On the development of a cybernetic hand prosthesis

P. Dario*, M.C. Carrozza*†, A. Menciassi*, S. Micera*, M. Zecca*,
G. Cappiello†, F. Sebastiani†, and C. Freschi*

* Scuola Superiore Sant'Anna, Polo Sant'Anna Valdera
Viale Rinaldo Piaggio, 34 - 56025 Pontedera (PI), Italy
†Centro INAIL RTR, via della Vetraia, 7 - 55049 Viareggio (LU), Italy
Email: dario@mail-arts.sssup.it

Abstract

In a broad sense, the research on humanoids can be seen as efforts aiming at replicating the human being in his integrity or some of her/his main components. Thus, the development of a cybernetic prosthesis, replicating as much as possible the sensory-motor capabilities of the natural hand, can be seen as an important goal in this field.

This paper presents the current research efforts towards the development of this cybernetic hand prosthesis which will overcome some of the drawbacks of current prosthetic systems. This new prosthesis will 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 (thus reducing the discomfort of the current EMG-based control prostheses).

In particular, in this paper three main issues will be discussed: the design optimization of the existing developed mechatronic prostheses, the sensorization of the prosthetic hand, and its control.

1 Introduction

In a broad sense, the research on humanoids can be seen as efforts aiming at replicating the human being in his integrity or some of his main components. Thus, the development of a cybernetic prosthesis, mimiking as much as possible the sensory-motor capabilities of the natural hand, can be seen as an important achievement of humanoid robotic research.

The human hand is a marvellous example of how a complex mechanism can be implemented, capable of realizing very complex and useful tasks using a very effective combination of mechanisms, sensing, actuation and control functions [1,2]. The human hand is not only an effective tool but also an ideal instrument to acquire information from the external environment. Imitating the capabilities of the human manipulation systems has been for centuries the dream of scientists and engineers. In fact, developing a truly human-like artificial hand is probably one of the most widely known paradigm of "bionics".

Despite of several research efforts aimed at innovating artificial hands technology, surveys on user's satisfaction in using prosthetic hands revealed that 30 to 50% of the upper extremity amputees do not use their prosthetic hand regularly [3,4]. The main factors that cause the loss of interest for myoelectric hand prostheses can be synthesized in three points: low functionality; low cosmetic; and low controllability [5].

In this paper the research efforts towards the realization of a cybernetic hand prosthesis will be presented. In particular, the mechanical structure of the prosthesis, its sensorization and its control scheme, together with the first experimental results, will be described in the following sections.

2 Three fingered anthropomorphic hand

A three fingered anthropomorphic powered hand is being developed by the researchers at the INAIL RTR Center in the framework of the CYBERHAND project [6]. This hand will incorporate tactile and joint angle sensors developed at Scuola Superiore Sant'Anna. Four motors will be employed, one to operate the adduction/abduction of the thumb, and the others for the opening and closing of the three fingers. Emphasis is on developing a device that is light weight, reliable, cosmetic, energy efficient and highly functional and that will ultimately be commercially viable.

The development of this new hand is based on the RTR II hand [7], in which the solution proposed by Shigeo Hirose in the Soft Gripper [8] has been applied to the two fingers and the thumb.

Commercial hand prostheses have one or two degrees of freedom (DoFs) providing finger movements and thumb opposition. Due to the lack of DoFs, such devices are characterized by a low grasping functionality. In fact, they do not allow adequate encirclement of objects, in comparison with the adaptability of the human hand. As a result, objects must be grasped accurately to be held securely [9].

Underactuated mechanisms allow obtaining self-adaptive grasping capabilities, thanks to a large number of DoFs controlled with a limited number of actuators and differential mechanisms. This approach allows reproducing most of the grasping behaviors of the human hand without augmenting the mechanical and the control complexity. This feature is particularly important in prosthetic hands, when only few control signals are available from the EMG Control Interface, and therefore it is not possible for the amputee to control in a natural way more than two actuators [10].

The RTR II hand has three fingers, the middle, the index and the thumb, and nine DoFs in total, but only two motors: one for the flexion and extension movements of all the fingers and the thumb (power grasp) and one for the adduction and abduction movements of the thumb (precision grasp). Index and middle fingers are identical (both have three phalanges), while the thumb has two phalanges, as in the human hand (see Figure 1(a)).

