University, Japan [109]

Namiki and Ishikawa [78] present a three-fingered robot hand which is not anthropomorphic but presents a quick finger motion. Two of the fingers have three degrees of freedom and the other finger has two dofs. Fast grasping motion, in which the dynamics needs to be taken into account, has not been as studied as slow grasping. The authors experimented with fast catching motion paired with visual feedback and derived the dynamical analysis, with very promising results, especially those presented in [34]. See also [39] for a similar solution, depicted in Figure 11, and [106].

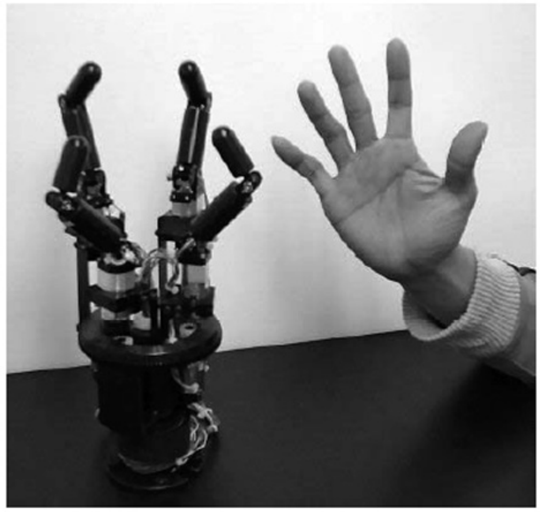

Figure 11: Four-fingered hand from [39]

Kargov, Dillman et al. [49], [26] from the Research Center of Karlsruhe, Germany, present an anthropomorphic hand (see Figure 12) whose design follows precisely the human hand regarding link lengths and shape of palm and fingers, able to perform most of human grasping tasks. It has 8 active and 3 passive joints. The joints are driven by small flexible fluidic actuators connected to a micro gear pump. See also [90] for their older design.

Figure 12: Anthropomorphic hand from [49]

Hoshino and Kawabuchi [41] are developing a lightweight robotic hand especially designed to mimic human motion, in particular the fingertip pinching action. The hand has four fingers, each of them with three joints and four degrees of freedom (two for the MCP joint); all flexion joints are coupled for each finger, and the thumb presents three degrees of freedom. In order to allow for the pinching, the DIP joint of each finger is decoupled from the rest of the flexural joints. See Figure 13.

Figure 13: Anthropomorphic hand with pinching capabilities [41]

A different approach is being taken in developing the ACT hand (anatomically correct testbed), at Carnegie Mellon University. The project aim is to develop a hand that can be used as a working model to study the behavior of the hand and for surgical test. So far the skeleton [107], the muscle actuator [37] and the kinematic model of the thumb [18] have been developed.

Stellin et al. [93] are developing the Cub hand as a part of the RobotCub EU Integrated project to create a humanoid for cognition research. In addition to the common tasks of dexterous manipulation and grasping, this hand must also support the function of crawling of the robot. The authors decided on 9 active joints and 5 passive joints as a good compromise between antrhopomorphic manipulability and hand size and complexity. The actuators are placed on the palm and the forearm. This project is under development.

In summary, many researchers are working on developing prosthetic hands with different goals and degrees of success. For other hands not mentioned above, see also [64].

3.6 Prosthetic Hands

The design of commercial upper-limb prostheses has experienced little advance since the early 1960's, an that leads to the dissatisfaction of the users; see for instance the review of literature about this topic in [110]. The needs for a "satisfactory" prosthetic hand can be outlined as easy to control (body controlled), comfortable to wear (good arm interface and correct weight/ inertia) and cosmetically pleasing (skin and design properties). To this, we should add that the hand must be able to move with the complexity of a human hand. This last condition goes often against the other three, and this is the reason why this part has not been fully developed. A more pragmatic approach is usually taken, in which key motions for manipulability, grasping and gripping are identified and those are the ones that are implemented in the prosthetic hands.

The need for more functional, as well as more aesthetically pleasing prosthetic hands, led to the development of several hands in the 70's and 80's; the Waseda Hand by Kato et al. around 1970 [50], Skinner 1975, Hanafusa and Asada 1982, Okada 1982, the Salisbury Hand (Stanford/JPL hand) by Mason et al. 1985, Utah/MIT Hand by Jacobsen et al. around 1984 [46], NYU Hand by Demmel et al., 1988, Styx hand by Murray et al., 1990, Belgrade/USC hand by Iberall et al., 1993. All these references of what we could call the pioneer work were taken from [110] and [20].

Bigger advances took place in the 90's with the integration of better mechanical designs and new control strategies. Among prostheses having some of these more human-like characteristics we can cite the Oxford Intelligent Hand prosthesis, by Kyberd, Evans and Wynkel [57], the work of Doshi et al. at Stanford [30], the Southampton hand developed by Kyberd, Light and Chappell [56], [66], with a more recent study of needs and performance in this review from 2001 [58].

The need for a simple control strategy has led to simplify the topology to the minimum necessary for basic useful grasping motions; however, the grasping capabilities also get diminished with the decreasing of the mobility of the hand. One solution is to consider the individual motion of the fingers as less important than the grasping posture, with its distribution of forces. Underactuated systems are beneficial in reducing the complexity. The following paragraphs contain some of the prosthetic hand solutions proposed in recent years.

Huang and Chen, of National Taiwan University, developed the NTU Hand [44], see Figure 14. They were able to identify eight prehensive postures from EMG signals to be applied to the actuation and control of the hand.

