World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:1, No:2, 2007

Robotic Hands: Design Review and Proposal of New Design Process

Jimmy W. Soto Martell, and Giuseppina Gini

Open Science Index, Mechanical and Mechatronics Engineering Vol:1, No:2, 2007 publications.waset.org/9034.pdf

Abstract**—**In this paper we intend to ascertain the state of the art on multifingered end-effectors, also known as robotic hands or dexterous robot hands, and propose an experimental setup for an innovative task based design approach, involving cutting edge technologies in motion capture. After an initial description of the capabilities and complexity of a human hand when grasping objects, in order to point out the importance of replicating it, we analyze the mechanical and kinematical structure of some important works carried out all around the world in the last three decades and also review the actuators and sensing technologies used. Finally we describe a new design philosophy proposing an experimental setup for the first stage using recent developments in human body motion capture systems that might lead to lighter and always more dexterous robotic hands.

Keywords**—**Dexterous manipulation, grasp, multifingered end-effector, robotic hand.

I. Introduction

HUMAN hand is one of the most complex organs of the human body after brain; thus, we understand why its behavior had intensively interested former philosophers, and in the past decades has been object of study and research not only in the medical field but also in the engineering field.

From empirical studies of human grasping in medicine due to the interest for hand surgery and the design of prosthetic devices, a substantial medical literature is available. Much of it refers to the categorization and study of six grasps: cylindrical, fingertip, hook, palmar, spherical and lateral, as in [1] and [2]; leading to associating the kind of human grasps with the shapes of the objects to be manipulated.

However, Napier [3] noticed that the choice of grasp actually depends more on the task to perform than on the shape and size of objects, therefore suggested to categorize grasps according to function instead of appearance. In his scheme, grasps are divided only into two groups: power grasps and precision grasps. In the first group there is a predomination of stability and security (holding a heavy tool or getting a jar lid unstuck), and are characterized by large areas of contact between the hand and the object. On the other hand, when it comes to precision grasps, considerations of sensitivity and dexterity predominate (writing with a pencil), using the tips of the fingers and the thumb to hold the object. From these basic categories a further study based on observations of single-handed operations by machinists working with metal parts and hand tools was carried on by Cutkosky and Wright, who proposed a partial taxonomy of manufacturing grasps [4].

The study of grasping and manipulation can be both experimental, by studying grasping of humans and animals to learn from these natural systems how to construct similar performing mechatronic ones; and analytical, by modeling the interactions between the hand and the grasped object using the laws of physics.

In the following Sections we describe the characteristics of the most relevant research projects in the engineering field attempting to replicate the functionality of a human hand. Then we propose our design criteria.

II. Review of Kinematical Structures

A. The Belgrade/USC Hand

As an attempt to mimic human hand functionality, the University of Southern California and the University of Novi-Sad at Belgrade jointly developed a multifingered robot hand called the Belgrade/USC Hand. It is a five-fingered robot hand which requires to control only four degrees of freedom; in fact a rocker arm mechanism mechanically couples two pairs of fingers [5]. The design is based on the Belgrade prosthetic hand [6] which originally had five fingers controlled by a single motor, and based its grasping principle on a very simple control strategy in which after a finger pad contacted the object to be grasped the other fingers close until the pressure on all the finger pads was approximately equal, thus achieving a high degree of automatic shape adaptability.

The goal of this anthropomorphic hand was to be well-suited to grasping tasks and capable of autonomous adaptation while applying simple control architecture based on the principles of non-numerical or reflex control ([7], [8]) to drive the hand.

In the Model II, the thumb has two joints and can rotate 120° around an axis parallel to the wrist from its fully extended position into opposition to fingers No. 2,3, or 4, which are identical in size and consist of three joints each. The joint rotations are supported by miniature ball bearings and

Manuscript received February 27, 2007.

J. W. Soto Martell is graduated in Mechatronic Engineering at the Universidad Nacional de Ingenieria, Lima, PERU'. He is now a PhD. Candidate at the Department of Mechanical Engineering at the Politecnico di Milano, Milano, Italy (e-mail: jimmy.sotomartell@polimi.it).

