

# A Methodology for the Design of Robotic Hands with Multiple Fingers

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**Abstract:** This paper presents a methodology that has been applied for a design process of anthropomorphic hands with multiple fingers. Biomechanical characteristics of human hand have been analysed so that ergonomic and anthropometric aspects have been used as fundamental references for obtaining grasping mechanisms. A kinematic analysis has been proposed to define the requirements for designing grasping functions. Selection of materials and actuators has been discussed too. This topic has been based on previous experiences with prototypes that have been developed at the Laboratory of Robotics and Mechatronics (LARM) of the University of Cassino. An example of the application of the proposed method has been presented for the design of a first prototype of LARM Hand.

**Keywords:** Methodology, design, robotic hands, anthropomorphic

## 1. Introduction

The design of grasping mechanisms has been the aim of several researches in the field of Robotics. These researches have addressed attention to a physical interface between a robotic system and its environment. This interface provides interaction with objects and offers dexterity manipulation and grasping functionalities. Developments of industrial robotics have produced several types of gripper mechanisms. Robotic grippers are employed in robotic manipulators that perform repetitive tasks. These grippers can only execute limited and specific manipulation tasks, [Penisi et al., 2003]. They are limited to objects that are very similar in terms of shape, weight and manipulation requirements, [Chen, 1982]. The use of grippers is also limited to the grasping of objects with regular geometries. Considerable disadvantages of industrial grippers have been found as regarding with the stability of the grasping of objects with irregular geometries or complex manipulation operations.

Due to these limitations, research efforts have been dedicated to the development of multiple finger robotic hands. These devices try to mimic one or more characteristics of the human hand. Important architectures for robotic hands have been developed in recent years, as for example Barret Hand, [Townsend, 2000], Manus Colobi, [Gosselin et al., 1993], LMS Hand, [Gazeau et al., 2001], TBM Hand, [Dechev et al., 2001], DLR II Hand, [Butterfass et al., 2001], Tuat/Karlsruhe Hand, [Fukaya et al., 2000], BUAA Hand, [Zhang et al., 2001], Gifu II Hand, [Kawasaki et al., 2002], RTR II Hand, [Massa et al., 1985], Standford JPL Hand, [Mason &

Salisbury, 1985], Torino Hand, [Raparelli et al., 2000], MA-I Hand, [Suarez & Grosch, 2004], SARAH Hand, [Martin et al., 2004], MIT hand, [Edsinger-Gonzales, 2004], RCH-I hand, [Zollo et al., 2006], and the super hand, [Kaneko & Higashimori, 2005].

Most of these robotic hands have a high number of degrees of freedom and a complex control system. Moreover, their architectures require high costs of manufacture. The above-mentioned robotic hands are mainly used on specific applications, laboratory tests and research projects. A few of them have been sold on the market for industrial and non-industrial applications, like Barret hand, SARAH hand and Stanford/JPL hand.

In the last decade at the Laboratory of Robotics e Mechatronics (LARM) of the University of Cassino many research activities have been addressed to development of low-cost anthropomorphic hands with simple commercial actuators and easy-operation systems. Some of these efforts have included formulation of procedures for the design of robotic hands, as reported in [Ceccarelli et al., 2003; Ceccarelli et al., 2004; Nava et al., 2004; Nava et al., 2006].

In this paper a method for the design of robotic hands is proposed. This method has been based on a product design process with five basic phases, [Dym & Little, 1999]. The proposed method establishes a sequence of tasks that involve the design process.

## 2. A Method for the Design of Multiple Finger Robotic Hands

The product design process can be described as a five-step systematic and task oriented process, as shown in

Fig. 1. The first step of the design process, named as “problem definition”, consists of establishing a clear definition of the design problem. In this phase, the design objective must be clarified. A set of requirements must be identified by recognizing the design problem. The next step of the design process, name as “concept design”, is a phase which involves establishing a set of specifications and design alternatives. In the “preliminary design”, alternatives are modelled, analysed and evaluated. One of these alternatives can be exported to the next step in the design process. The next step, named as “detail design”, involves definition of design details that produce a set of manufacturing specifications for an optimised design.

Finally, the “design communication” step consists in elaborating a documentation of the final design by specifying the obtained characteristics of the process.

In Fig. 2 the product design process of Fig. 1 refers to a design of a robotic hand, as referring to the process that has been applied to the design of anthropomorphic robotic hands during previous research activities at LARM. In the proposed methodology for robotic hand design, the phase of “definition of the problem” has been divided in two sections: the first concerns with the application of the robotic hand and the second is an analysis of the human hand. The “conceptual design” phase has been considered to address to three main elements: actuation, sensors, and control system. The design specifications for a robotic hand are characterized by these three components.