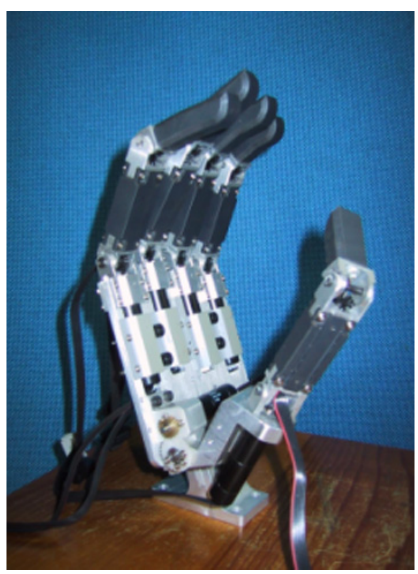

Figure 14: The NTU hand [44]

The Wilmer group at Deft University has been working in prostheses from the last 30 years. Herder and deVisser [25] developed a voluntary-closing hand prosthesis oriented towards grasping tasks, consisting of three adaptive and flexible fingers plus thumb actuated by tendons.

The research group at the University of Pisa has been active in developing new solutions for hand prostheses since the early 2000's. Figure 15 shows the RTR II hand, an underactuated prosthetic hand with three fingers and nine degrees of freedom actuated by two motors using tendon transmissions for flexion/extension and a four-bar mechanism for abduction/adduction [113]. This hand includes also a series of sensors described below in the sensing section. An updated version can be found in [118]. See [22] for some recent results in control strategies.

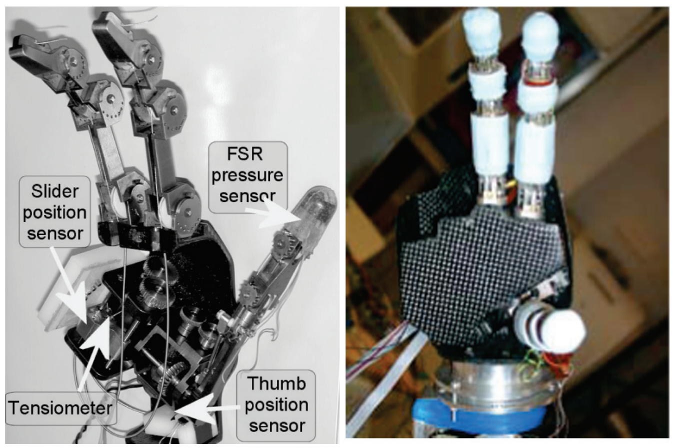

Figure 15: The RTR-II hand from University of Pisa. Left: model of 2003 [113]; right: model of 2006 [118]

Carrozza et al. [16] developed the SPRING hand, an underactuated, myoelectrically controlled hand. More recently, Carrozza et al. [17] present a compliant underactuated prosthetic hand, casted from soft polymer with compliant joints driven by tendons actuated by a single motor which is controlled by EMG signals. This allows for adaptive grasping but no other type of motion. See Figure 16.

Figure 16: The compliant hand from University of Pisa, as presented in [17]

De Laurentis and Mavroidis developed a five-fingered, twenty-degree-of-freedom robotic hand at Rutgers University [24], for possible application as a prosthetic device. This was actuated by shape memory alloy artificial muscles.

Loh, Yokoi and Arai [67] are working in reducing the size of the actuators in a prosthetic hand with 13 active degrees of freedom, currently actuated by servomotors that attach to the forearm; see Figure 17.

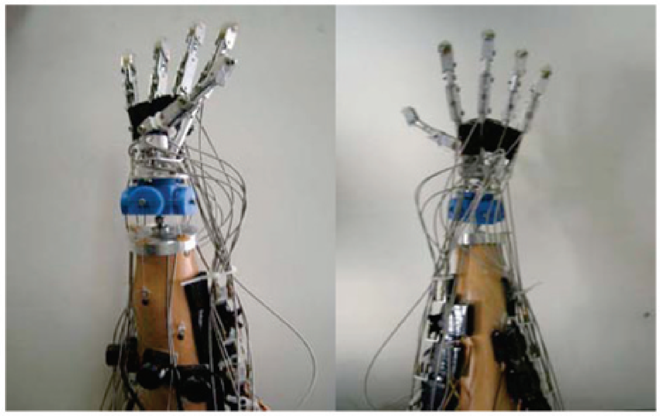

Figure 17: Prosthetic hand from University of Tokyo [67]

Jobin et al. [47] present an underactuated prosthesis finger mechanism, consisting of two phalanges plus the thumb. The fingers are actuated through rolling contact joints. These joints have the advantage of being more robust, both in load capability and precision, to manufacturing and assembly errors. Both phalanges are driven by a single tendon, which simplifies the force control during the grasping, even though it does not allow full control of the motion of each dof of each phalanx.

Yang et al. [110], [111], and more recently [84], present the design and analysis of a cable-actuated hand prosthesis, dubbed the IOWA hand. Cable actuation is one of the most popular actuation systems for artificial hand because of the similarity with the tendon system and the advantages of space, simplicity,etc. This hand presents four fingers with three joints each (MCP, PIP, DIP) plus a thumb with three joints. Each joint is based on loading a compression spring using cables; the actuators are placed in the waist. The spring design allows for adjustable stiffness/compliance characteristics. The hand is fitted with a cosmetic glove for better appearance, see Fig. 18

The research group of Karlsruhe, Germany, adapted their artificial hand presented above in the robotic hands section to be used in prosthetics in [85] and [86]. Som pending problems with the fluidic actuators (weight, location and leakage) and the development of a good control strategy need further research.

Saito et al., from Tokyo Denki University, present their approach of fitting the size and appearance of the prosthesis to the age and body shape of the patient. In [88], the authors review their experiences, successes and failures in designing prostheses. See Figure 19 for their most recent hand prosthesis.

