Humanoids 2000

# Blackfingers: an Artificial Hand that Copies Human Hand in Structure, Size, and Functions.

Michele Folgheraiter, Giuseppina Gini
DEI, Politecnico di Milano,
piazza Leonardo. da Vinci 32, I-20133 Milano, Italy
gini@elet.polimi.it

**Abstract.** The construction of an artificial hand able to reproduce the functions of the human hand has never been of interest in industrial robotics. Now it is a must in humanoid robotics. In the paper we will illustrate the structure of the human hand and propose a choice of materials and actuators that can reproduce it. The design, the complete model and the prototype are also presented. The basic controller for the fingers is illustrated.

## 1 Introduction

We approach here the construction of an artificial hand made to resemble as much as possible the natural hand. To start we studied both the interesting area of artificial hand development in robotics and the human hand. In fact we easily recognized that the artificial hands do not reproduce exactly the anatomy and physiology of the natural one.
While the construction of gripping tools has a long history in robotics [2, 5], the construction of a hand similar to the human one has its roots in biomechanics, mainly in the prosthetic devices. So far, no construction of a hand totally identical to the human one in number and organization of joints, weight and dimensions, functionality, has been found.

However useful ideas are present in the most advanced multi-fingers hands so far implemented. Mechanical hands with at least 3 fingers offer useful solutions.

We shortly cite a few of the most relevant models [4, 6, 7], including 3 finger hands and other non-anthropomorphic hands because of their role in solving some of the open issues in mechanics, materials, actuators, sensors or control.

- *TheJPL-Stanford hand*, with 3 finger and 9 joints, has developed an interesting actuator system based on pneumatics.
- The *Belgrade/USC hand*, [Ward] with 5 fingers, a single electric actuator, a control able to move all the fingers to the same position, has demonstrated a simple control system.
- The *Utah/MIT hand*, with 4 fingers and 4 d.o.f. each, the wrist with 3 dof, a transmission made with tendons, a pneumatic actuation, is one of the most advanced and well studied. It has also rich sensing system, with position sensing on the joints, tactile and tension transducers. Also interesting is the control system, because it is able to accomplish tasks through trajectory planning and the integration with vision.
- *DLR hand*, from the German aerospace centre, has the actuators in the palm. The 12 actuators arranged in the palm move the 16 joints of the hand.
- The *Omni hand*, from NASA, is far from a human hand but is innovative in its design that requires no transmission.
- The *Rovetta hand*, from Politecnico di Milano, has only 3 fingers and is teleoperated by a user with a glove; the glove provides also the force feedback to the hand of the user.
- The *Cranfield hand* duplicates exactly the 4fingers and thumb of the human hand;
- The *Grasper hand*, with 3 fingers and 9 d.o.f., has only 3 actuators and the joints are actuated in sequence.

The strong point we want to make is that it is possible to extend some of the studies done so far and to develop a new hand, which replicates the human hand in size, organization of d.o.f., and control.

In this paper we develop both the model and the construction of the prototype; the controller is still under experiments.

The first step of our design is a good understanding of the human hand, because we want to obtain all the flexibility of it, and now no artificial complete solutions do exist. The mechanical problem of packing all the hardware for actuators and sensors in a small enough space to fit in a forearm linkage, and the routing of tendons through the palm and the wrist have found a solution in our design.

In our opinion the lack of flexibility in artificial hands also derives from the reduced sensing available. It is important to study the natural sensing of the hand, which presents different characteristics from the sensing systems developed in manipulator control. Unfortunately sensors used in industrial robotics are hardly adaptable to the characteristics needed in our design

Also the current models for grasping are inadequate for controlling a natural hand, that in nature is controlled by a two levels systems, one acting locally the other through the encephalon.

The paper is so organized.

Section 2 illustrates the basic of anatomy and physiology of the human hand.

Section 3 approaches the construction of the artificial hand starting from the skeleton (bones and joints), then discussing ligaments and tendons.

The actuation solutions illustrated in Section 4 are an implementation of the biological study.

Section 5 discusses the sensing system of the human hand.

Section 6 develops the control system based on the miotatic reflex.

Section 7 presents the global prototype hand, the construction and the first experiments.

Finally conclusions are drawn.

In the Appendices A and B we see pictures of the prototype and its 3D model.