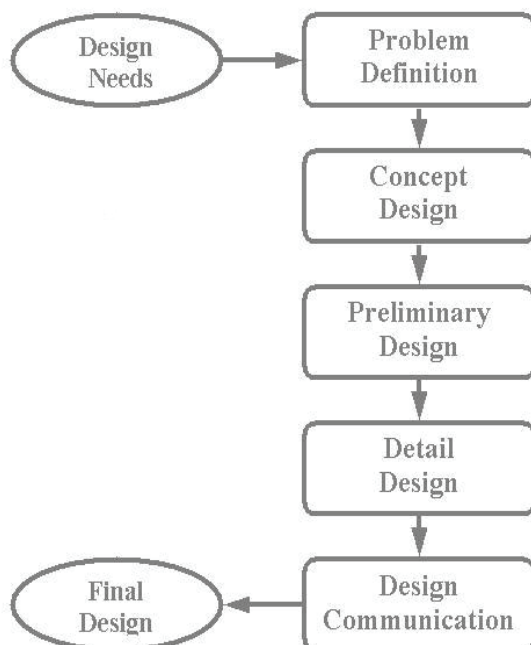


Fig. 1. A scheme for a design process of a product

The consideration of these three components reflects the importance of a simultaneous design of actuators, control and sensory systems for a robotic hand.

The “preliminary design” is presented in [Dym & Little, 1999] as a design step for selection and synthesis of the hand mechanism. The herein proposed method is more specific in reflecting an effective design process for a robotic hand. The design process must be understood as an iterative procedure in which solutions and decisions can be evaluated and optimised recursively. The analysis has been represented as a feedback loop that should be followed by an optimisation routine. This procedure allows possible improvements to be translated into new requirements for the “conceptual design”. This feedback loop reflects the design process that has been developed at LARM. During this process computational methods have been used for evaluating and improving the design before the construction of any model or physical prototype, [Nava et al., 2006]. In the proposed design process of Fig 2, an “experimental phase” follows the “preliminary design” phase.

A prototype can be built for an experimental validation. A local feedback loop is presented on this step to reflect the improvements that can be made on the physical system by considering new experimental information. Finally, the details of the design are the output of the process.

### 3. Identification of Applications

The phase that involves identification of applications for a robotic hand is fundamental.

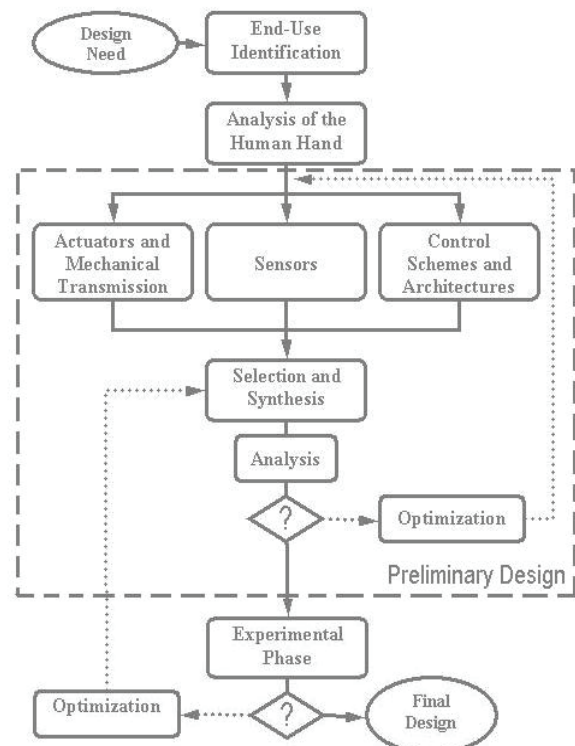


Fig. 2. A proposed design process for robotic hands

It allows to focus the design problem in a more specific way by referring to technological and market requirements.

Many of the research efforts for conception of dexterous hands have been oriented to specific applications, [Banks, 2001]. Some of these applications can be listed as:

- Prosthesis;
- Manipulators for Astronautic Purposes;
- Humanoid Robotics;
- Industrial Manipulators.