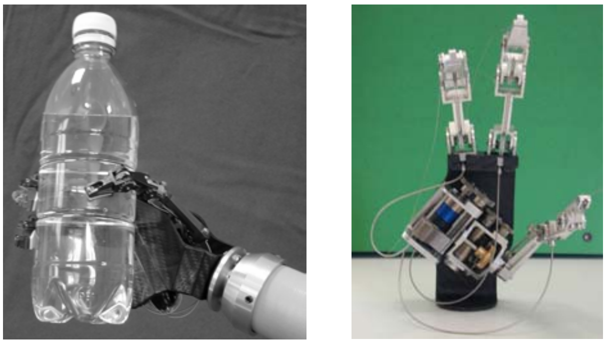
(a) (b)

Figure 1: The RTR II prosthetic hand (a) and the actuation and transmission system of the RTR II hand (b).

The hand is based on a tendon transmission system. The tension of the tendons generates a flexing torque around each joint, by means of small pulleys, and allows the flexion movement; this transmission structure acts in the same way as the *flexor digitorum profundus* [11]. The extension movement is realized by torsion springs. The adduction and abduction movements of the thumb are realized by means of a four bar link mechanism. Figure 1(b) shows the actuation and the transmission systems.

In order to perform an adaptive grasp between the fingers, an adaptive grasp system has been designed. The system is based on compression springs: both finger wires are connected to a linear slider, through two compression springs (see Figure 2). During a general grasp, index and middle fingers may not come in contact with the grasped object at the same time, one of the fingers and the thumb will come into contact first. When this occurs, in a conventional prosthesis, the other finger will no longer be able to reach the object to improve the grasp stability. Thank to the adoption of the compression springs this problem can be solved: when the first finger (e.g. middle finger) comes in contact with the object, the relative spring starts to compress, the slider is now free to continue its motion and the second finger (e.g. index finger) can flex, reaching the object.

When high forces are required, compression springs behave as a rigid link and all force is transmitted from the slider to the fingers; this is the main advantage of using compression springs instead of extension spring.

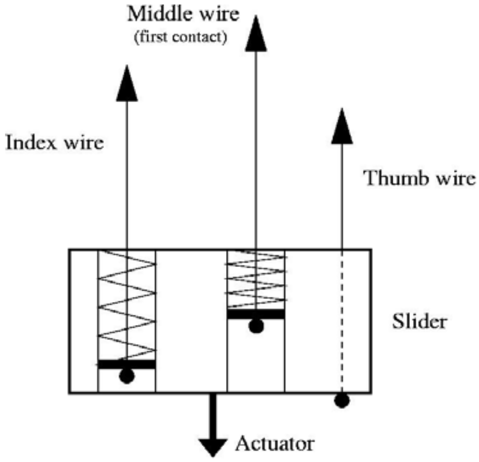

Figure 2: Adaptive grasp mechanism schematization

3 The artificial sensory system

The artificial sensory system is the core of the hand control system, and has a twofold function: first, it provides 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. Moreover, it generates sensory signals to be transmitted to the user through an appropriate neural interface. The aim of the sensory design is to integrate in the artificial hand a great number of different sensors in order to confer to the hand similar functionalities as of the human hand.

The hand sensory system is necessary to enable automatic control of grasping tasks without requiring special attention and efforts to the hand user. In addition the sensory system is studied to enable a first set of experiments intended to investigate the feasibility of providing the amputee with cognitive feedback about the grasping task that is performed.

For these reasons, according to a biomechatronic approach [5], the artificial sensory system is inspired at replicating the natural sensory system providing both proprioceptive and exteroceptive sensing abilities.

In particular, the current prototype is provided with position sensors for the thumb and for the slider that drives the three fingers, a tensiometer on the cable that drives the index finger, and a force sensor on the tip of the thumb. In the following subsections the sensory system will be described in details.

3.1 Proprioceptive position sensing: Slider position sensor

A qualitative measurement of phalanges positions is obtained by detecting the displacement of the slider where a Hall effect sensor (model SS496B, Honeywell Inc, Freeport, Il, USA) is mounted. This sensor detects the position of the slider along its stroke during the flexion/extension movements of the fingers, like the physiological angular sensors in the joint capsules [12].

The main problem encountered when developing this position sensor was to cover the entire slider's stroke (about 20 mm) which is large compared to the normal working range of Hall effect sensors; for this reason we have simulated and compared a number of different magnets configurations by means of the software Ansys® Multiphysics (ANSYS Inc. Corporate, Canonsburg, PA, USA). A specific optimal configuration has been experimentally found by using 12 Honeywell International Inc. 103MG5 magnets.

