The CyberHand: on the design of a cybernetic prosthetic hand intended to be interfaced to the peripheral nervous system

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***Abstract*— The objective of the project described in this paper is the development of a cybernetic prosthesis, replicating as much as possible the sensory-motor capabilities of the natural hand. The human hand is not only an effective tool but also an ideal instrument to acquire information from the external environment. The development of a truly human-like artificial hand is probably the most widely known paradigm of ”bionics”. The Cyberhand Project aims to obtain a cybernetic prosthetic hand interfaced to the peripheral nervous system. In particular this paper is focused on the hand mechanisms design and it presents preliminary results in developing the three fingered anthropomorphic hand prototype and its sensory system.**

I. INTRODUCTION

A prosthetic hand is composed of several modules: a biomechatronic device with its actuators, a transduction device to decode patient's intentions, a sensory system, a control system, and one or more batteries. The main characteristics of a typical (and largely used in clinical practice) prosthetic hand are: one or two Degrees of Freedom (DoFs), a maximum pinch force of about 100 N, and a weight of approximately 600 g. Although innovative prosthetic hands have been developed in the last 30 years (such as myoelectric prostheses), surveys on using such artificial hands reveal that 30 to 50% of the upper extremity amputees do not use their prosthetic hand regularly [1], [2]. The main factors that cause the loss of interest in myoelectric hand prostheses can be synthesised in three points [3]: low functionality, low cosmetics and poor controllability. Current prosthetic hands are just simple grippers with one or two DoFs [2], [4]–[6], and this affects the grasping movement that results unnatural. In fact, they do not allow adequate encirclement of objects, in comparison with the adaptability of the human hand, and the low compliance leads to instability of the grasped object in presence of external perturbations [7]. Moreover advanced prostheses have been developed but their control requires a considerable training and a great attention during grasping activities. Commercial prostheses [6] are equipped with a limited set of sensors, just a force sensor on the thumb and a simple strain-gauge on the transmission system used to regulate the grasping force and to protect the device against potentially dangerous situations. Consequently, feedback information to the user are poor or absent at all, besides direct visualisation and such subtle clues as the sound of the speed changes of the motor and transmission [8].

The use of neural interfaces may overcome some of the drawbacks of current prosthetic hands. The objective of the Cyberhand Project is the development of a cybernetic prosthesis, replicating as much as possible the sensory-motor capabilities of the natural hand [9]. The prosthesis must be felt by an amputee as the lost natural limb delivering her/him a natural sensory feedback by means of the stimulation of some specific afferent nerves. Moreover, it will be controlled in a very natural way by processing the efferent neural signals coming from the central nervous system (reducing the discomfort of the current electromyography-based control prosthesis).

In this paper some research efforts towards the realization of a cybernetic hand prosthesis are presented with specific focus on the biomechatronic design. In particular, the mechanical structure of the prosthesis and its sensory system are described in the following sections.

II. THREE FINGERED ANTHROPOMORPHIC HAND

A three fingered anthropomorphic powered hand is being developed in the framework of the Cyberhand project by the researchers at the INAIL RTR (”Rehabilitation Technology Research”) Centre promoted jointly by INAIL and by SSSA. The development of this new prosthetic hand is based on the RTR2 hand [10].

Starting from its dimensions and its sensory system [11], [12], a more functional and cosmetic hand is under development. The results of the cinematic and dynamic analyses, the design criteria and the first prototypes have been described in the following sections.

A. Cinematic and dynamic analysis

A 3D CAD model of the hand has been created using ProMechanica® Motion . This model is useful to evaluate the performance of every underactuated hand based on

RTR2 finger mechanism. It is the result of a design process that can be applied for developing a generic robotic or prosthetic hand with a cable actuation system.