Human prostheses and astronautic manipulators seem to be the most demanding and ambitious applications. For example, the design that is oriented to develop infant or adult prosthesis is a complex problem for robotic hand design, since geometric, ergonomic and functional characteristics of human hands have to be matched in order to develop successful hand prosthesis. The hand structure and material are important aspects to consider for aeronautical applications because of the hard conditions in the working environment. In general, the anthropomorphic characteristics of a design are not strong requirements, as are precision of control system and dexterous capabilities of manipulation, as pointed out for example in [Martin et al., 2004].

A design problem for a robot hand with similar complexity can be the application for a sub-system in a humanoid robot, as discussed in [Ceccarelli, 2003]. A design objective for a grasping sub-system of a humanoid robot can be to generate an autonomous, flexible and anthropomorphic design. In the case of prosthesis, the autonomy can not be established as a design requirement, as illustrated in [Suarez & Grosch, 2004].

Anthropomorphism is not necessarily a design requirement in the case of many robotic applications like mobile robots. In this case the requirements may be translated to the development of a sensory and cognitive system. It allows the robot an ability to perceive and explore an unknown surrounding.

Finally, in the case of industrial manipulators design objectives are directed to exploit grasping characteristics of dexterous hands. The robotic hand must provide enough flexibility for the system to perform precise manipulation. At the same time, it must provide ability for manipulation of large or heavy objects.

#### 4. Analysis of Human Hand

Human hands are universal grasping mechanisms with great flexibility in manipulation, [Belforte, 1985]. The dexterity of this complex biological mechanism is capable for a great diversity of applications. The sensory system of human hand permits to identify a cognitive representation of grasped objects that is a very desired ability for medical prosthesis as well as in advanced developments in mobile and humanoid robotics. Anthropomorphism and dexterity are two of the main desirable characteristics for robot hands.

Anthropomorphism can be described as the ability of robot end-effector to mimic characteristics of human hand. The dexterity is recognized as a fundamental functional aspect of human hands. Anthropomorphism is not in itself a necessary or sufficient condition for achieving dexterity of a robot hand. Anthropomorphism can be considered a design objective for the following reasons:

- The robot hand will be able to operate in human-used environments and may interact with tools or objects that have been modelled and designed according to the ergonomic requirements of human operators;
- The robot hand can be teleoperated by a user with the help of an adequate interface that reflects the behaviour of the human operator hand;
- In the case of humanoid robotics, the robot sub-system is required to mimic the human-like behaviour for multiple operations.

The analysis of human hand can be divided in two items; namely the biomechanical architecture and sensory cognitive system. Design requirements can be generated for a mechanical system regarding with structural characteristics, dimensions of palm and fingers, articulations, movements and types of grasps of human hand. All these requirements will lead to a very specific characterization of the design and they represent the variables and parameters for the mechanical synthesis during the design process.

Several research efforts have been devoted to the study of anthropometric characteristics of human hand. In 1919, Schlesinger developed taxonomy of the grasp that was widened later on by Napier, [Taylor & Schwarz, 1955; Cutkosky, 1989]. In [Taylor & Schwarz, 1955] the authors present one of the first extensive engineering analyses on the anatomy and mechanical properties of human hand. In [An, 1979; Buchholz & Armstrong, 1991; Buchholz et al., 1992; Buchholz & Armstrong, 1992] exhaustive studies of kinematical characteristics of the human hand are presented. These studies were performed to evaluate the ergonomic design of hand tools. They can be understood as an important basis for establishing kinematical requirements of robot hands. In particular, in [Buchholz & Armstrong, 1991] a kinematical model is presented for simulating of finger positions that are required for grasping objects with known geometry. This work presents measured sizes of the metacarpal and carpal bones that can be directly used as dimensional restrictions for a robot hand design.

Further analysis is required on the sensory capabilities of human hand and human nervous system to identify requirements for sensory and control systems of robot hands [Banks, 2001].

The next phase in a design process consists in mechanical synthesis that is closely related to the topology of the main functional elements; which are the fingers, palm and wrist. The synthesis process provides the geometric characteristics, materials and actuators for a robot hand.

## 5. Selection and Design of Components

The synthesis process determines topology and dimensions of a kinematic chain of mechanism that can drive robot fingers. A dimensional synthesis requires a previous definition of the topology that should be approximated to human hand structure. In practice, the characteristics of commercial actuators will limit this possibility. Therefore, the synthesis problem suggests a careful selection of actuators, sensors and control algorithms. These components set the boundary conditions for the design problem and prescribe specifications that will be used for the kinematic synthesis, as outlined for example in [Duraismy et al., 2006].