The Hall electrical tension generated in this configuration is able to cover the entire slider's stroke and its trend is monotonic and quite linear, as shown in Figure 3. A Matlab® (The MathWorks, Inc., Natick, MA, USA) model, described in [7], has been developed to correlate the slider position with the joints angles: through this model it is possible to estimate the joints position during an opening-closure motion.

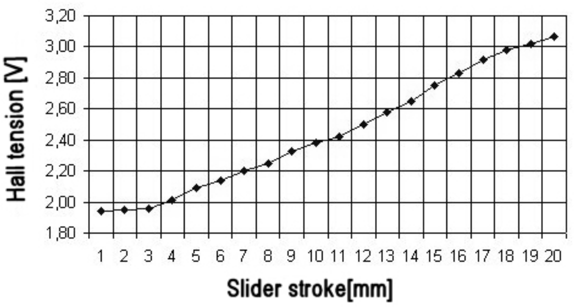

Figure 3: Hall tension versus linear slider's stroke. Hall tension trend is monotonic and quite linear over the entire slider's stroke.

The experimental analysis has assessed the simulation and the final calibration on board has provided good linearity and repeatability (enhanced by reducing the machining and assembling tolerances) [7].

3.2 Proprioceptive joint angular position sensing: Thumb position sensor

A round-shaped cap with two magnets has been assembled at the base of the thumb, at the center of rotation of the four bar link mechanism providing abduction/adduction capabilities to the thumb. A Hall effect sensor (model SS496B, Honeywell Inc, Freeport, Il, USA), located in front of the cap, measures the angle displacement of thumb metacarpus when performing the thumb adduction/abduction movements, thus behaving like the physiological angular joint sensors in the joint capsules [12].

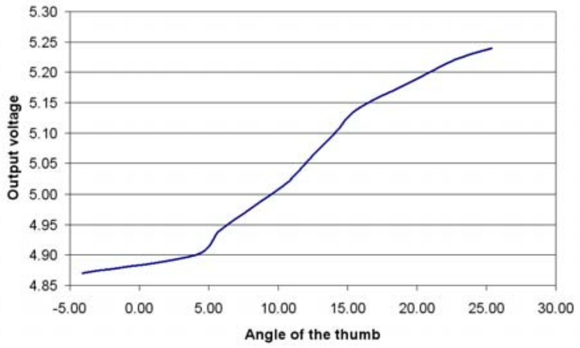

Figure 4: response of the thumb position sensor.

The sensor has an operative range of 30° and has shown good sensitivity, repeatability and linearity performance.

3.3 Proprioceptive tendon force sensing: Tendon tensiometer

In the RTR II hand, the transmission cables are fixed on one end to the index and middle distal phalanges and, on the other end, they are connected to the linear slider through the two compression springs of the differential mechanism. The cables act directly on two mobile elements, which compress the springs during the adaptive grasp of an object of irregular shape. The force sensor is obtained by sensorizing an elastic element acting as a mechanical stop for the cables.

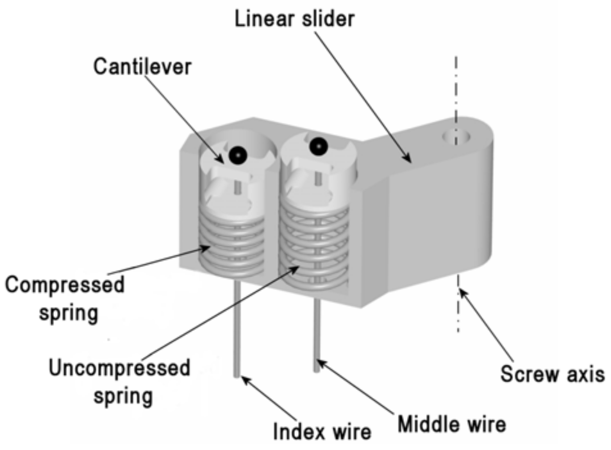

Figure 5: Cross section of the linear slider. The value of cable tension is estimated through the measurement of the elastic deformation of the cantilevers realized on the mobile elements.

The tendon tensiometer is based on strain gauges sensors (model ESU-025-1000, Entran Device Inc, Fairfield, NJ, USA). The micromechanical structure has been fabricated to obtain a deformable cantilever (Figure 5), in order to continuously monitor the cable tension applied by the motors, as the Golgi tendon organ in series with a muscle [12].