The human hand geometric and kinematics characteristics have been studied [13] in order to develop a hand much closer to the anthropomorphic size and movements. In particular we focused on the thumb, index and middle finger sizes and joints range. We tried to replicate all the human hand data and we built the 3D CAD model considering each hand component as a rigid body with its inertial characteristics very close to the human hand ones. Each hand component has been assembled and the whole hand has been placed in the space trying to mimic the reaching of human hand to an object. The underactuated RTR2 finger mechanism is based on a single cable that wraps around free pulleys placed in each finger joint [10]. Unfortunately ProMechanica® Motion cannot simulate cables. This software is called being ”drivers and force based”. In other words the user can only impose a joint time law or a generalized force and then analyze the system dynamics. In this case we removed the cable and the pulleys and we substituted the cable with the tension applied to the joint axes. The tension cable follows the positions of the phalanges and has the direction of the pulleys tangents. We have supposed that this tension is constant along the cable. This hypothesis comes from the fact that we can neglect the friction between the cable and the pulleys being made of Teflon. So we have imposed a tension cable law vs time (linear for example) and we have evaluated the open direct kinematics and dynamics of each finger. The figure 1 shows the ProMechanica® model of the hand.

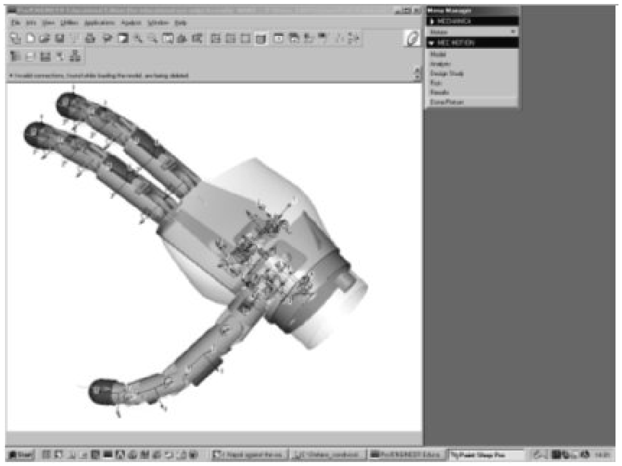
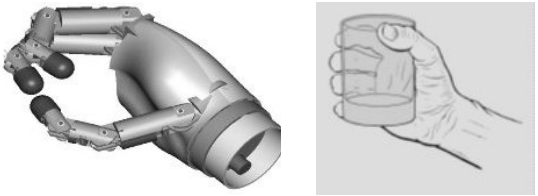


Fig. 1. Example of the 3D CAD model of the hand created using ProMechanica® Motion.

To evaluate the slope of this linear law, we run a static analysis imposing a tension and than evaluating the flexion of each finger. The iterations stopped when all the joints angles reproduced the total flexion of human finger. So we calculated the tension and, for a known closure time, the curve slope has been calculated. After that we evaluated the finger closure dynamics. The human tendon system has been replicated using the cable for flexion and a set of torsional springs placed in each joint for extension. The spring constant is an unknown variable of the problem and we evaluated it comparing the flexion kinematics of the artificial finger with the human one known from literature. From this analysis we found that in order to have an anthropomorphic finger movement the ratio between spring constant must be equal to the ratio of pulleys radius. This model is also useful for optimizing the thumb position in order to mimic the lateral and cylindrical posture of human hand.

In order to choose the proper electromagnetic motor of the actuation system we have also developed the 3D CAD model of the linear actuator. We have applied the same linear tension law to the slider of the actuator and we have imposed an acceleration law to the motor shaft. In this way we developed an open inverse kinematics and dynamic analysis and we calculated the torque law vs time needed to obtain the fingers dynamics evaluated before. This torque has been used in the elecromagnetic model of the motor choosen and we obtained the supply and current law vs time. These laws must be compatible with the performance of the chosen motor. If this is not the case we can modify the motor or change the hand dynamics (i.e. time closure). The model is also useful to evaluate the reaction forces of each component and so to dimension it properly also from a structural point of view.

The figures below show the four most important posture of the hand during the simulated grasps (see figures 2-5) compared to the analogous functional tasks of the human hand.