Lotti et al., from University of Bologna [68] present a spring design called the UB Hand 3, see Figure

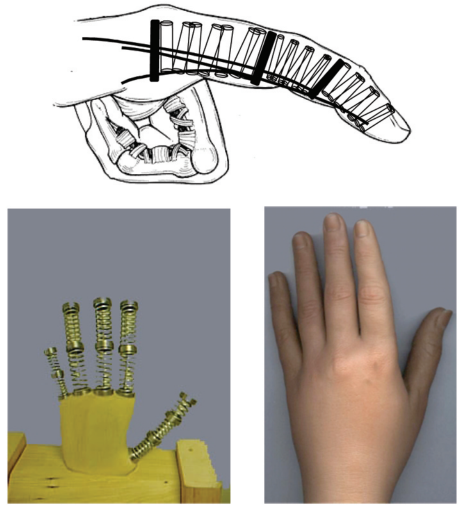

Figure 18: The IOWA hand: finger and hand concept and cosmetic glove, as presented in [110]

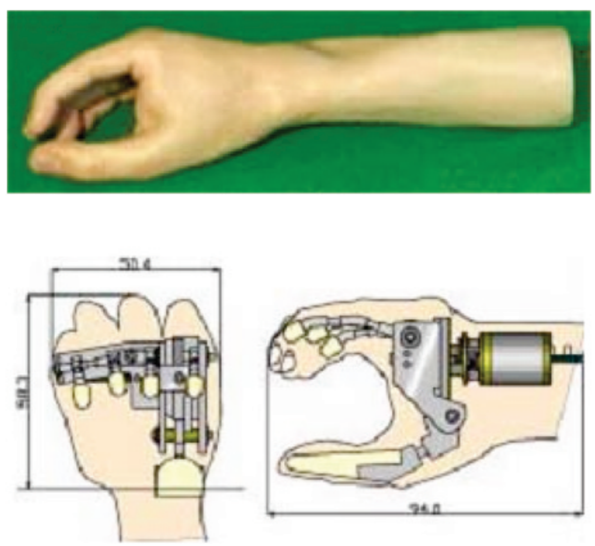

Figure 19: Electric prosthetic hand developed at Denki University. Sketch of the mechanism and cosmetic glove. [88]

20. The hand has a five-fingered endoskeleton of rigid links connected by elastic hinges made with helical springs and actuated by tendons. The endoskeleton is covered by a skin of deformable material. The hand has 20 degrees of freedom, out of which 16 are independently actuated and the rest are coupled (4 dof for thumb and index, 3 dof for middle and little finger and 2 dof for ring finger). The actuation is accomplished with 16 DC motors which are located outside of the hand. The hand is equipped with force and position sensors. This hand has not been fully tested yet, and there issues with the complex control, limited stiffness of the joints, and behavior of the tendons.

Zhao, Hirzinger et al. [115], [116] present a five-fingered underactuated prosthetic hand, with a

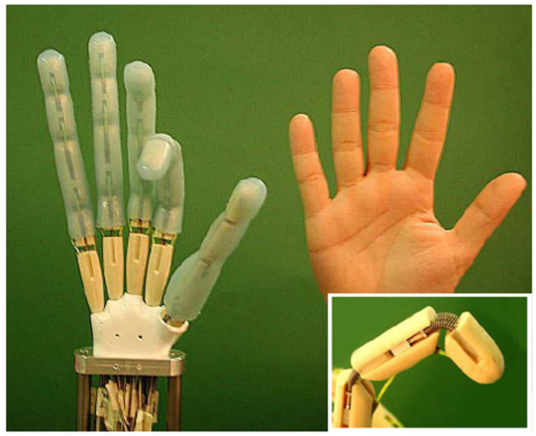

Figure 20: Hand design from University of Bologna [68]. Hand design and comparison with real hand; detail of finger joint.

weight of 0.55 Kg (Figure 21). Only the thumb, index and middle finger are actuated, by means of three stepper motors, with the rest of fingers being coupled to the middle finger. Each finger has three joints. The hand is controlled by EMG signals; the authors were able to identify three types of motion of the thumb, index and middle finger, and to achieve several prehensile postures.

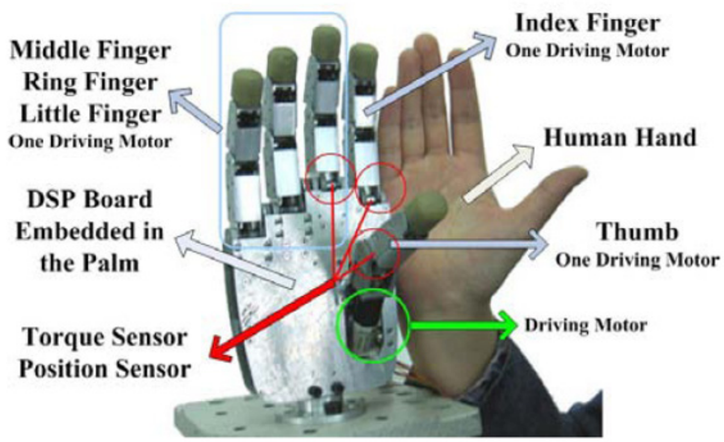

Figure 21: Five-fingered prosthetic hand by Zhao et al. [115]

Cosmetic gloves are a widely used solution for giving the prosthesis a natural appearance and to adapt the mechanism to the looks of the patient. Much work needs to be done in order to improve the mechanical behavior of the gloves as well as to incorporate sensing devices into them. In this line, Herder and Plettenburg [38] studied the mechanical behavior of the cosmetic gloves and suggested improvements.

In summary, the myriad of design existing in artificial hands are a little more limited when it comes

Hand	Weight	Fingers	Palm	Active DOF	Total DOF	Links	Joints
Southampthon Hand							
Iowa Hand							
Spring Hand							
NTU Hand							
RTR-III Hand							
Rutgers Hand							
Univ. of Tokyo Hand							
Karsruhe Hand							
UB Hand 3							
Zhao Hand							
Tokyo Denki Hand							
Jobin Hand							
Wilmer Hand							
Pylatiuk Hand							

Table 1: Comparison among actual prosthetic hands developed at research laboratories: Mechanical structure.

to their application in prosthetics; however, that gap is being closed. Some work has been done in comparison of performance of research prosthetic hands, see [91], [59] and [87], and [96] for a study of existing commercial prostheses.