Few computational tools are available to assist this design process. Numerical computational codes are mainly used for solving multi-criteria optimisation problem that can be properly formulated for optimal synthesis of mechanism. Computational design tools are available for simulating kinematic and dynamic performance of mechanisms, mechanical interference analysis, and control architectures. By using suitable computational feedback loops, the analysis and optimisation of a robot hand can be developed. CAD/CAE technologies helps to determine a solution and to make corrections of design problems before the construction of a physical prototype. Recent research works have illustrated usefulness of 3D-CAD technologies during the design process of robot hands, as outlined in [Zollo et al., 2006]. Integrating controller synthesis at this point is necessary to give to robot systems a proper degree of controllability and robustness for manipulation operations.

Developing the design of a control system with a certain level of autonomy, reactivity and robustness can be considered an important factor for a successful design.

A proper control system provides to the hand prototype desired characteristics of human hand operation, [Stellin et al., 2006]. For example, recent research works present important developments in the use of electromyography signals for the control of prosthetic hands, as outlined for example [Lee et al., 2006; Rodriguez-Cheu & Casals, 2006].

The most common actuators that are used for robot hands are electric powered motors. These actuators can be conveniently used to transfer directly the movement to the input joints of fingers. Alternatively, the movement can be transferred by using tendons, bevels or train of gears that can be specifically designed for this type of applications.

The actuator design or selection is a crucial phase for developing efficient finger mechanisms. A goal for the proposed design process has been to establish a set of desirable conditions for the actuator selection that are proper to the desired application. Some of the most important parameters in this case are the number of required motors; their size, torque, speed, and energy

consumption; direct or remote actuation system; and cost of the commercial solutions.

A wide variety of commercially sensors are available in the market. They can be used as position and force sensors in robot hands. Desirable characteristics of the sensors can be outlined as:

- They should be relatively cheap and energy efficient;
- Sensible elements should be located on a thin flexible support that can be installed on fingers and palm giving the possibility of sensor adaptation to the surface of grasped object while performing a firm grasp;
- High sensitivity, low hysteresis, repeatability and a suitable bandwidth.

Most of commercial transducers available in the market can be used as sensors for robot hands. Resistive transducers, piezoelectric and capacitive, magnetic and photoelectric are commonly used as part of specific systems in available robot hands, as pointed out for example in [Butterfass et al., 2001; Jacobsen et al., 1984].

The selection of components of a mechanical hand depends mainly of the robot applications. Using available components in the market can give a suitable and low-cost design for the hand systems. Industrial applications can permit a robotic hand design with commercial components, but other specific applications, such as prosthesis and astronautics, can require especial shapes and materials of components. Nevertheless, the design of hand prototypes with low-cost and easy-operation architectures for applications that require complex designs is also a goal for a research activity, as reported in [Ceccarelli, 2003].

A proper selection of actuators, energy sources, joints and sensors must provide suitable characteristics of design for the robotic hand. These characteristics of the mechatronic architecture provide a certain potential dexterity for a designed robot hand, [Bicchi, 2000].

## 6. Design of LARM Hand, a Three Finger Hand

LARM Hand has been enhanced through an application of the proposed methodology. The LARM Hand design has been conceived mainly for industrial manipulations and human prosthesis. A built prototype has been designed for grasping objects with regular geometries, such as cylinders, cubes and spheres, as is discussed in [Ceccarelli et al., 2003].

As an initial phase in the LARM Hand design, anthropomorphic characteristics of human hands have been investigated. Dimensions and movements have been measured and analysed. The phalanx sizes and transmission radius between phalanxes have been measured and these dimensions have been used for the fingers of the LARM Hand in order to achieve an anthropomorphic design that can copy the performance of the human index finger, as illustrated in [Nava et al., 2004].

Grasp force has also been measured and analysed in human operation. A measurement system has been installed on a human hand of volunteers in order to study experimentally the grasp forces that can be applied during the grasp of objects with regular geometries. The obtained grasp forces by human hand can be used to validate the grasped forces that are obtained by robotic hands during experimental tests. Commercial force sensors have been used for measuring grasp forces and a virtual instrument has been set up in LabView environment in order to manage the force sensors, as reported in [Ceccarelli et al., 2004].

The mechanism of LARM Hand fingers is shown in Fig. 3 as a series of crossed-four bar linkages. By using this articulated mechanism, a robotic finger can performance movements which are similar to those of human index finger but through a mechanical movement with only one degree of freedom, [Nava et al., 2006]. Repeated kinematic analysis has been carried out for achieving optimal dimensions for the finger mechanism by using the human index finger as model, as illustrated in [Nava et al., 2006].