## 2 Structure of the natural hand

The human hand [1, 3] is the system we need to study to develop a flexible robot grasping system. Three areas are of interest and will be shortly presented:

1. osteological, to study the skeleton;
2. ortological, to study the articulations and the ligaments..
3. miofunctional, to study tendons, muscles, and overall functionality.

The main *bones* of the hand, illustrated in Fig. 2. 1, are divided into 3 parts: finger, metacarpal, and carpal. From the fingertip we find the distal phalanx, second phalanx, and first phalanx.

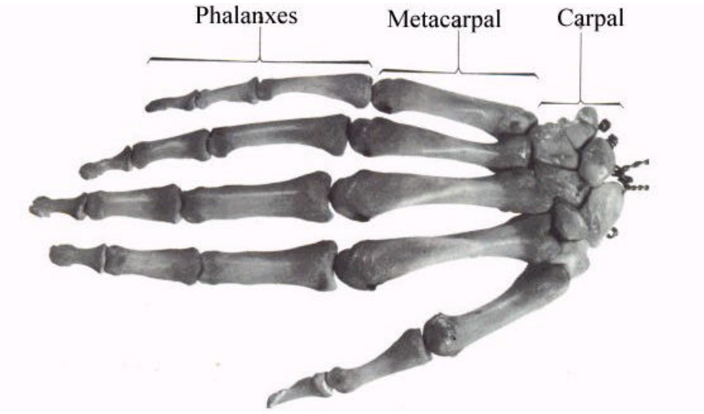

**Fig. 2. 1**. The bones of the hand are organized into three parts.

The first phalanx is connected to the metacarpal bone.

The fingers are all equal but the thumb, which has only two phalanxes. The metacarpal bones constitute the palm and are connected to the carpal bones. The movements of the carpal bones allow the hand to rotate with respect to the arm. Metacarpal bones present an asymmetry, with a semi-spherical surface to connect to carpal bones, but a spherical surface to connect with the first phalanx.

The *joints* on the hand are named: dip (distal interphalangeal) joint, first joint, metacarpophalangeal (MP) joint Each joint is characterized by the geometry of the contacting surfaces and by a maximum angle.

The movements of the hand are of different kinds: each finger can move in the hand plane (adduction) to go closer to the medial axis, can move far from the axis (abduction), can flex and extend. The thumb is also able to move in opposition with other fingers.

*Ligaments* in the palm connect metacarpal and carpal bones. They can block some movements of the metacarpal bones to give a more rigid structure to the palm Phalanxes are connected by reduced connection ligaments.

*Tendons* connect muscles and bones. They are internally made of collagen and are elastic, so they are able to put back the fingers in the original position after a flexion. They are attached in different ways to the muscle and to the bone. Flexor superficial tendons start from muscles in the forearm: from the first layer start the tendons to the medium and the ring finger, from the second layer tendons for index and little finger. The tendons after the connection to the first phalanx divide into two and are attached to the two sides of the second phalanx. They move in sequence the second phalanx then the distal. Deep tendons also originate from the forearm, divide in four and are attached to the distal phalanxes. They flex the distal phalanx after the superficial tendon has closed the two first ones. The thumb has only one flexor. Extensor tendons start from a muscle in the upper part of the forearm, and divide into 3 to go to the index, medium, and ring finger. The little finger is connected to ring finger.

Human *muscles* can apply forces by contracting. Two sets of muscles act on the hand: extrinsic, which are located in the forearm, and intrinsic, which are less powerful and located in the hand. Intrinsic muscles are responsible for most of the dexterity and flexibility of the hand.

The tendon is held closed to the intermediate bones by sheaths, which maintain the position of the tendon relative to the phalanxes, and thus to the line of action of the finger. The sheaths are responsible for the smooth action of the tendon.

Flexors are used to close the fingers to grip objects, while extensors are used to open the hand again. A flexor tendon acts through sheaths and across joints to move the three phalanxes.

An intrinsic muscle attached to the first phalanx acts as a metacarpophalangeal joint flexor and an interphalangeal joint extensor. The thumb is moved by 8 muscles acting across the joint at its base (the carpometacarpal thumb joint). Four are extrinsic and individually act on the joint by means of long tendons that cross the wrist before reaching the thumb. Four are intrinsic, and six of the muscles act on the distal joint of the thumb.

A flexor tendon connects the distal phalanx (the last bone at the tip of the finger) to a muscle, and it transmits the force produced by the muscle.