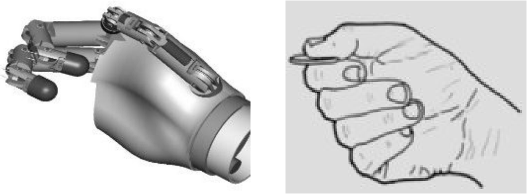


(a) (b)

Fig. 2. Example of the 3D CAD model (a) replicating the cylindrical palmar grasp of the human hand (b).

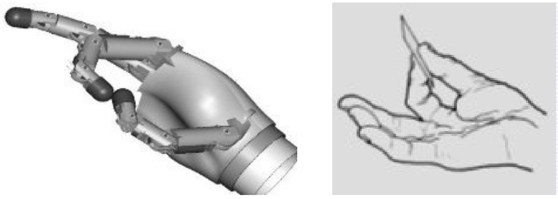
Among all the results available from this analysis, the joints axis positions vs time are of big interest for us. They can be compared with the human ones coming from experimental results and with the analytical model developed for the RTR2 Hand (see figures 6 and 7).

The model seems to be quite good and it can be considered a good tool in order to shorten the time of the prototype development. The analysis is made for a



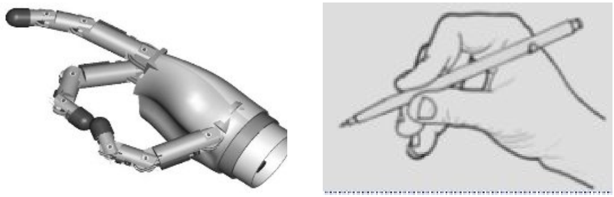
(a) (b)

Fig. 3. Example of the 3D CAD model (a) replicating the lateral grasp of the human hand (b).



(a) (b)

Fig. 4. Example of the 3D CAD model (a) replicating the prehension by subterminal opposition of the thumb and the index of the human hand (b).



(a) (b)

Fig. 5. The three fingers can be moved independently (figure (a) shows the middle opposing the thumb) in order to allow more complex grasping configurations like tridigital grip (b).

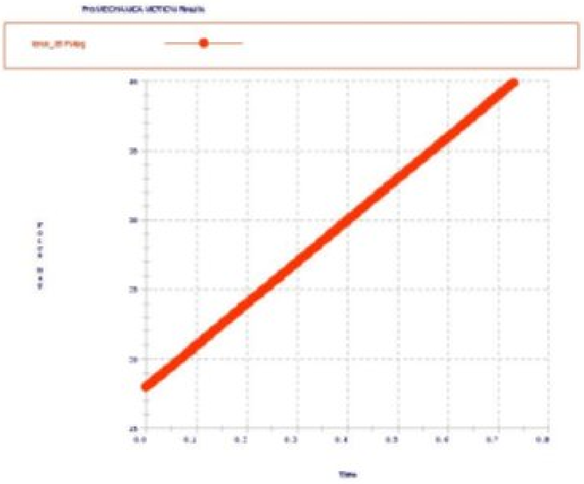


Fig. 6. Linear cable tension vs. time.

prosthetic hand with three fingers but can be extended to a 4 or 5 fingered hand without great problems. These hand dimensions are very close to the human ones but the model could be extended to a smaller hand (i.e. for a children) even if we think that could be a problem especially from a technological point of view. In fact the components used in this hand design are the minimum we have found.

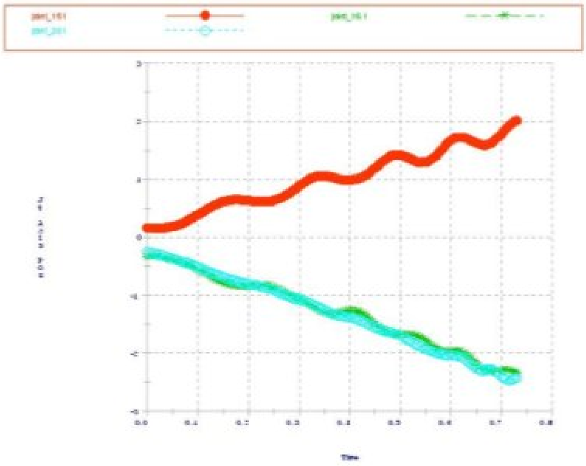


Fig. 7. Simulated axis positions of the three joints of one finger vs. time.