3.7 Comparative of Designs

We present in this section a table comparing the actual prosthetic hands developed in research laboratories. We do not attempt the comparison of robotic artificial hands, as basically every robotics lab has its own design; the ones presented here can be considered a sample of the research being developed in that area. The comparison of prosthetic hands presented in the following tables uses some of the classification parameters presented in [87]; the authors believe that a compromise among anthropomorphism, dexterity, controllability and cost is necessary, and analyze some hand design based on the first three criteria. However, the tables presented here have a descriptive nature and does not include performance indices or assessment, which can be created based on these data.

Table 1 presents the comparison in terms of the mechanical structure of the hands.

Table 2 presents the comparison in terms of sensing, actuation and driving signals.

Table 3 presents a description of performance parameters.

Hand	Propr. sensors	Ext. sensors	Underactuated	Actuation	Transmission	Driving signal
Southampthon Hand						
Iowa Hand						
Spring Hand						
NTU Hand						
RTR-III Hand						
Rutgers Hand						
Univ. of Tokyo Hand						
Karsruhe Hand						
UB Hand 3						
Zhao Hand						
Tokyo Denki Hand						
Jobin Hand						
Wilmer Hand						
Pylatiuk Hand						

Table 2: Comparison among actual prosthetic hands developed at research laboratories: Sensing, actuation and control.

Hand	Grasping	Dexterity	External aspect
Southampthon Hand			
Iowa Hand			
Spring Hand			
NTU Hand			
RTR-III Hand			
Rutgers Hand			
Univ. of Tokyo Hand			
Karsruhe Hand			
UB Hand 3			
Zhao Hand			
Tokyo Denki Hand			
Jobin Hand			
Wilmer Hand			
Pylatiuk Hand			

Table 3: Comparison among actual prosthetic hands developed at research laboratories: Performance.

3.8 Proposed Research

The goal of this project is the development of a prosthetic hand that fulfills the expectations of the amputees, that is, to perform and look as much as possible like a human hand. In order to achieve this goal, the mechanical design of the hand needs to be approached from a biomechatronics point of view, that is, considering the integration of biological and medical issues and findings in a design that harmonizes the control and sensing, the electric and electronic issues within the mechanical framework.

Because of the fact that many of these issues are still unresolved for this project, we cannot define a mechanical design for the hand yet; its structure will depend on the type and number of signals that can be identified to control the hand; on the interface with the human hand, etc.

However, some requirements can be defined a priori, based on the research of previous work and the expectations of the amputees. As most of the prosthetic hands under development, our prosthetic hand will be as similar as possible to the human hand in size and weight; the design should be adaptable to the dimensions and external aspect of the user.

Unlike most of the actual prosthetic hands, we require our design to provide richness not only in the grasping capabilities but also in dexterous manipulation. Literature shows that underactuated, adaptive hands are a good solution for grasping of different objects; however, they greatly limit the manipulation capabilities. It seems that a design that can be switched from underactuated to fully actuated depending on the task would give good solutions for both cases. This is something that has not been attempted, and requires a high-level control as well as some specific solutions in the mechanical design. This solution replicates the behavior of the human hand, where sometimes the phalanx are actuated as coupled, while with some effort, they can be actuated separately for more dexterous motions.

This solution requires more actuated degrees of freedom, hence more actuators and a more complex control. The hand will include position sensors for the actuated joints, as well as tactile and/or force sensors, whose signal will be fed to the control algorithm. In addition, the feedback to the user will be studied and incorporated if necessary.

References

[1] Ablamowicz, R. and Sobczyk, G., *Lectures on Clifford (Geometric) Algebras and Applicatons*, Birkhauser, Boston 2004.

[2] Bae, J-H., Arimoto, S., Ozawa, R., Yoshida, M., and Sekimoto, M., 2006, “Concurrent Grasping and Manipulation by Arm-Hand Coordinated Movements Based on Task-Distribution”,

Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06, Pisa, Italy, February 20-22, 2006.

[3] Bayro Corrochano, E., *Geometric Computing for Perception Action Systems*, Springer-Verlag, New York, 2001.

[4] Bicchi, A., 2000, "Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity", *IEEE Transactions on Robotics and Automation*, **16**(6):652-662.

[5] Bicchi, A., and Kumar, V., 2000, "Robotic grasping and contact: a review", *Proc. of the 2000 IEEE Int. Conf. on Robotics and Automation*, Vol. 1, pp.348-353.

[6] Birglen, L., and Gosselin, C.M., 2004, "Kinetostatic analysis of underactuated fingers", *IEEE Transactions on Robotics and Automation* **20**(2):211 - 221.

[7] Birglen, L., and Gosselin, C.M., 2006, "Geometric Design of Three-Phalanx Underactuated Fingers", *ASME Journal of Mechanical Design* **128**:356-364.

[8] Boreki, G., and Zimmer, A., 2005, "Hand geometry: a new approach for feature extraction", *Fourth IEEE Workshop on Automatic Identification Advanced Technologies*, 17-18 Oct. 2005.

[9] Borst, Ch. Fischer, M., Haidacher, S., Liu, H., and Hirzinger, G., 2003, "DLR Hand II: Experiments and experiences with an anthropomorphic hand", *Proc. of the 2003 IEEE Intl. Conf. on Robotics and Automation*, Taipei, Taiwan, September 2003.

[10] Borst, Ch., Fischer, M., and Hirzinger, G., 2004, "Grasp Planning: How to Choose a Suitable Task Wrench Space", *Proc. of the 2004 IEEE Intl. Conf. on Robotics and Automation*, New Orleans, LA, USA, 2004.

[11] Bray, M., Koller-Meier, E., Muller, P., Van Gool, L., Schraudolph, N.N., 2004, "3D hand tracking by rapid stochastic gradient descent using a skinning model", *1st European Conference on Visual Media Production (CVMP)*, 15-16 March, 2004.