The surfaces of joints and sheaths that surround tendons have very low friction coefficients. At each point where the tendon crosses a joint space, it acts as a moment couple tending to flex that joint. At every joint traversed by a tendon, changes in the joint position use part of the potential excursion of the muscle. If a muscle acts across many joints, it must have a large capability of movements, The human is optimal for strength in flexion, not extension. Consequently, it contains more flexors that extensors. Extensors and their tendons are more compact and less powerful than flexors

## 3 Structure of the artificial hand

A robot hand is usually constructed with steel, which is a though and cheap material. Lighter and softer materials are necessary for the anthropomorphic hand.

Material chosen for the *bones* is oil charge nylon (Nyloil), which is stable, undeformable, and has low friction. From bars of 15-mm diameter all the bone pieces have been obtained.

The *joints* in the human hand are of two kinds: spherical or cylindrical (revolute joints with axes perpendicular to the link). The first is the kind of joints that connect metacarpi to the first phalanxes, and that provide in practice 2 d.o.f., with a limited range of values. All other joints are cylindrical.

In the Utah/MIT hand spherical joints have been obtained with two perpendicular cylindrical joints. This choice is mechanically good but far from the human hand.

In our hand all the joints have been obtained with a special cutting of the bone structure, which replicates the natural shapes of the contact parts.

The *ligaments* are obtained with elastic bands that connect joints allowing them a limited movement.

The *tendons* are obtained with iron cables covered with a 0.5 mm of Teflon. The metallic part has a plait structure to present low resistance to flexion and high resistance to extension. Tendons with a lubricant are inserted into a silicone sheath, and are attached to the bones through small screws. To make the tendons connected with bones, plastic bands have been applied.

In the following Fig. 3. 1. we see an artificial finger.

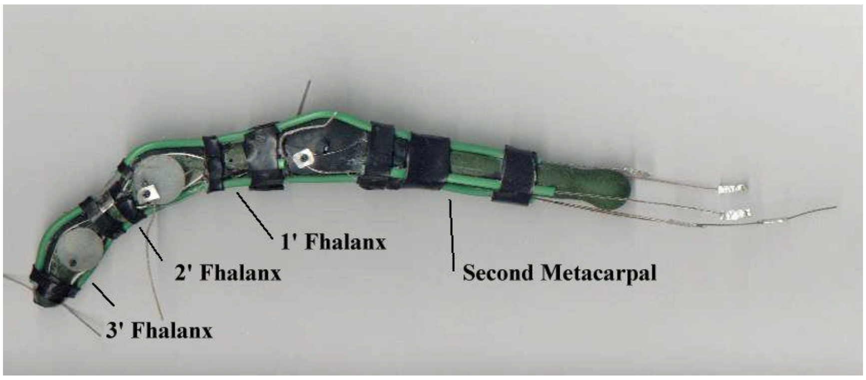

**Fig. 3. 1** – an artificial finger

## 4 Actuators for the artificial hand

The natural actuators are the muscles, whose structure is quite complex. Many fibres build them. We can model a muscle with two basic components acting in parallel: one is an elastic component, the other is a series of one elastic and one contractile component. The elastic component in parallel is due to the connective tissues around the fibres; the one in series is due to tendons.

With different loads the muscle shows an exponential growth in length. When the nervous system sends the contraction order, the contraction part starts shortening; the elastic part in series slowly elongates, so tendons are subject to a smooth increase in tension. When the contractile element returns to the initial position, the elastic part follows with a time delay. The speed of this phenomenon depends upon the forces to exert, in practice from the applied load. The speed is highest when the force is null (no load), is zero when the force is maximum. For the hand the muscles require 80 to 200 ms to complete a contraction at the maximum speed. The maximum load for a muscle varies from 2 to 5 Kg/cm2

To build artificial muscles with this kind of behaviour is very difficult. We have considered the classical pneumatic, hydraulic, electric actuators as well as the more modern NiTi fibres and fluid-pneumatics.

Tendons move in a linear way, so we need to produce a linear movement. We have so decided to use a hybrid actuation with cylinders both using air and liquid. The two actuators are used in integration: in the pneumatic cylinder it is easy to set the pressure but difficult to regulate the position of the cylinder. In hydraulic cylinders it is easy to fix the position, difficult to set pressure; the integration of both can offer a solution. The schema of the actuators is illustrated in Fig. 4. 1.