The first prototype of LARM Hand is shown in Fig. 4. This first prototype has been designed for industrial operation of grasping objects with regular geometries. The first prototype is approximately 1.5 times bigger than human hand. The kinematic chain of Fig. 3 has been used for each finger. DC electric motors have been used for the actuation of each finger. A commercial PLC controls all three DC motors of the LARM Hand prototype of Fig. 4. A second prototype of the LARM Hand is shown in Fig. 5. This second design of LARM Hand fulfils the requirements of compactness and dimension constraints as applications of human prosthesis. The LARM Hand of Fig. 5 uses actuators and control systems that have been implemented in the first prototype of Fig. 4. This prototype has approximately the sizes of human hand and uses trains of gears as actuation system for obtaining a more compact design, as shown in Fig. 5.

Alternatives for the LARM Hand architecture have been studied for prosthesis applications. Two of the proposed alternative designs for LARM Hand are shown in the 3D-CAD models of Fig. 6.

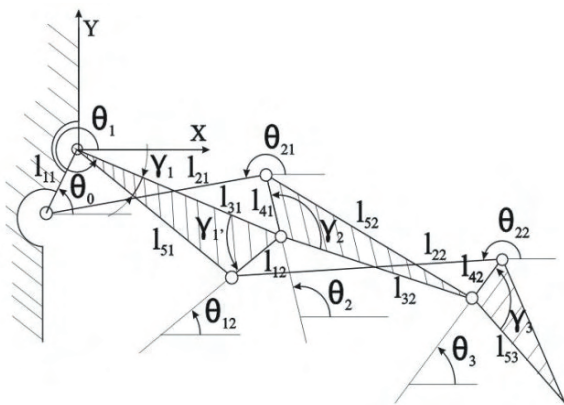


Fig. 3. Kinematic structure of LARM Hand fingers

In the architecture of Fig. 6(a), the base of the hand includes the frames of the fingers and actuators and the palm is made of an aluminium plate above the hand base. The hand of Fig. 6(b) presents a different design for the base of fingers. This base is composed by a component that locates the fingers with 90 degrees between them in fully-opening position of the hand.

The LARM Hand is equipped with low-cost force sensors that provide the necessary contact detection. Figure 7 shows the scheme of the whole system for the LARM Hand that has been implemented during experimental validations, [Nava et al., 2004].

Ten force sensors have been installed on the LARM Hand, namely one on each finger phalanx and one on the palm. The force signals have been amplified by an amplification card and they have been acquired by a National Instruments card.

The control system for the LARM Hand is equipped with a commercial low-cost PLC. This PLC has been programmed to perform the opening and closing of the hand by giving a required time of grasping. The palm sensor provides a contact signal that allows the interaction between the grasped object and control system. The control system identifies the grasped object by using the signal from the palm sensor.

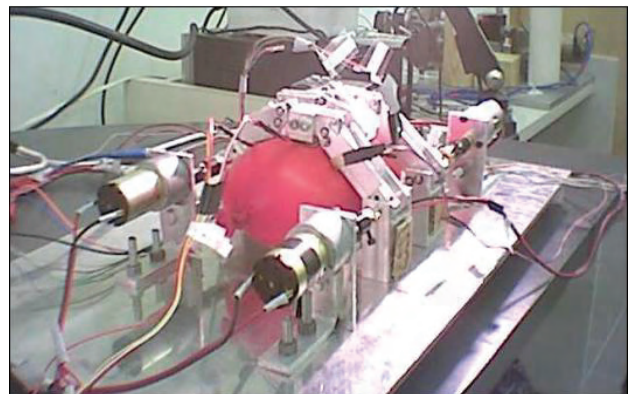


Fig. 4. The first prototype of LARM Hand

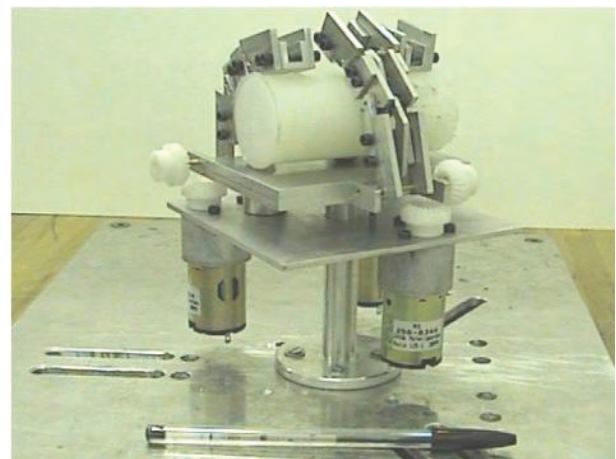


Fig. 5. The second prototype of the LARM Hand with human size



The PLC activates the counter for the grasping time and the after releasing of the object.