[12] Bundhoo, V., and Park, E.J., 2005, "Design of an artificial muscle actuated finger towards biomimetic prosthetic hands", *Proc. of the12th Int. Conf. on Advanced Robotics, ICAR 05*, July 18-20, 2005.

[13] Cabas, R., Cabas, L.M., and Balaguer, C., 2006, "Optimized Design of the Underactuated Robotic Hand", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[14] Caffaz, A., and Cannata, G., 1998, "The design and development of the DIST-Hand dextrous gripper", *Proc. of the 1998 IEEE International Conference on Robotics and Automation*, May 16-20, 1998.

[15] Cannata, G., and Maggiali, M., 2005, "An Embedded Tactile and Force Sensor for Robotic Manipulation and Grasping", *Proc. of the IEEE-RAS Int. Conf. on Humanoids, Humanoids 2005*, Tsukuba, Japan, December 5-7, 2005.

[16] Carrozza, M.C., Suppo, C., Sebastiani, F., Massa, B., Vecchi, F., Lazzarini, R., Cutkosky, M.R., and Dario, P., 2004, "The SPRING hand: Development of a self-adaptive prosthesis for restoring natural grasping", *Autonomous Robots*, **16**(2):125-141.

[17] Carrozza, M.C., Cappiello, G., Stellin, G., Zaccone, F., Vecchi, F., Micera, S., and Dario, P., 2005, "A Cosmetic Prosthetic Hand with Tendon Driven Under-Actuated Mechanism and Compliant Joints: Ongoing Research and Preliminary Results", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[18] Chang, L.Y., and Matsuoka, Y., 2006, "A Kinematic Thumb Model for the ACT Hand", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[19] Chen, F. S., Fu, C. M., and Huang, C. L., 2003, "Hand Gesture Recognition Using a Real-Time Tracking Method and Hidden Markov Models", *Image and Vision Computing*, **21**:745-758.

[20] Cho, K-J., and Asada, H., 2005, "Multi-Axis SMA Actuator Array for Driving Anthropomorphic Robot Hand", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[21] Cho, K-J., Rosmarin, J., and Asada, H., 2006, "Design of Vast DOF Artificial Muscle Actuators with a Cellular Array Structure and Its Application to a Five-Fingered Robotic Hand", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[22] Cipriani, C., Zaccone, F., Stellin, G., Beccai, L., Cappiello, G., Carrozza, M.C., and Dario, P., 2006, "Closed-loop Controller for a Bio-inspired Multi-fingered Underactuated Prosthesis", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[23] Cutkosky, M.R., 1989, "On grasp choice, grasp models, and the design of hands for manufacturing tasks", *IEEE Transactions on Robotics and Automation*, **5**(3):269-279.

[24] De Laurentis, K.J., and Mavroidis, C., 2002, "Mechanical design of a shape memory alloy actuated prosthetic hand", *Technology and Health Care*, **10**: 91-106.

[25] deVisser, H., and Herder, J.L., 2000, "Force-directed design of a voluntary closing hand prosthesis", *Journal of Rehabilitation Research and Development*, **37**(3):261-272.

[26] Dillmann, R., Becher, R., and Steinhaus, P., 2004, "ARMAR II - A Learning and Cooperative Multimodal Humanoid Robotic System", *International Journal of Humanoid Robotics* **1**(1):143-155.

[27] Dipietro, L., Sabatini, A.M., and Dario, P., 2003, "Evaluation of an instrumented glove for hand-movement acquisition", *Journal of Rehabilitation Research and Development*, **40**(2):179-190.

[28] Dollar, A.M., Wagner, C.R., and Howe, R.D., 2006, "Embedded Sensors for Biomimetic Robotics via Shape Deposition Manufacturing", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[29] Dollar, A.M., and Howe, R.D., 2006, "Joint coupling design of underactuated grippers", *Proc. of the ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, September 10-13, 2006, Philadelphia, PA, USA.

[30] Doshi, R. , Yeh, C., LeBlanc, M., 1998, "The design and development of a gloveless endoskeletal prosthetic hand", *Journal of Rehabilitation Research and Development*, **35**(4):388-395.

[31] Dubey, V.N., and Crowder, R.M., 2005, "Photoelasticity Based Dynamic Tactile Sensor", *Proc. of ASME IDETC/CIE 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Long Beach, CA, USA, September 24-28, 2005.

[32] Duraisamy, K., Isebor, O., Perez-Gracia, A., Schoen, M., and Naidu, D.S., 2006, "Kinematic Synthesis for Smart Hand Prosthesis", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[33] Erol, A., Bebis, G., Nicolescu, M., Boyle, R.D., Twombly, X., 2002, "A Review on Vision-Based Full DOF Hand Motion Estimation", *Proc. of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 05).*

[34] Furukawa, N., Namiki, A., Taku, S., and Ishikawa, M., 2006, "Dynamic Regrasping Using a High-speed Multifingered Hand and a High-speed Vision", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[35] Gams, A., and Lenarcic, J., 2006, "Humanoid arm kinematic modeling and trajectory generation", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[36] Gazeau, J.P., Zehloul, S., Arsicault, M., and Lallemand, J.P., 2001, "The LMS hand: force and position controls in the aim of the fine manipulation of objects", *Proc. of the 2001 IEEE International Conference on Robotics and Automation.*

[37] Gialias, N., and Matsuoka, Y., 2004, "Muscle Actuator Design for the ACT Hand", *Proc. of the 2004 IEEE International Conference on Robotics and Automation*, May, 2004.

[38] Herder, J.L., Cool, J.C., and Plettenburg, D.H., 1998, "Methods for reducing energy dissipation in cosmetic gloves", *Journal of Rehabilitation Research and Development* ,**35**(2):210-209.