G. Gini is an Associate Professor of Robotics at the Department of Electronics and Information, Politecnico di Milano, Milano, Italy (e-mail: gini@elet. polimi.it).

Open Science Index, Mechanical and Mechatronics Engineering Vol:1, No:2, 2007 publications.waset.org/9034.pdf

driven by DC servomotors located within the wrist structure. Motions of each phalanx are not individually controllable since they are connected by means of linkages in a way they can display similar motions to human fingers during grasping. The autonomous adaptation to the shape is obtained thorough a rocker arm; if the motion of one finger of the driven pair is inhibited, the second finger continues to move, thus providing additional degrees of freedom to the fingers without active control. This architecture determines a hand well-suited to grasping tasks although does not have dexterity for applications requiring larger number of externally controllable degrees of freedom.

B. The Utah/MIT Hand

Developed by the Center for Engineering Design at the University of Utah, and the Artificial Intelligence Laboratory at the MIT, this robotic end effector was intended to function as a general purpose research tool for the study of machine dexterity [9]. Originally intended to resemble a human hand, the final configuration of the Utah/MIT Dextrous Hand is a quasi-anthropomorphic hand with 3 fingers and 1 thumb. The reasons to resemble a human hand were in first place to have a test bed for control and sensing issues; secondly to allow a human researcher to compare operations of the robot hand with operations of his own l hand. Finally its anthropomorphic configuration suggested its use in a teleoperation system.

*Mechanical Struct*ure

The hand has 4 fingers. Each finger has four joints; the first joint connects the knuckle to the palm, and allows the rotation of the finger around an axis perpendicular to the palm. The other three joints (distal joints) are also rotational and their axis are parallel to the palm and perpendicular to the finger as shown in Fig. 1.

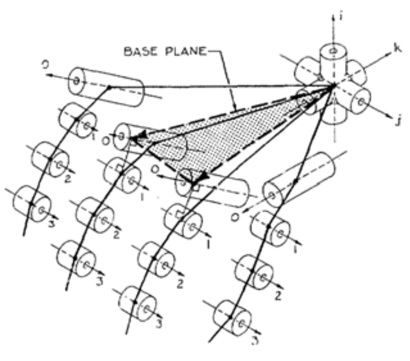

Fig. 1 Configuration of the Dextrous Hand (In the Version III hand, the 0 joints are parallel to the base plane) [9]

This robotic hand uses a tendon-pulley mechanism for the actuators to activate each of the 16 degrees of freedom. In this type of mechanism one end of the tendon is connected to a pneumatic actuator and the other end is fixed at a hinge which is located on the finger segment to be moved. To allow a reliable operation, the first two joints of each finger were separated in a way that the tendons could be routed properly.

The distal joints (1, 2 and 3) of the fingers and the thumb are capable of excursions ranging from 0 to 95 degrees while the proximal joint (0 joint) functions differently depending on whether it is the base for a thumb or a finger. In a finger, the proximal joint is capable of motions from -25 to +25 degrees, and in the thumb from -45 to +45 degreesThe wrist includes two perpendicular axes in a crossed yoke mechanism, permitting wrist flexion/extension in a range from -45 to +45 degrees and wrist abduction/adduction in a range from -15 to +15 degrees.

Wrist rotation around a third orthogonal axis in the range from -135 to +135 is made possible by the rotation of the remotizer compression rods. The remotizer is an element of the structure that carries tendons from the actuator package.

C. The Robonaut Hand

Designed by the Robotic Systems Technology Branch at the NASA Johnson Space Center to reproduce the size, kinematics and strength of the space suited astronaut hand and wrist, the Robonaut Hand meets the requirements for EVA (Extra Vehicular Activity) use. Such operations could be of maintenance or construction, interacting with planned space station EVA crew interfaces and tools, with the objective of reduce the time astronauts should spend outside the relative safety of the space station [10].

The Robonaut Hand has an anthropomorphic configuration with 5 fingers and twelve degrees of freedom. The wrist has two DOF for a total of fourteen degrees of freedom. A forearm completes the structure, housing all fourteen motors, twelve circuit boards and the wiring of the hand and measures four inches diameter at the base and is approximately eight inches long.