B. *Mechanical structure*

The three fingered RTR2 hand has been redesigned. Four DC motors will be used: three will control independently the flexion/extension movements of the three fingers and the last one will be used for the adduction/abduction movement of the thumb. The total number of degrees of freedom (DoFs) is 10 and the expected weight is 400 *gr*. In order to improve the hand grasp functionality and its anthropomorphisms, all the phalanges have a cylindrical shape without sharp edges. Their dimensions are much closer to the anthropomorphous ones and the proximal phalanges have a diameter of only 16 *mm*. Each finger is underactuated and the mechanism is the same of the RTR2. Its performance has been improved changing the thumb mechanism and position, and designing a new palm. The thumb has 3 phalanges and a trapezometacarpal (TM) joint with 2 DoFs placed at the base of the palm, near the wrist (see figure 8). The TM joint allows the movement of the thumb along the flexion plane in order to allow several grasping configuration.

The palm contains a passive mechanism which makes it compliant. It is composed of three parts:

1) An outside shell made of a soft volar side (silicon rubber) and a rigid dorsal side (carbon fibres);
2) An internal aluminum frame that holds the fingers, and contains the thumb ab/adduction transmission chain and the carpo-metacarpal joints of the passive ring and little fingers;
3) Two passive ring and little metacarpal ”bones”

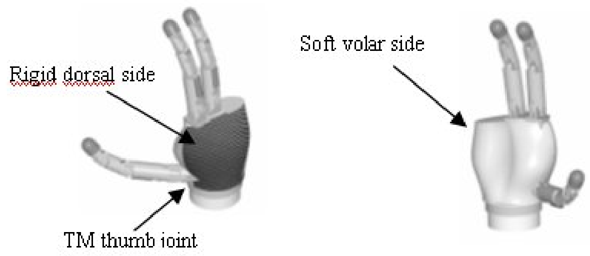


Fig. 8. The 3D CAD model of the cyberhand prosthetic hand showing the TM joint and double sides of the palm.

which hollows the palm improving the resulting grasp.

III. SENSORY SYSTEM

The Cyberhand prosthesis is intended to be controlled by an amputee in a very natural way, by processing the efferent neural signals coming from the CNS. Moreover, the prosthesis must be felt by the amputee as the lost natural limb since a natural sensory feedback must be delivered to him/her by means of the stimulation of some specific afferent nerves (i.e., the nerves which bring the sensory information to the central nervous system). This will re-create the ”life-like” perception of the natural hand thus increasing the acceptability of the artificial device. As a consequence, the artificial sensory system is the core of the Cyberhand control system and it should have a twofold function:

1) It should provide input signals for the low-level control loop of the grasping phase, thus enabling local and autonomous control of the grasp without requiring user’s attention and reaction to incipient slippage. The low-level control system should increase the grasping force as soon as incipient slippage occurs and the object is going to slip, and thus it should replicate natural user’s reaction without requiring his/her attention and specific effort. The regulation grasping force must be an unconscious process, since also humans don’t ”feel” muscles when they use them. The ideal control requires a simple starting command to perform a secure grasp, independently of the specific object characteristics in terms of shape, size and texture.
2) The artificial sensory system should generate sensory signals to be transmitted to the user through an appropriate neural interface (high-level control loop) and neural algorithms. It is clear that the Cyberhand prosthesis should be equipped with an artificial-sensory system specifically intended to transmit sensing signals to the neural interface: in this way it will be possible to restore the cognitive feedback, at least partially.