[39] Higashimori, M., Jeong, H., Ishii, I., Namiki, A., Ishikawa, M., and Kaneko, M., 2005, "A New Four-Fingered Robot Hand with Dual Turning Mechanism", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[40] Holden, E. J., and Owens, R., 2001, "Visual Sign Language Recognition", *R. Klette et. al.: Multi-Image Analysis, LNCS 2032*, pp. 270-287.

[41] Hoshino, K., and Kawabuchi, I., 2006, "Dexterous robot hand with pinching function at fingertips", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[42] Hoshino, K., and Tanimoto, T., 2006, "Real-Time Hand Posture Estimation without Deviation of Search Time", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[43] Hourtash, A., 2006, "The CX-Space A Unified Paradigm for Grasping Using Multifingered Hands", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[44] Huang, H-P., and Chen, C-Y.,1999, "Development of a myoelectric discrimination system for a multi-degree prosthetic hand", *Proc. of the 1999 IEEE International Conference on Robotics and Automation*, 10-15 May 1999.

[45] Huang, C. L. and Chung, C. Y., 2004, "A real-time model-based human motion tracking and analysis for human computer interface systems," *EURASIP J. on Applied Signal Processing*, **11**:1648-1662.

[46] Jacobsen, S., Iversen, E., Knutti, D., Johnson, R., and Biggers, K., 1986, "Design of the Utah/M.I.T. Dextrous Hand", *Proc. of the1986 IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 1520-1532.

[47] Jobin, J-P., Buddenberg, H.S., and Herder, J.L., 2004, "An Underactuated Prosthesis Finger Mechanism With Rolling Joints", *2004 ASME Int. Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Salt Lake City, USA, September 28-October 2, 2004.

[48] Kargov, A., Pylatiuk, C., Martin, J., Schulz, S., and Döderlein, L., 2004, "A comparison on the grip force distribution in natural hands and in prosthetic hands", *Disability and Rehabilitation*, **26**(12):705-711.

[49] Kargov, A., Asfour, T., Pylatiuk, C., Oberle, R., Klosek, H., Schulz, S., Regenstein, K., Bretthauer, G., and Dillmann, R., 2005, "Development of an anthropomorphic hand for a mobile assistive robot", *9th International Conference on Rehabilitation Robotics, ICORR 2005*, 28 June-1 July 2005.

[50] Kato, I., Yamakawa, S., Ichikawa, K., and Sano, M., 1970, "Multifunctional Myoelectric Hand Prosthesis with Pressure Sensory Feedback System - Waseda Hand 4P", *Proc. of the 3rd Int. Symposium on External Control of Human Extremities*, Dubrovni, 1970.

[51] Kato, M., Chen, Y-W., and Xu, G., 2006, "Articulated Hand Tracking by PCA-ICA Approach", *7th International Conference on Automatic Face and Gesture Recognition, FGR 2006*, 10-12 April, 2006.

[52] Kawasaki, H., Komatsu, T., and Uchiyama, K., 2002, "Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II", *IEEE/ASME Transactions on Mechatronics*, **7**(3): 296-303.

[53] Kim, G., Asakura, Y., Okuno, R., Akazawa, K., 2005, "Tactile Substitution System for Transmitting a Few Words to a Prosthetic Hand User", *27th Annual International Conference of the Engineering in Medicine and Biology Society, IEEE-EMBS 2005*, 01-04 Sept. 2005.

[54] Kim, Y.S., Soh, B.S., and Lee, S.G., 2005, "A New Wearable Input Device: SCURRY", *IEEE Transactions on Industrial Electronics*, **52**(6):1490-1499.

[55] Knoop, S., Vacek, S., and Dillmann, R., 2006, "Sensor Fusion for 3D Human Body Tracking with an Articulated 3D Body Model", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[56] Kyberd, P.J., and Chappell, P.H., 1994, "The Southampton Hand: An intelligent myoelectric prosthesis", *Journal of Rehabilitation Research and Development*, **31**(4):326-334.

[57] Kyberd, P.J., Evans, M.J., and Winkel, S., 1998, "An intelligent anthropomorphic hand, with automatic grasp", *Robotica* **16**:531-536.

[58] Kyberd, P.J., Light, C., Chappell, P.H., Nightingale, J.M., Whatley, D., and Evans, M., 2001, "The design of anthropomorphic prosthetic hands: A study of teh Southampton Hand", *Robotica*, **19**:593-600.

[59] Kyberd, P.J., and Pons, J.L., 2003, "A comparison of the Oxford and Manus intelligent hand prostheses", *Proc. of the 2003 IEEE International Conference onRobotics and Automation*, 14-19 Sept. 2003.

[60] Laliberte T., and Gosselin, C.M., 1998, "Simulation and design of underactuated mechanical hands", *Mechanism and Machine Theory*, **3**:39-57.

[61] Lee, J., and Kunii, T.L., 1995, "Model-based analysis of hand posture", *Computer Graphics and Applications*, **15**(5):77-86.

[62] Lee, M.J., Jung, S.H., Lee, S., Mun, M.S., Moon, I., 2006, "Control of IPMC-based Artificial Muscle for Myoelectric Hand Prosthesis", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[63] Lee, Y.K., and Shimoyama, I., 2002, "A multi-channel micro valve for micro pneumatic artificial muscle", *The 15th IEEE Int. Conf. on Micro Electro Mechanical Systems*, January 20-24, 2002.

[64] Lee, J., Youm, Y., Chung, W., 2004, "The development of Postech Hand 5", *Proc. of the 2004 IEEE Int. Conf. on Robotics and Automation*, Apr 26-May 1, 2004.

[65] Li, J., Zhang, Y., Zhang, Q., and Gruver, W.A., 1999, "An algorithm for the kinematics of dexterous manipulation", *Proc. of the IEEE SMC '99 Conference: Systems, Man, and Cybernetics*, Vol. 6:792-797.

[66] Light, C.M., and Chappell, P.H., 2000, "Development of a lightweight and adaptable multiple-axis hand prosthesis", *Medical Engineering and Physics*, **22**:679-684.