The hand presents two subsets, a dexterous work set which is used for manipulation and a grasping set that allows the hand to maintain a stable grasp while maintaining or actuating a given object. The dexterous set consists of two three DOF fingers (medium and index) and a three DOF opposable thumb. The last two fingers (ring and pinkie) present only one DOF and with the palm conform the grasping set. All of the fingers are shocked mounted into the palm.

In order to match the size of an astronaut's gloved hand, the motors are mounted outside the hand, and mechanical power is transmitted through a flexible drive train. To avoid reliability problems associated with tendons when used in EVA space environment, the hand uses flex shafts to transmit power from the motors in the forearm to the fingers.

The rotary motion of the flex shafts is converted into linear motion in the hand using small modular leadscrew assemblies resulting in a compact drive train.

D. The Shadow Hand

Developed by the Shadow Robot Company, , the Shadow Dextrous Robot Hand, in Fig. 2, is an advanced humanoid robotic hand system available for purchase and regarded as the most advanced robot hand in the world at this days.

This hand reproduces closely the 24 degrees of freedom of the human hand and provides force output and movement sensitivity similar to that of its human counterpart. However, in terms of speed, the Shadow Hand has a general movement at approximately half the speed of a human hand.

The 24 degrees of freedom are distributed as follows: 4 DOF each for the first, middle and ring finger, 5 DOF for the little finger, 5 DOF for the thumb and 2 DOF for the wrist. Table I shows in detail the connection for each joint and the range of motion in degrees.

Fig. 2 The Shadow Dextrous Robot Hand [11]

The form factor of the Shadow Hand meets that of a typical human male. The overall weight including sensors, muscles and valve manifold is approximately 4 kg only, due to the materials used to build it. Steel is only used for the forearm bone while other materials as aluminum, polycarbonate, rubber, etc are used to built fingers, palm and base.

TABLE I
KINEMATIC STRUCTURE OF THE SHADOW HAND

Joint	Connects	Range
First, Middle, Ring finger		
1	Distal - Middle	-20 – +90
2	Middle - Proximal	0 – +90
3	Proximal - Knuckle	-20 – +90
4	Knuckle - Palm	-25 – +25
Little Finger		
1	Distal - Middle	-20 – +90
2	Middle - Proximal	0 – +90
3	Proximal - Knuckle	-20 – +90
4	Knuckle - Metacarpal	-25 – +25
5	Metacarpal - Palm	0 – +40
Thumb		
1	Distal - Middle	-20 – +90
2	Middle - Proximal 1	-40 – +40
3	Middle - Proximal 2	-15 – +15
4	Proximal - Palm 1	0 – +80
5	Proximal - Palm 2	-60 – +60
Wrist		
1	Palm - Wrist	-55 – +45
2	Wrist - Forearm	-30 – +10

E. Blackfingers

Blackfingers and Whitefingers, illustrated in Figs. 3 and 4, are part of the experience developed by the authors.

The first project was born at Politecnico di Milano in 2000 [12] while the second derived from the collaboration between Politecnico di Milano and the Intelligent Robotics Laboratory of the Portland State University Both artificial hands were designed on the basis of anatomical studies of the human limb.

Blackfingers has five fingers with 4 mechanical degrees of freedom (DOF) each. In particular the first phalanx is provided by a spherical joint wrapped by an elastic band that allows only two DOF. The joints between the first and the second phalanx and between the second and third phalanx are cylindrical, and they permit only the rotation respect the axial axis. All the joints have been made from Nyloil using a special cutting technique that replicates the natural shapes of the bone structures. Each finger is moved by the combined action of six tendons, actuated by a new version of McKibben pneumatic actuators.