The extensor tendon is connected to the pneumatic single effect cylinder, the flexor tendon to the double effect cylinder, with one chamber filled with high pressure air and the other with low pressure oil. The high pressure of air is regulated by an electro-valve, especially designed.

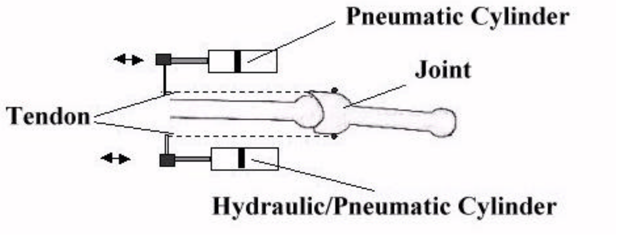

**Fig. 4. 1** - The actuator for a joint

To define how to attach tendons, the anatomic study has shown that 5 tendons act in the finger and lateral tendons are connected to the extensor. We reduced the number of the tendons to:

- two extensors connected to the upper side of the first and last phalanxes,
- two flexors connected to the bottom side of the same phalanxes,

- two other tendons connected to the side of the first phalanx, to make abduction and adduction possible, as shown in appendix B.

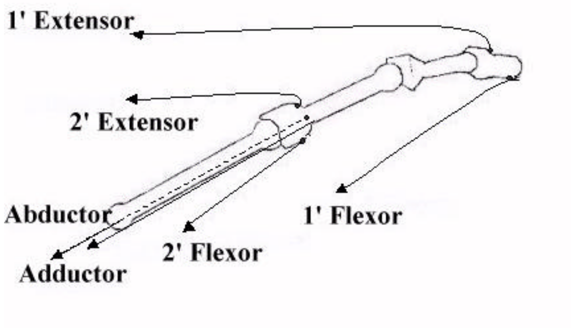

**Fig. 4.2**. – The artificial tendons

Tendons and positions where they are attached are illustrated in Fig. 4. 2. The lack of the tendon attached to the middle phalanx, differently from the natural hand, requires that the movements of the last phalanxes be done by the co-operation of all the tendons.

To find the right dimensions of the actuator system, we have considered the forces exerted by the human hand. Forces in flexion are from 20 to 40 Newton, in extension from 5 to 10 Newton. From the needed torques we have defined the dimensions for the cylinders and the pressure. The diameter of the cylinders is between 10 and 20 mm. A final view of the actuator system for one finger is illustrated in Appendix A. The general schema is in Fig. 4. 3.

Since we need 6 cylinders for each finger and 3 for the wrist, we need a total number of 31 cylinders and 70 electro-valves. Only one finger is at the moment totally actuated.

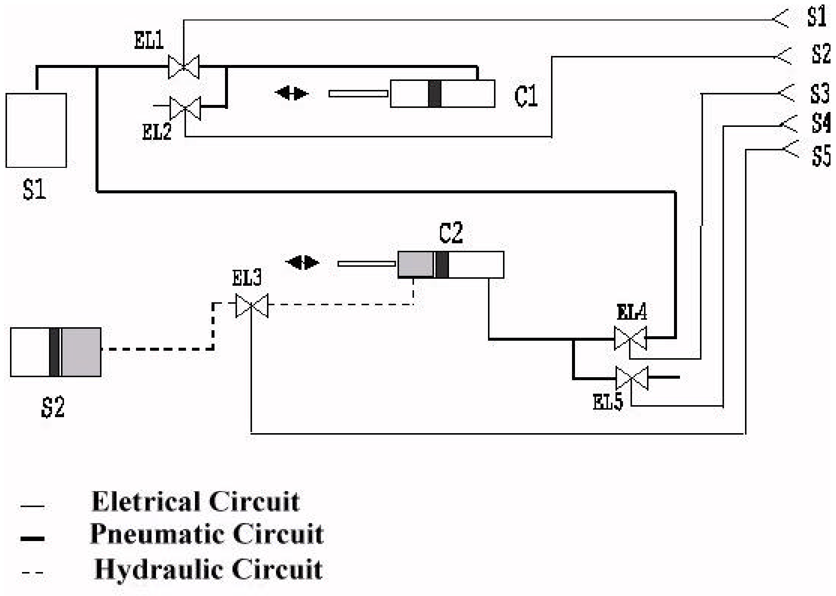

**Fig. 4. 3** –The schema of the actuation circuit.

## 5 Sensing for the hand

*Sensory receptors* in the hand are of different kinds.