[67] Loh, C.S., Yokoi, H., and Arai, T., 2005, "New Shape Memory Alloy Actuator: Design and Application in the Prosthetic Hand", *27th Annual International Conference of the Engineering in Medicine and Biology Society, IEEE-EMBS 2005*, 01-04 Sept. 2005.

[68] Lotti, F., Tiezzi, P., Vassura, G., Biagiotti, L., Palli, G., and Melchiorri, C., 2005, "Development of UB Hand 3: Early Results", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[69] Lu, S., Metaxas, D., Samaras, D., and Oliensis, J., 2003, "Using Multiple Cues for Hand Tracking and Model Refinement", *Proc. of the 2003 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 03).*

[70] McCarthy, j.m., *Introduction to Theoretical Kinematics*, The MIT Press, 1990.

[71] Micilotta, A., and Bowden, R., 2004, "View-based Location and Tracking of Body Parts for Visual Interaction", *Proc. BMVC04*, **2**:849-858, Kingston, UK, Sept. 2004.

[72] Micilotta, A., Ong, E., and Bowden, R., 2005, "Real-time Upper Body 3D Reconstruction from a Single Uncalibrated Camera", *Eurographics 2005*, Dublin, Ireland, August 29-September 2, 2005.

[73] Moldenhauer, J., Boesnach, I., Beth, T., Wank, V., Bös, K., 2005, "Analysis of Human Motion for Humanoid Robots", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[74] Montambault, S., and Gosselin, C.M., 2001, "Analysis of Underactuated Mechanical Grippers", *Journal of Mechanical Design*, **123**(3):367-374.

[75] Mouri, T., Kawasaki, H., and Umebayashi, K., 2005, "Developments of new anthropomorphic robot hand and its master slave system", emphIEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2005, 2-6 Aug., 2005.

[76] Murray, R., Li, Z. and Sastry, S., *A Mathematical Introduction to Robotic Manipulation*, CRC Press, Boca Raton, 1994.

[77] Nakagawara, S., Kajimoto, H., Kawakami, N., Tachi, S., and Kawabuchi, I., 2005, "An Encounter-Type Multi-Fingered Master Hand Using Circuitous Joints", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[78] Namiki, A., and Ishikawa, M., 2005, "The Analysis of High-speed Catching with a Multi-fingered Robot Hand", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[79] Nolker, C., and Ritter, H., 2002, "Visual recognition of continuous hand postures", *IEEE Transactions on Neural Networks*, **13**(4):983 - 994.

[80] Ong, E., and Bowden, R., 2004, "Detection and Segmentation of hand shapes using Boosted Classifiers", *Proc. 6th Int Conf on Automatic Face and Gesture Recognition, FGR'04*, Korea 2004, pp. 889-894.

[81] Ong, S.C.W., and Ranganath, S., 2005, "Automatic sign language analysis: a survey and the future beyond lexical meaning", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **27**(6):873 - 891.

[82] Okamura, A.M., Smaby, N., and Cutkosky, M.R., 2000, "An overview of dexterous manipulation", *Proc. of the 2000 IEEE International Conference on Robotics and Automation.*

[83] Palli, G., and Melchiorri, C., 2006, "Model and Control of Tendon-Sheath Transmission Systems", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[84] Potratz, J., Yang, J., Abdel-Malek, K., Peña Pitarch, E., and Grosland, N., "A Light Weight Compliant Hand Mechanism with High Degrees of Freedom", *Transactions of the ASME Journal of Biomechanical Engineering*, **127**(6):934-945.

[85] Pylatiuk, C., Mounier, S., Kargov, A., Schulz, S., and Bretthauer, G., 2004, "Progress in the development of a multifunctional hand prosthesis", *Proc. of the 26th Annual Int. Conf. of the Engineering in Medicine and Biology Society, EMBC 2004.*

[86] Pylatiuk, C., Schulz, S., Kargov, A., and Bretthauer, G., 2004, "Two Multiarticulated Hydraulic Hand Prostheses", *Artificial Organs*, **28**(11):980-986.

[87] Rodriguez-Cheu, L.E., Casals, A., Cuxart, A., and Parra, A., 2005, "Towards the definition of a functionality index for the quantitative evaluation of hand-prosthesis", *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2005*, 2-6 Aug., 2005.

[88] Saito, Y., Ogawa, A., Negoto, H., Ohnishi, K.,, 2005, "Development of intelligent prosthetic hand adapted to age and body shape", *9th International Conference on Rehabilitation Robotics, ICORR 2005*, 28 June-1 July, 2005.

[89] Salisbury, J.K., and Craig, J.J., 1982, "Articulated Hands: Force Control and Kinematic Issues", *International Journal of Robotic Research*, **1**:4-17.

[90] Schulz, S., Pylatiuk, C., and Bretthauer, G., 2001, "A new ultralight anthropomorphic hand", *Proc. of the 2001 IEEE Int. Conf. on Robotics and Automation*, Vol. 3, pp. 2437-2441.

[91] Sebastiani, F., Roccella, S., Vecchi, F., Carrozza, M.C., and Dario, P., "Experimental analysis and performance comparison of three different prosthetic hands designed according to a biomechatronic approach", *Proc. of the 2003 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics*.

[92] Selig, J.M., *Geometrical Methods in Robotics*, Springer, London 1996.

[93] Stellin, G., Cappiello, G., Roccella, S., Carrozza, M.C., Dario, P., Metta, G., Sandini, G., and Becchi, F., 2006, "Preliminary Design of an Anthropomorphic Dexterous Hand for a 2-Years-Old Humanoid: towards Cognition", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[94] Su, Y., Fisher, M.H., Wolczowski, A., Bell, G.D., Burn, D., and Gao, R., 2005, "Towards an EMG Controlled Prosthetic Hand Using a 3D Electromagnetic Positioning System", *Proc. of the IEEE Instrumentation and Measurement Technology Conference, IMTC 2005*, 16-19 May, 2005.