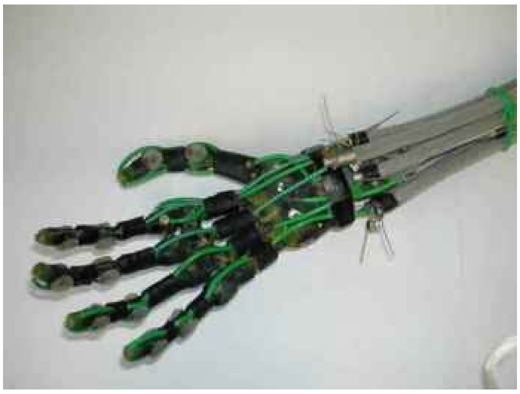

Fig. 3 Blackfingers

After the experience developed in the construction of Blackfinger, a new simplified version has been developed. All the pieces are obtained with laser cutting technology from a polycarbonate sheet.

Fig. 4 The Whitefingers hand of Politecnico di Milano

Open Science Index, Mechanical and Mechatronics Engineering Vol:1, No:2, 2007 publications.waset.org/9034.pdf

Open Science Index, Mechanical and Mechatronics Engineering Vol:1, No:2, 2007 publications.waset.org/9034.pdf

A characteristic of those hands is the controller, based on a dynamic neural net that simulates the motoneurons [13].

In this controller, there are 3 combined subsystems:

Reflex Circuits – to control the single joint position and stiffness.

Inverse Kinematics - to calculate the joints reference position receiving as input a specific object position in Cartesian coordinates.

Pattern Generator – to decide the trajectory in terms of instantaneous joint's position and stiffness.

III. Sensing Technologies and Actuator Systems

A. The Belgrade/USC Hand

Sensors

1. Position sensors indicate the rotation of the finger base with respect to the palm plane. These are small conductive plastic potentiometers compact (35x10x3mm), with good resolution (320 ohms/mm) and high life expectancy (of the order of one million cycles).

2. Touch-pressure sensors are force sensing resistor (FSR) located in the fingertips to detect contact with an object and the force being exerted in the range of 20 grams to 5 kg. These sensors can also report contact events when they sense a minimum normal force.

Actuators

Four DC torque motors are assigned as follows: one motor for the flexion of each pair of fingers, a third motor to produce the thumb flexion and a fourth motor for the thumb rotation. The characteristics of the first three motors are: 36 volts, 6 watts, 8810 rpm no load speed, 43 mNm stall torque and gear reduction ratio 30:1. The fourth motor has almost the same characteristics except for the reduction ratio of 102:1.

B. The Utah/MIT Hand

Sensors

Internal sensors are located at each joint to measure angular deflection and the sensor system is based on a Hall effect;a magnetically sensitive Hall effect device is located in the proximal link and two cobalt samarium magnets, operating in a dipole configuration, are attached to the distal link.

Other internal sensors used are included in each of the 32 tendon tension sensing systems located in the wrist. Since the pulley is positioned in a way that perturb the path of the tendon, tendon tension imposes a load on the cantilevered beam and a semiconductor strain gauge bridge detects beam strain providing a linear output for that tendon tension in a range from 0 to 30 pounds.

Actuators

Since each joint receives two tendons, the number of actuators required to drive them doubles the number of finger joints. The version III of the Utah/MIT hand uses a dual actuator module which consists of two pressure controlling valves, two actuator cylinders and two adjustable pneumatic dampers. Spring tensioning systems are also included to maintain tendon tensions when the system is unpressurized.

The cylinders for actuation and damping are made of glass and close fitting graphite pistons and the actuator modules are placed in a compact rectangular assembly of 4.25 x 4.25 x 24 inch and weights 20 pounds.

C. The Robonaut Hand

Sensors

In total, the hand has forty three sensors not including tactile sensing. Each joint is equipped with an embedded absolute position sensor.

Each motor is equipped with absolute encoders. Each of the leadscrew assemblies as well as the wrist ball joint links are instrumented as load cells to provide force feedback.

Actuators

The Robonaut hand uses fourteen brushless DC motors equipped with an encoder and a 14 to 1 planetary gear head. Coupled to the motors are stainless steel high flexibility flexshafts. The wrist is actuated in a differential manner through two linear actuators:

D. The Shadow Hand

Sensors

Position sensors, which sense the rotation of each joint of the Shadow Hand are Hall effect sensors with 0.2 degrees of resolution. A 12 bit ADC is used to sample data coming from the sensors and then transmitted on the CANBUS (Controller Area Network BUS), an interface between the hand system and the outside world.