Experimental tests with the LARM Hand prototypes, as reported in [Nava et al., 2004], have provided satisfactory results for grasping forces and firm grasps during the grasping of objects with regular geometries.

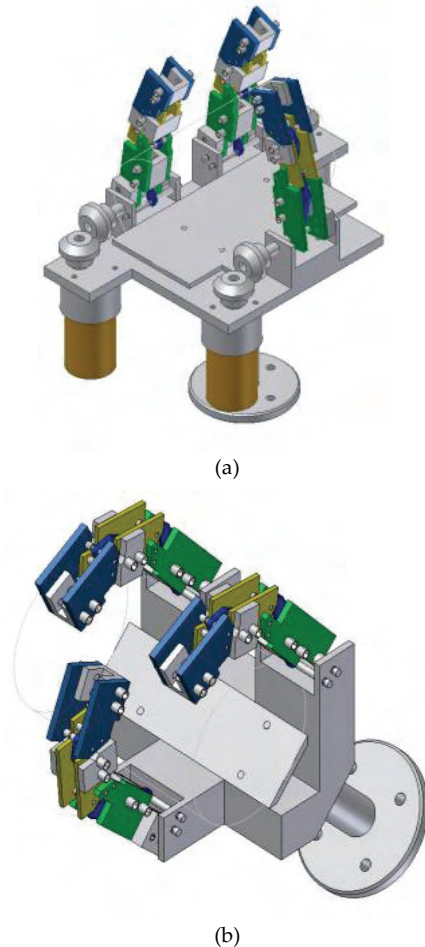


Fig. 6. Alternative architectures for the LARM Hand with human size: (a) first solution; (b) second solution

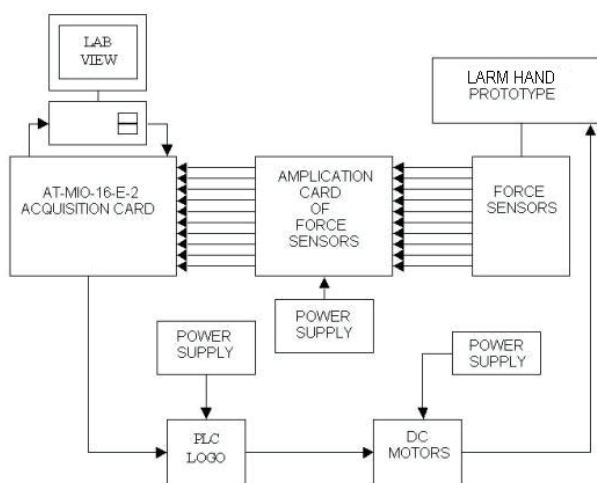


Fig. 7. A scheme of the control and measurement systems that have been installed in the LARM Hand prototypes

## 7. Conclusions

A methodology has been proposed and validated for a design process of multi-fingered robotic hands. This methodology is composed by phases that permit a sequence design of mechanical hand prototypes. The optimization loops of the propose methodology assurance a successful design of the robot hand. The identification of applications for the hand is an important initial step. This defines the parameters and requirements for the next steps of the design process. The study of the human hand plays an important role in the design of anthropomorphic architectures since it presents successful versatility, flexibility and manipulation capabilities. The aim of this methodology is to obtain a successful architecture and systems of a robotic hand that fulfil the requirements of the design application. The design of the LARM Hand constitutes a practical application of the proposed methodology. Satisfactory results of the design process have been obtained. The requirements that have been initially proposed for LARM Hand have been fulfilled. This application has validated the feasibility of the proposed methodology for the design of mechanical hands.