The sensory system will be developed following a biomimetic approach mimicking the natural proprioceptive and exteroceptive sensory systems

A. *Proprioceptive sensory system*

The biological motor control and the cognitive feedback for/from the hand requires proprioceptive information provided through the muscle spindle signals, the Golgi tendon organ signals and the joint angular sensors.

The proprioception on the cybernetic hand has been designed in order to provide the required information on all the phalanges of the hand. The solution consists of eight joint position sensors (Hall effect sensor based) embedded in all the joints of each finger, an incremental encoder on each motor, three tension sensors on the cables and an accelerometer inside the palm. This choice allows both reading the position of all the phalanges during the tasks of grasping and manipulation through the Hall effect sensors and controlling the hand acting on the motors by exploiting the reading from the encoders [14]. The joint position outputs return information on hand posture and on the approximate shape of the grasped objects.

As the Golgi tendon organs give information on the tendon stretches, three tensiometers measure the tension on the cables controlling the fingers flexion [11]. Finally, the contact of the hand and of the hand-held object with the environment is detected by means of an accelerometer integrated in the palm.

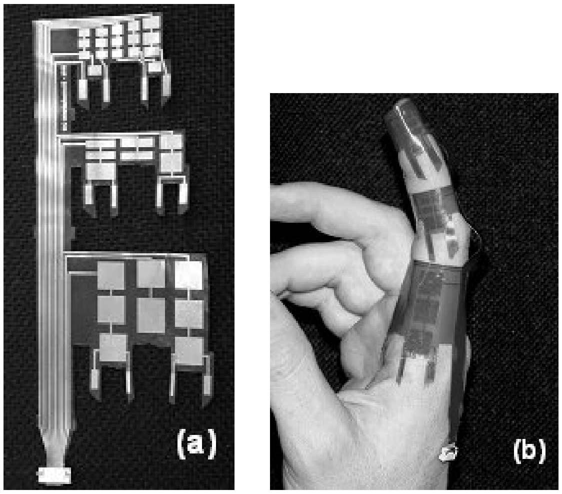
B. *Exteroceptive sensory system*

The main required output of the tactile sensory system is the force vector at contact point between the hand and the grasped object. The control system should extract from the sensory outputs the following information:

1) contact making and breaking between object and fingertips;
2) contact making and breaking between hand-held object and environment;
3) the slip friction between object and fingertips;
4) the local shape at contact points;
5) the overall object shape;
6) the force vector at the contact point (tangential and normal force components).

The exteroceptive information are essentially tactile information. The idea developed was to distribute tactile sensors over and inside the hand. It is obtained using two types of sensors, on-off touch sensors (for contact detection) and 3-component force sensors (for force vector measurement).

On-off touch sensors are thought to be placed on the internal and lateral face of the phalanges and on the palm of the hand in order to sense the contact with the whole hand and to have a perception of the contact area. More sensitive on-off touch sensors will be placed on the hand dorsum in order to detect accidental contact with the environment. As regards the sensor design, it was decided to incorporate the on-off sensors on a flexible matrix in order to allow a uniform and closed distribution of the sensors as well as an easier disposition of the sensors on the cylindrical shaped phalanges. The first prototype of the on-off touch sensor has been already designed, developed and preliminary tested (see figure 9). The threshold value of each sensor is $\sim 1\ N$, the dimension of the sensitive areas in the distal phalange is $\sim 3x2.5\ mm^2$ and the density of sensors in the distal phalange is $\sim 6\ sensors/cm^2$ ($\sim$ 40% of the contact area).



(a) (b)

Fig. 9. The prototype of the finger on-off touch sensor (a) and an example of its application on human finger (b).

The fabrication technology used is based on the standard photolithography process even if, in this case, the procedure has been applied to kapton (polyimide) sheets with copper cladding obtaining flexible electrical circuits. The sensor spatial distribution was intended to replicate the fovea where the sensor density decreases starting from the most receptive area (fingertip) to the periphery (other phalanges and palm). The matrix of on/off contact sensors has 44 sensitive areas for each finger (21 on the distal phalange, 11 on the intermediate phalange, 12 on the proximal phalange), 10 sensitive areas on the palm and 4 sensitive areas on the dorsum.