Pressure sensors, mounted directly on the valve manifold, are solid-state pressure sensors that measure the pressure in each muscle with 12 bit of resolution in a range from 0 to 4 bar.

Actuators

Forty Shadow Air Muscles mounted on the forearm and coupled to the joints by tendons. are used to drive the Shadow Hand. The pneumatic valves for each muscle are driven by integrated electronics at the base of the hand, managing also the corresponding muscle pressure sensors.

Each Muscle behaves in a way similar to a biological muscle, contracting by up to 40% of its original length when actuated with compressed air, and providing a force that decreases with the increasing of the percent of contraction.

E. Blackfingers

Sensors

Position and force sensorS are directly installed into the McKibben actuator, developed in house, together with micro-valves. Each actuator weights less than 25g.

Actuators

As illustrated before, also Blackfingers uses McKibben pneumatic actuators. Since a muscle can only contract, two of them are needed to move a joint in either directions.

Open Science Index, Mechanical and Mechatronics Engineering Vol:1, No:2, 2007 publications.waset.org/9034.pdf

IV. Considerations about Achieved Tasks and Next Steps

It is clear that most or all of the research already carried on to develop a robotic hand, including projects not presented in this paper, involves one common purpose, i.e. the study of control techniques on dexterous manipulation.

One of the firstly arising problems is that the mechanical configuration by itself penalizes the achievement of a good final design since it's harder for a non anthropomorphic robotic hand to manipulate with dexterity objects which have been designed to be manipulated by a human hand.

The reduction of the controlled DOF in order to reduce the number of actuators and sensors may lead to a complex mechanism as seen in the Belgrade/USC Hand, but is an approach that can be partially reused in a design process depending on the task. The Robonaut Hand proposes an interesting division of the hand into two sets, one for manipulation and a second for maintaining a stable grasp. From the Utah/MIT Hand we've learned that it is better to have a thumb designed differently from the other fingers and copying that of a human being.

Even if cables proved to provide more dexterity and the possibility to have more powerful actuators placed out of the hand, there are still limitations in reliability and the speed reaches just half of that of a human, as seen in the Shadow Hand.

Some other considerations can be made from these and other projects carried out ([14]-[19]), but there is one we consider should be at the top of the list, reinventing the design process. In near future robotic hands will be used in a lot of different tasks, and so produced as cars or mp3 players are produced nowadays. Therefore, starting from the fact that certain tasks are completely different from others, whereas for the precision needed, complexity of the manipulation, power required or number of degrees involved, etc. we consider that a novel task-based design process is required. A process that includes also the challenge of developing new actuators is small enough to be integrated in the hand thus avoiding bulky hardware (as in air muscles) to power them and powerful enough to perform the required task.

The significant developments on power computation and graphic rendering in personal computers in the past recent years, the growing interest and development on haptic systems, new developments on smart materials and other areas, have given us the tools to undertake the design process from a different point of view. The approach in such a new task-based design process would be as follows:

- First identify a subfamily of grasps corresponding to a certain type of activity requiring power or precision at different levels, for example in a domestic environment a hypothetic domestic humanoid robot would need to do some repetitive tasks using a few number of grasp configurations, and from this smaller group of grasps select for example the most common.
- High tech devices these days allow us to retrieve information about the hand motion, capturing fingers movement during an experimental test of the grasp previously selected. By processing this data is possible to get more specific information on the kinematics related to each single joint and link.
- This data can be used as the input for the control system of our till now inexistent robotic hand but at the same time the reference for the output, in other words, the robotic hand must replicate that movement. At this point we enter in the virtual world by using a virtual model of a human hand as an ideal configuration of robotic hand, and since we are in a virtual world, this is perfectly possible.
- By using the characteristics of the human hand such weight and form in the virtual model and assuming non-conventional actuators and sensors strategically located we proceed to develop a control architecture that will evolve with the evolving of our virtual robot hand.
- Due to the fact that no specific information is available for the single actuators and sensors, our model have some black boxes and thus, the use of traditional control techniques is not possible. Therefore, since we have only inputs and outputs with no mathematical description of the model, the only path is the use of neural networks to make the outputs to follow the inputs by a sequence of training sessions.
- The control system will give us information about the desired specifications of the actuators and sensors. The idea is to develop new actuators since we noticed it was a major problem in the design choices of the reviewed robot hands. New developments in technology (i.e. MEMS, EAP, etc.) can provide new sensors and actuators to complete the mechatronic design.
- Finally, with a virtual robotic hand completely defined, it is possible to proceed to the adjustment of the control system to achieve the other grasps of the subfamily selected in the first step.