## 8. Acknoledgments

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## 9. References

- Penisi, O. H.; Ceccarelli, M. & Carbone, G. (2003). Classification of Mechanisms for Industrial Fingers With Two fingers. *Iberoamerican Journal of Mechanical Engineering*. Vol. 7, No 1, 2003, pp 59-75. (in Spanish)
- Chen, F. Y. (1982). Gripping Mechanisms for Industrial Robots. *Mechanism Machine Theory* Vol. 17, 1982, pp. 299-311.
- Townsend, W. (2000). The BarrettHand Grasper Programmable Flexible Part Handling and Assembly. *Industrial Robot: An International Journal*. Vol. 27, No. 3, 2000, pp. 181-188.
- Gosselin, C. M.; Mountambault, S. & Gosselin C. J. (1993). Manus Colobi: Preliminary Results on the Design of a Mechanical Hand for Industrial Applications, *Advances in Design Automation, Proceeding of ASME Design Automation Conference*, pp. 585-592, 1993, Albuquerque.
- Gazeau, J.; Zeghloul, S.; Arsicualt, M. & Lallemand, J. (2001). The LMS Hand: Force and Position Controls in the Aim of Fine Manipulation of Objects, *Proceeding of IEEE International Conference on Robotics and Automation*, pp. 2642-2648, 2001, Seoul.

- Dechev, N.; Cleghorn, W. & Nauman, S. (2001). Multiple Finger, Passive Adaptive Grasp Prosthetic Hand. *Mechanism and Machine Theory*. Vol. 36, 2001, pp. 1157-1173.
- Butterfass, j.; Grebenstein, M.; Liu, H. & Hirzinger, G. (2001). DLR-Hand II: Next Generation of a Dexterous Robot Hand, *Proceeding of IEEE International Conference on Robotics and Automation*, pp. 109-114, 2001, Seoul.
- Fukaya, N.; Toyama, S.; Asfour, T. & Dillmann, R. (2000). Design of the TUAT/Karlsruhe Humanoid Hand, *Proceeding of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1754-1759, 2000, Takamatsu.
- Zhang, Y.; Han, Z.; Zhan, H.; Shang, X.; Wang, T. & Guo, W. (2001). Design and Control of the BUAA Four-fingered Hand, *Proceeding of International Conference in Robotics and Automation*, pp. 2517-2522, 2001, Seoul.
- Kawasaki, H.; Komatsu, T. & Uchiyama, K. (2002). Dexterous Anthropomorphic Robot Hand with Distributed Tactile Sensor: Gifu hand II. *IEEE/ASME Transactions on Mechatronics*. Vol. 7, No. 3, 2002, pp. 269-279.
- Massa, B.; Roccella, S.; Carrozza, M. C. & Dario, P. (1985). Design and Development of an Underactuated Prosthetic Hand, *Proceeding of International Conference in Robotics and Automation*, pp. 3374-3379, 2002, Washington.
- Mason, M. T. & Salisbury, J. K. (1985). Robots Hands and the Mechanics of Manipulation. *MIT press*, 1985.
- Raparelli, T.; Mattiazzo, G.; Mauro, S. & Velardocchia, M. (2000). Design and Development of a Pneumatic Anthropomorphic Hand. *Journal of Robotic Systems*. Vol. 17, No. 1, 2000, pp. 1-15.
- Suares, R. & Grosch, P. (2004). Dexterous Robotic Hand MA-I Software and Hardware Architecture, *Proceeding of Intelligent Manipulation and Grasping*, pp 91-96, 2004, Genova.
- Martin, E.; Desbiens, A. L.; Laliberté, T. & Gosselin, C. (2004). SARAH Hand Used for Space Operation on STVF Robot, *Proceeding of Intelligent Manipulation and Grasping*, pp 279-284, 2004, Genova.
- Edsinger-Gonzales, A. (2004). Design of a Compliant and Force Sensing Hand for a Humanoid Robot, *Proceeding of Intelligent Manipulation and Grasping*, pp 291-295, 2004, Genova.
- Zollo, L.; Roccella, S.; Tucci, R.; Siciliano, B.; Guglielmelli, E.; Carrozza, M. C. & Dario, P. (2006). BioMechatronic Design and Control of an Anthropomorphic Artificial Hand for Prosthetics and Robotic Applications, *Proceeding of IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, paper F198-BioRob2006, 2006, Pisa.
- Kaneko, M. & Higashimori, M. (2005). Design of Super High Speed Robot Hand, *Proceeding of International Workshop on Computational Kinematics*, paper 01-CK2005, 2005, Cassino.
- Ceccarelli, M.; Jauregui, J. M.; Parada, J. M.; Nava, N. E.; Lanni, C. & Carbone, G. (2003). Experimental Activity for Designing a Hand with 1 DOF Anthropomorphic Fingers of Human Size, *Proceeding of Workshop on Robotics in Alpe-Andria-Danube Region*, paper 009RAAD03, 2003, Cassino.
- Ceccarelli, M.; Nava, N. E.; Jauregui, J. M.; Parada, J. E. & Carbone, G. (2004). Design and Validation of a 1-DOF Anthropomorphic Articulated Finger for a Robotic Hand. *Iberoamerican Journal of Mechanical Engineering*. Vol. 8, No. 2, 2004, pp. 15-24. (in Spanish)
- Nava, N. E.; Carbone, G.; Ottaviano, E. & Ceccarelli, M. (2004). An Experimental Validation of a Three - Fingered Hand With 1 D. O. F. Anthropomorphic Fingers, *Proceeding of Intelligent Manipulation and Grasping*, pp. 285-290, 2004, Genova.
- Nava, N. E.; Carbone, G. & Ceccarelli, M. (2006). Optimal Design of Driving Mechanism in a 1-d.o.f. Anthropomorphic Finger. *Mechanism and Machine Theory*. Vol. 41, No. 8, 2006, pp. 897-911.
- Dym, C. L. & Little, P. (1999). *Engineering Design*, John Wiley & Sons, New York.
- Banks, J. L. (2001). *Design and Control of an Anthropomorphic Robotic Finger with Multi-point Tactile Sensation*, Massachusetts Institute of Technology, Master Thesis, Cambridge.
- Ceccarelli, M. (2003). Low-Cost Robots for Research and Teaching Activities. *IEEE Robotics & Automation Magazine*. Vol. 10, No. 3, 2003, pp. 37-45.
- Belforte, G. (1985). Grasping Devices for Robots. *Technical Journal AMMA*. 1985, pp. 128-136. (in Italian)
- Taylor, C. L. & Schwarz, R. J. (1955). The Anatomy and Mechanics of the Human Hand. *Journal of Artificial Limbs*. Vol. 2, 1955, pp. 22-35.
- Cutkosky, M. R. (1989). On Grasp Choice, Grasp Model, and the Design of Hands for Manufacturing Tasks. *IEEE Transactions on Robotics and Automation*. Vol. 5, No.3, 1989, pp. 269-279.
- An, K. N. (1979). Normative Model of Human Hand for Biomechanical Analysis. *Journal of Biomechanics*. Vol. 12, No 10, 1979, pp 775-788.
- Buchholz, B. & Armstrong, T. J. (1991). An Ellipsoidal Representation of Human Hand Anthropometry. *Human Factors*. Vol. 33, No 4, 1991, pp 429-441.
- Buchholz, B.; Armstrong, T. J. & Goldstein, S. A. (1992). Anthropometric Data for Describing the Kinematics of the Human Hand. *Ergonomics*. Vol. 35, No 3, 1992, pp 261-273.
- Buchholz, B. & Armstrong, T. J. (1992). A Kinematic Model of the Human Hand to Evaluate Its Prehensile Capabilities. *Journal of Biomechanics*. Vol. 25, No 2, 1992, pp 149-162.
- Duraisamy, K.; Isebor, O.; Perez, A.; Schoen, M. P. & Naidu, D. S. (2006). Kinematic Synthesis for Smart Hand Prosthesis, *Proceeding of IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, paper F82-BioRob2006, 2006, Pisa.