[95] Sugimoto, K., 1987, "Kinematic and Dynamic Analysis of Parallel Manipulators by Means of Motor Algebra", *ASME Journal of Mechanisms, Transmissions and Automation in Design*, **109**(1):3-5.

[96] Supan, J., 2003, "Active functional prostheses", *Hand Clinics*, **19**: 185-191.

[97] Tahara, K., Luo, Z.W., Ozawa, R., Bae, J.H., and Arimoto, S., 2006, "Bio-Mimetic Study on Pinching Motions of A Dual-Finger Model with Synergistic Actuation of Antagonist Muscles", *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, Orlando, FL, USA, May 15-19, 2006.

[98] Tanibata, N., Shimada, N., and Shirai, Y., 2002, "Extraction of Hand Features for Recognition of Sign Language Words," *Proc. Int. Conf. Vision Interface*, pp. 391-398, 2002.

[99] Tsai, L. W., 1999, *Robot Analysis: The Mechanics of Serial and Parallel Manipulators*, John Wiley and Sons, New York, NY.

[100] Ueda, j., Ishida, Y., Kondo, M., and Ogasawara, T., 2005, “Development of the NAIST-Hand with Vision-based Tactile Fingertip Sensor”, *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[101] Vacalebri, P., Lazzarini, R., Roccella, S., Vecchi, F., Carrozza, M.C., Zecca, M., and Dario, P., 2003, “A Robotic System for Soft Tissue Characterization”, *International Journal of Human-friendly Welfare Robotic Systems* **4**(2).

[102] Varga, E., Horvath, I., Rusak, Z., de Smit, B. and Broek, H., 2004, “Survey and Investigation of Hand Motion Processing Technologies for Compliance with Shape Conceptualization”, *ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, September 28-October 2, 2004, Salt Lake City, USA.

[103] Veber, M., and Bajd, T., 2006, “Assessment of Human Hand Kinematics”, *2006 IEEE International Conference on Robotics and Automation*, Orlando, Florida, May 15-19, 2006.

[104] Villa-Uriol, M.C., Perez-Gracia, A. and Kuester, F., 2006 ”Humanoid Synthesis Using Clifford Algebra”, *2006 IEEE International Conference on Robotics and Automation*, Orlando, Florida, May 15-19, 2006.

[105] Vogler, C., and Metaxas, D., 1998, “ASL Recognition Based on a Coupling between HMMs and 3D Motion Analysis”, *Proc. sixth IEEE Int. Conf. Computer Vision*, pp. 363-369, Mumbai, India, January 4-7, 1998.

[106] Wang, H., Low, K.H., Wang, M.Y., and Gong, F., 2005, “A Mapping Method for Telemanipulation of the Non-Anthropomorphic Robotic Hands with Initial Experimental Validation”, *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[107] Vande Weghe, M., Rogers, M., Weissert, M., and Matsuoka, Y., 2004, “The ACT Hand: design of the skeletal structure”, *Proc. of the 2004 IEEE Int. Conf. on Robotics and Automation*, Apr 26-May 1, 2004.

[108] Wu, Y., Lin, J., and Huang, T.S., 2005, “Analyzing and capturing articulated hand motion in image sequences”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **27**(12):1910-1922.

[109] Yamano, I., and Maeno, T., 2005, “Five-fingered Robot Hand using Ultrasonic Motors and Elastic Elements”, *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[110] Yang, J., Abdel-Malek, K., and Peña Pitarch, E., 2004, “Design and Analysis of a Cable Actuated Hand Prosthesis”, *2004 ASME Int. Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Salt Lake City, USA, September 28-October 2, 2004.

[111] Yang, J., Peña Pitarch, E., Abdel-Malek, K., Patrick, A., and Lindkvist, L., 2004, "A multi-fingered hand prosthesis", *Mechanism and Machine Theory*, **39**:555-581.

[112] Yang,M-H., Ahuja, N., and Tabb, M., 2002, "Extraction of 2D motion trajectories and its application to hand gesture recognition", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **24**(8):1061 - 1074.

[113] Zecca, M., Cappiello, G., Sebastiani, F., Roccella, S., Vecchi, F., Carrozza, M.C., and Dario, P., 2003, "Experimental analysis of the proprioceptive and exteroceptive sensors of an under-actuated prosthetic hand", *International Journal of Human-friendly Welfare Robotic Systems*, **4**(4).

[114] Zhang, Y., Han, Z., Zhang, H., Shang, X., Wang, T., Guo, W., and Gruver, W.A. ,200, "Design and control of the BUAA four-fingered hand", *Proc. of the 2001 IEEE Int. Conf. on Robotics and Automation*.

[115] Zhao, J., Xie, Z., Jiang, L., Cai, H., Liu, H., and Hirzinger, G., 2005, "Levenberg-Marquardt based Neural Network Control for a Five-fingered Prosthetic Hand", *Proc. of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 18-22, 2005.

[116] Zhao, J., Xie, Z., Jiang, L., Cai, H., Liu, H., and Hirzinger, G., 2006, "A Five-Fingered Underactuated Prosthetic Hand Control Scheme", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.

[117] Zhou, H., and Ruan, Q., 2002, "A Method of Hand Tracking Based on Articulated Model", *Proc. of the Int. Conf. on Signal Processing, ICSP 2002*, Beijing, China, August 26-30, 2002.

[118] Zollo, L., Roccella, S., Tucci, R., Siciliano, B., Guglielmelli, E., Carrozza, M.C., and Dario, P., 2006, "BioMechatronic Design and Control of an Anthropomorphic Artificial Hand for Prosthetics and Robotic Applications", *Proc. of the 1st IEEE/RAS Int. Conf. on Biomedical Robotics and Biomechatronics, BioRob 06*, Pisa, Italy, February 20-22, 2006.