Esteroceptors as well as proprioceptors are present in the hand. The *transducers* are mechanical, electrical, photo- and termo-electrical. A large number of receptors send continuously information about the strain of muscles and tendons. Most of the signals are not perceived but gives information for the movement of the fingers.

Receptors are organized in series and in parallel with muscle fibres, as illustrated in Fig. 5. 1.

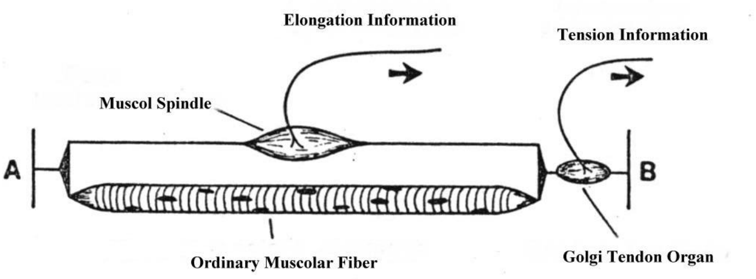

**Fig. 5. 1** – Sensing system for muscles and tendons: A muscle fibre with a Golgi organ in series and a fibre in parallel.

Golgi organs for instance are in series with the muscle fibber and are able to measure strain on tendons. Ruffini terminators, in the connective tissue of the articulations, are sensible to flexion or extension; many are present in the hand. Touch, heat, and pain signals are provided by many receptors in the skin.

In our prototype it was impossible to reproduce all the receptors. We decided to limit our sensors to the most important for basic control, as

- position of tendons
- strain on tendons
- contact with other objects

*Position* is measured by a micro-potentiometer, with 150 V of maximum voltage. The resistance is in the range 0 – 10 KΩ, and is linearly correlated to the cursor position. The sensor is installed in each cylinder.

Two sensors mimic the sensing system provided by the Golgi organs as in Fig. 5.1. To measure the *strain* on the tendon, we use two sensors: the first gives only the presence or not, the second gives a continuous value.

To get the binary output we use a micro-switch; to get the continuous value we use a piezoelectric transducer. Both of them are built with a micro-piston, acting in the first case on a micro-switch, in the second case on a piezoelectric transducer, as illustrated in Fig. 5.2.. All the sensors have been built ad hoc.

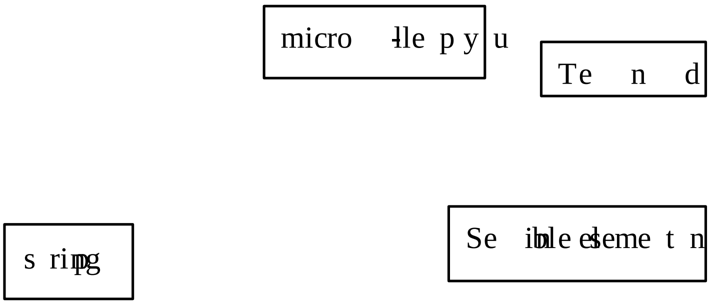

**Fig. 5. 2** – Structure of the strain sensors.

Contact sensors are still under study.

## 6 Control for the artificial hand

The first step in control design is usually the definition of the *cinematic model*. We made the same with the artificial hand and we built the matrices necessary to transform positions and orientations expressed in the reference systems of the wrist, of the first phalanx (considering null the movements of the metacarpal bones), and the second phalanx.

After that we found the relation between the position of a joint and the tendons strain. A generic joint has two tendons attached to both sides in given positions. The relation between the joint angle and the tendon position is computed from the geometry of the joint.

We need also to compute the position of the fingertip with respect to the last coordinate system. However the same tendons actuate the second and the distal phalanxes. So we have experimentally found this relation moving the artificial hand without finger contact, and saving many cases. We have been able to see how the two last phalanxes move with different tendons lengths; while the movement of the second phalanx is almost linear with the tendon length, the distal phalanx starts the movement after a while and rapidly goes to the final position.

In the human hand, the distal phalanx usually moves to adapt to the objects and a similar behaviour can be observed in our prototype.

The transformation matrices, the table for the distal phalanx movement, the geometric data, constitute the cinematic model.

Of course our cinematic model is too crude to build a traditional controller, also considering that the flexibility of the materials and the high number of joints complicate the dynamics of the hand.