- Stellin, G.; Cappiello, G.; Roccella, S.; Carrozza, M. C.; Dario, P.; Metta, G.; Sandini G. & Becchi, F. (2006). Preliminary Design of an Anthropomorphic Dexterous Hand for a 2-Years-Old Humanoid: Towards Cognition, *Proceeding of IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, paper F172-BioRob2006, 2006, Pisa.
- Lee, M. J.; Jung, S. H.; Lee, S.; Mun M. S. & Moon, I. (2006). Control of IPMC-based Artificial Muscle for Myoelectric Hand Prosthesis, *Proceeding of IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, paper F92-BioRob2006, 2006, Pisa.
- Rodriguez-Cheu, L. E. & Casals, A. (2006). Sensing and Control of a Prosthetic Hand with Myoelectric Feedback, *Proceeding of IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, paper F248-BioRob2006, 2006, Pisa.
- Jacobsen, S. C.; Wood, J. E.; Knutti, D. F. & Biggers, K. B. (1984). The Utah/MIT Dexterous Hand: Work in Progress. *The International Journal of Robotics Research*. Vol. 3, No. 4, 1984, pp. 21-49.
- Bicchi, A. (2000). Hands for Dexterous Manipulation and Robust Grasping: A Difficult Road Toward Simplicity. *IEEE Transactions on Robotics and Automation*. Vol. 16, No. 6, 2000, pp. 652-662.