The design of the control system with the use of not yet developed actuators is the most relevant part of the design process proposed, and is key to develop the robotic hand in a virtual environment without compromising the further development of a hardware prototype.

V. Experimental Setup for our Case Study

Following the design philosophy proposed in section IV, we have chosen a subfamily from the precision grasp family proposed in [4], corresponding to a grasp using 3 virtual fingers while manipulating a disk.

In order to capture the hand movement while performing this task we have used an optical human motion capture system consisting on 5 cameras with a precision of 0.3mm, work station, passive markers and software tools for data preprocessing. The five cameras were distributed strategically in a way that the sum of the fields of vision generated a work volume sufficient to contain the right hand of the human operator in every instant while he performed the task.

After a series of data acquisition sessions we concluded that the number of markers required to capture enough data for the motion to be represented in an accurate manner is 25. The distribution is shown in Fig. 5, with four markers for each and every finger including the thumb, one for the counter-palm and four for the reference system situated around the wrist.

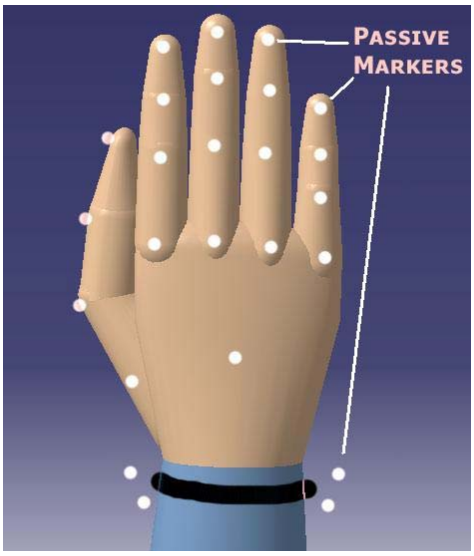

Fig. 5 Distribution of the passive markers

Once the hand of the human operator was properly prepared, he performed the task consisting in manipulating a disk to rotate it around its axis approximately 90 degrees, at a moderated speed. Fig. 6 illustrates the task.

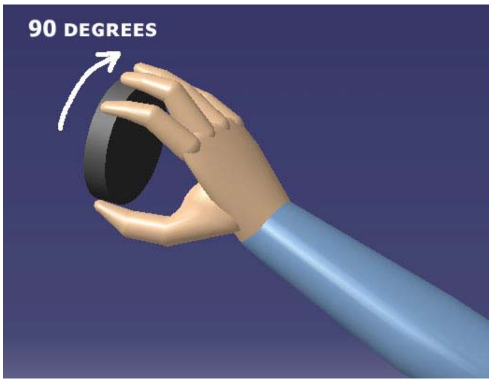

Fig. 6 Task: manipulate a disk using 3 virtual fingers

The final session consisted on the acquisition of 10 sets of data at a frequency of 60Hz. This data was preprocessed to reconstruct the motion of the real hand in the virtual environment. The use of an optical system presented a drawback, a loss of data due to occlusion, common to these systems. From the initial 10 sets of data, we managed to reconstruct the movement with 3 of them, but only one is necessary for post processing.

Further and ongoing work consist in the post process of the final data set in order to get a kinematical model of the robot hand with the minimum number of degrees of freedom necessary to perform such a task, DH parameters and design parameters for the actuators. Due to the compatibility of the preprocessed data with Matlab, we are using this tool for code generation.