In the human biological system the brain and the spinal cord compose the nervous system. As in all vertebrates, the motion control is distributed in many centres. A muscle receives nervous pulses from nervous fibres of the motoneurons. Pulses are regulated both by signals from peripheral receptors (reflex) and by the brain motor centres.

Reflex actions depend only on the spinal cord. The simplest biological control system is the reflex arc, which does not involve the encephalon activity, and which presents some basic characteristics as:

- reflex time – the time from the arrival of the stimulus to the receptor and the time when the answer appears. For simple reflexes this time is 0.5 to 1.5 ms.
- reflex area – the area where the receptors responsible for the reflex are located.
- reflex threshold – the minimum value of the stimulus to activate the reflex
- summation – more stimuli summate both in intensity and in space.
- reflex inhibition – some neurones are able to inhibit the reflex; for instance when flexing a finger, the extensors are inhibited.

According to the receptor involved, reflexes are esteroceptive as well as proprioceptive. The most important proprioceptive reflex is the miotatic reflex, which originates from the neuro-muscular fibres. This reflex is characterized by two phases; the first is a rapid contraction and is followed by a lower and longer contraction that stabilizes the muscle to a given length. The miotatic inverse reflex starts from the Golgi organs, go to the spinal centres, and inhibit the motoneurones of the given muscle that is relaxed back. This reflex aims at maintaining a safe strain on the tendons.

For the artificial hand we are interested only in the low-level control, because the high level will be approached when discussing about the brain. Our control system only provides the reflex arcs. The miotatic and inverse miotatic reflexes are also implemented.

All the low-level controllers are organised in a hierarchy: the high level controller is able to inhibit the reflexes, and the miotatic inverse reflex is able to inhibit the miotatic reflex.

## 7 Experiments

Together with the biological study a model of the hand has been produced, using 3D Studio. The obtained geometric model is illustrated in the Appendix B.

After this study we have built Blakfingers, a prototype of the hand. Here we see, in Fig. 7. 1, the particular shape of joints which reproduce the natural shape of the bones

Some pictures of the complete prototype and of the actuators are in Appendix A.

**Fig. 7. 1** – A cylindrical and a spherical joint of Blackfingers

.

To test the prototype we used a simple data acquisition board (PCL812). The control program, with the analogical inputs of the PCL 812, is able to acquire sensor data, to use them to calculate the correct control strategy, and to set the PCL812 digital outputs. The digital outputs activate the electrovalves, which are connected to pneumatics and hydraulic/pneumatics cylinders.

Until now the test program is able to control only one joint at a time, nevertheless this is enough to inspect the principal movement of an artificial finger: rotation of the first phalanx, flexion of the second and distal phalanxes, adduction and abduction of the first phalanx.

Whit some experiments we have verified that each artificial joint is able to reach every possible position like the biological equivalent.

A complete flexion of the finger needs about 700 ms at maximum speed and without load.

More experiments are needed to implement the actuation of all the other artificial fingers, and finally to test the prototype in more complex configurations, and to make grasping.

## 8 Conclusions

The study of the natural systems can offer interesting solutions to many robotics problems. However our objective has been more to reproduce the natural hand than to build some new robotic hand. Out from our imagination, we found that many natural solutions can be implemented, and we have built a first prototype.

In the next future we expect to continue on adding sensors to the hand. Our future development includes a possible cooperation with a medical school to study the use of the hand as a prosthesis, and the development of the controller for the full hand in the direction of autonomous robotics.

## Acknowledgments

We acknowledge the helpful cooperation of Fabrizio Bianchi, from Università degli Studi di Milano, Biology Department.

## References

1. Bairati A., Human Anatomy (in Italian),. Minerva Medica, Italy, (1980)..
2. Craig, J. J., Introduction to robotics, AddisonWesley (1986)
3. Field, D., Anatomy, palpation and surface markings, Butterworth Heinemann, (1987).
4. Mason, M. T., Salisbury, J. K., Robot hands and the mechanics of manipulation, MIT Press, (1985).
5. McKerrow, J. P., Introduction to robotics, Addison Wesley (1991).
6. Thompson, D. E., Biomechanics of the hand, Perspectives in Computing, 1, 3, (1981).
7. Ward D. K., Dunlop G. R. The kinematics of a fifteen dof six fingered hand, Ninth IFTOM (1995).
8. Williams, P. L., Warwik R., Anatomia del Gray (Italian edition) (1985).