In the exteroceptive sensory system design, the three components force sensors are mounted on the fingertips for measuring the force vector at the contact point. Currently, two versions of the 3-component force sensor have been designed, in order to use initially the sensor that can be more rapidly realised and then replace it with the second more performing version.

The first version is a sensor based on a cross disposition of the strain-gauges and located at the base of the fingertip so as to make the whole fingertip a 3-component force sensor (see figure 10).

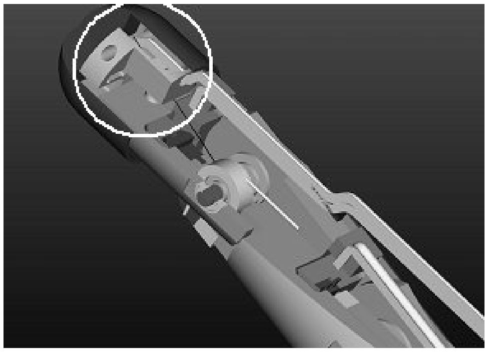
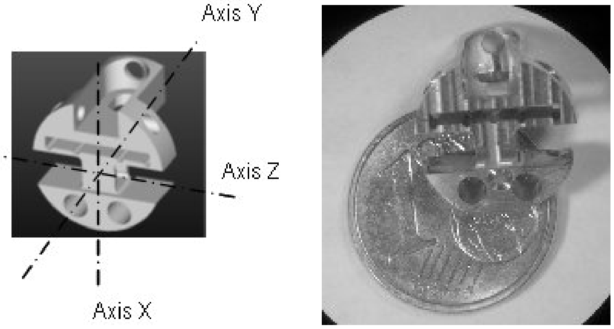


Fig. 10. The model of fingertip integrating strain-gauges sensors.

The sensor has been already fabricated at CRIM Lab (Scuola Superiore Sant'Anna, I) (see figure 11). Its expected sensitivity along the three axes is 1 mV/N and the expected resolution is $4,5\ mN$ along the X and Z axes, and 6 mN along the Y axis.



(a) (b)

Fig. 11. The model of the 3-component force sensor (a) and its prototype (b).

In the second version, the quantitative information (intensity and direction) about the force will be given by an array of three-component force silicon microsensors which are being developed at the CRIM Lab.

IV. SOCKET DESIGN

The problem to interface the patient's stump with the artificial hand creating a structure containing the actuators, the processing units, the energy supply and the telemetry systems, has been met acquiring the geometry of an existing prosthetic socket and by applying a process of reverse engineering. The virtual model has been created by means of a 3D laser scanning and then processed in order to build a modifiable solid model.

In this way, the actuator and transmission systems have been selected in order to be assembled inside the existing prosthetic socket (see figure 12). Three actuators, each of them for the flexion/extension of one finger, and their relative transmission systems have been integrated in the structure along with the electronic boards, the batteries and the telemetry unit.

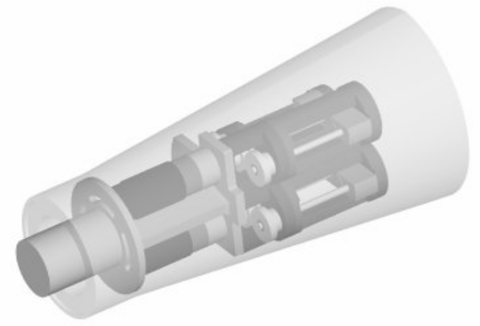


Fig. 12. The model of socket integrating three motors and the relative transmission systems.

V. CONCLUSIONS

In this paper, the design approach of the mechanical structure, of the sensory system and of the socket of a cybernetic prosthesis has been presented. The Cyberhand prosthetic hand is an evolution of the RTR2 hand. Some prototypes of the mechanical structure and of the sensory system components have been already developed. Their characterization and integration in the first hand prototype represent the ongoing activities

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