REFERENCES

[1] G. Schlesinger: Der Mechanische Aufbau der Kunstlichen Glieder. In: M. Borchardt et al (Eds.), *Ersatzglieder und Arbeitshilfen fur Kriedgsbeschadigte und Unfallverletzte.* Berlin: Springer, 321-699. 1919.
[2] C. L. Taylor, and R. J. Schwarz, The anatomy and mechanics of the human hand, *Artificial Limbs*, 2: 22-35. 1955.
[3] J. R. Napier: The prehensile movements of the human hand, *Journal of Bone and Joint Surgery,* 38B (4): 902-913. 1956.
[4] M. R. Cutkosky, and P. K. Wright: Modeling manufacturing grips and correlations with the design of robotic hands, *Proceedings 1986 IEEE International Conference on Robotics and Automation,* San Francisco, CA, 1533-1539.
[5] G. A. Bekey, George, R. Tomovic, and I. Zeljkovic: Control Architecture for the Belgrade/USC Hand, *Dextrous Robot Hands.* S.T. Venkataraman and T. Iberall. Springer-Verlag, New York Inc, pp. 136-149, 1990.
[6] R. Tomovic, and G. Boni: An Adaptive Artificial Hand, IRE *Transactions on Automatic control,* AC-7: 3-10. 1962.
[7] R. Tomovic: Control of assistive systems by external reflex arcs, *Proceedings IFAC Conference on Bioengineering Control Systems,* Pergamon Press, 555-562. 1983.
[8] G.A. Bekey, and R. Tomovic: Robot control by reflex actions, *Proceedings 1986 IEEE International Conference on Robotics and Automation,* San Francisco, CA, 240-247. 1986.
[9] S. C. Jacobsen, E. K. Iversen, D. F. Knutti, R. T. Johnson, and K. B. Biggers, Design of the Utah/M.I.T. Dextrous Hand, *Proc. IEEE International Conference on Robotics and Automation,* pp. 1520-1532. 1986.
[10] C. S. Lovchik and M. A. Diftler: "The Robonaut hand: a dexterous robot hand for space", Robotics and Automation, 1999. *Proceedings.1999 IEEE International Conference on vol. 2,* pp. 907-912.
[11] http://www.shadowrobot.com/ 2007.
[12] M. Folgheraiter, G. Gini " Blackfingers: an artificial hand that copies human hand in structure, size, and function ", Proc. I*EEE Humanoids* 2000, MIT, Cambridge, Mass, September 2000.
[13] M. Folgheraiter, G. Gini "Human-like hierarchical reflex control for an artificial hand", Proc. *IEEE Humanoids* 2001, Tokyo, Japan, November 2001.
[14] M. T. Mason, and J. K. Salisbury: "Robot hands and the mechanics of manipulation", MIT Press, Cambridge, MA, USA. 1985.
[15] J. K. Salisbury, and J. J. Craig: "Articulated hands, force control and kinematic issues", Int. J. of Robotics Research, Vol. 1, No. 1. 1982.
[16] J. Hollerbach: "Robot hands and tactile sensing", AI in the 1980's and beyond, W.E.L. Grimson and R.S. Patil, eds., MIT Press, pp. 317-343. 1987.
[17] M. R. Cutkosky, and I. Kao: Computing and controlling the compliance of a robotic hand, *IEEE Trans. on Robotics and Automation*, vol. 5, no. 2, pp. 151-165. 1989.
[18] J. K. Salisbury, and B. Roth: "Kinematic and force analysis of articulated mechanical hands", J. Mech. Transm. Automat. in Des., Vol. 105.1983.
[19] J. Butterfass, M. Grebenstein, H. Liu, and G. Hirzinger: "DLR-Hand II: Next Generation of a Dextrous Robot Hand", Proceedings of the IEEE Int. Conference on Robotics and Automation, pp. 109-114. 2001.

Open Science Index, Mechanical and Mechatronics Engineering Vol:1, No:2, 2007 publications.waset.org/9034.pdf