## APPENDIX A: Photos of Blackfingers

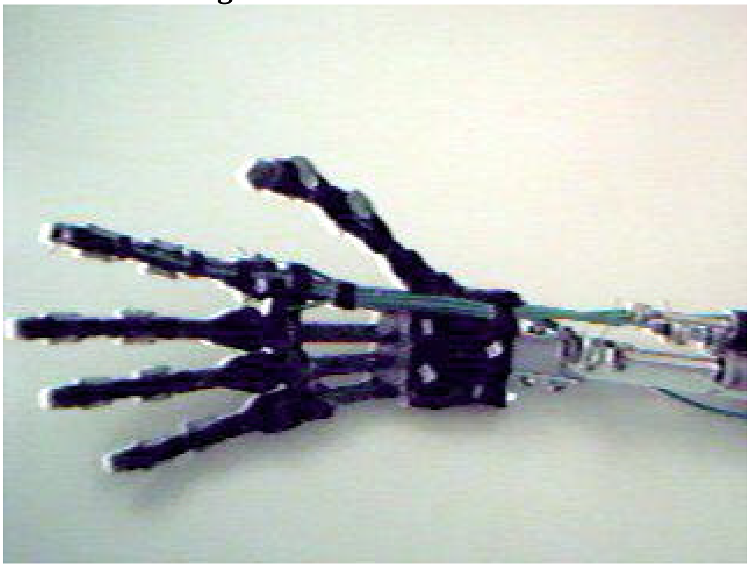

Fig A. 1 The Blackfingers hand

Fig A. 2 – The movement of the 3 phalanxes of the index;

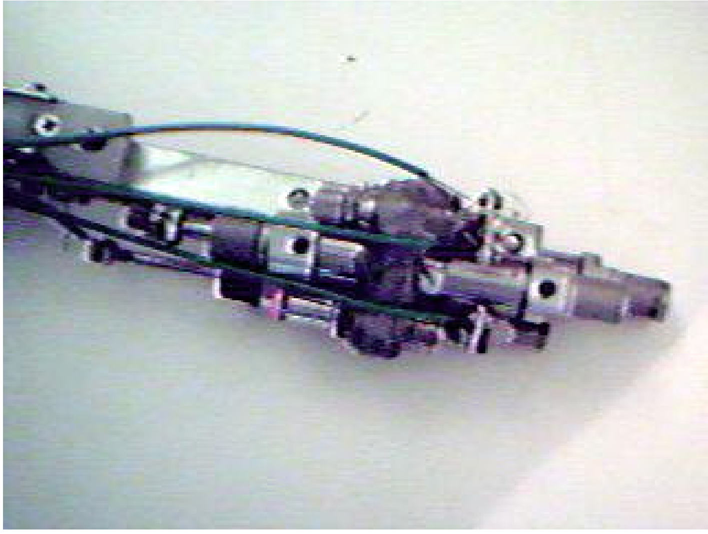

Fig. A. 3 – The actuators for one finger

## APPENDIX B – Blackfingers Models

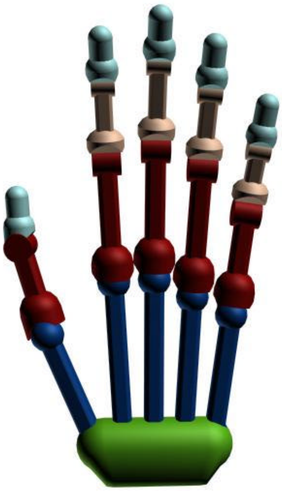

Fig B. 1. The Model of the hand

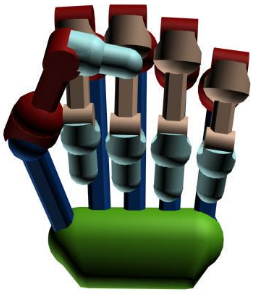

Fig. B. 2. – The model of the closed hand.

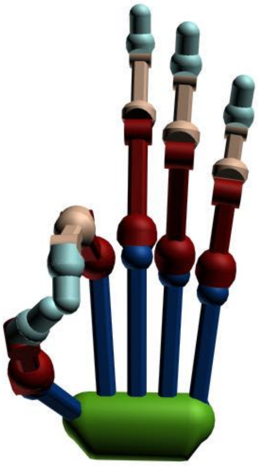

Fig. B. 3. – The movement of thumb and index in the model