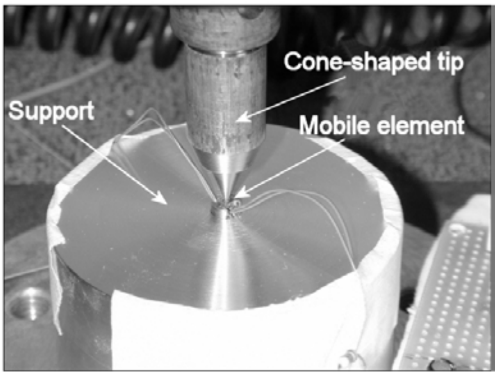

Figure 6: A cone-shaped tip applied the load deforming the cantilever realized on the mobile element (top).

The calibration has been performed with an INSTRONR4464 test machine (Instron Corporation, Canton, Massachusetts, USA) with a static load cell working in the range of ±1 KN. A cone-shaped tip, fixed to the load cell, has been used to apply the load, as shown in Figure 6. The strain gage sensors signal has been first amplified, then acquired through an acquisition board (National Instruments™ DAQ Card 1200), and finally processed by a custom LabVIEW™ interface to visualize in real time its output (Volts) versus the applied load (N).

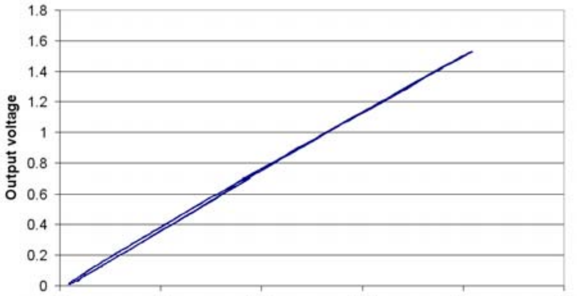

Figure 7: Output response of the tensiometer.

The sensing device has shown good dynamic, sensitivity and repeatability; a small hysteresis and time delay have been detected due to the differential mechanism of the hand (there is a spring under the strained component) [7].

3.4 Exteroceptive force sensing: thumb force sensor

An artificial mechanoreceptor is obtained by means of a FSR pressure sensor (part #400, Interlink Electronics, Camarillo, Ca, USA), 5 mm in diameter and 0.3 mm of nominal thickness, embedded at the thumb tip: the whole distal phalange, with the FSR at the volar side, has been immersed in a thumb shaped shell containing melted silicone. When the silicone polymerization has been over, a force sensitive thumb tip has been obtained. The force sensor has been applied only on the thumb tip that is significantly involved in all the functional grasping tasks [13].

The calibration has been performed with an INSTRONR4464 test machine (Instron Corporation, Canton, Massachusetts, USA) with a static load cell working in the range of ±1 KN. The hand was locked with the force sensor facing upwards, and a cylinder (5 mm in diameter), fixed to the load cell, has been used to apply the load.

Preliminary experiments have shown a low hysteresis, and high repeatability (Figure 8). The sensor gives information on the static pressure on a large area (more than 5 mm) and it has shown good dynamic characteristics. As a consequence, the developed force sensor could be likened to some features of the FA II and SA II physiological mechanoreceptors.

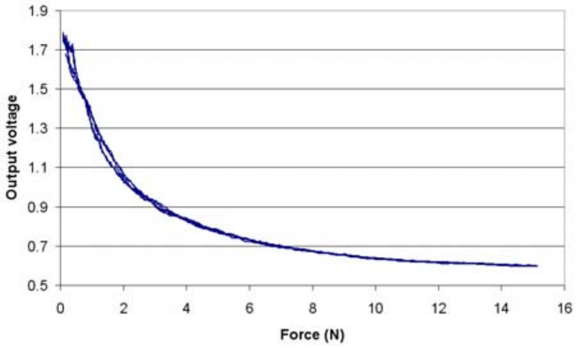

Figure 8: Output response of the thumb force sensor.

4 The control of the prosthesis

This research activity has three main objectives: (1) the development of the algorithms for the extraction of the information on the user's intentions by processing the natural efferent neural signals (this subsystem will be henceforth called "High Level Pattern Recognition Module (HLPRM)"; (2) the development of the algorithms for the closed-loop control of the artificial prosthesis according to the commands coming from the HLPRM and the sensory information obtained from the biomimetic sensors embedded in the prosthesis (this module will be henceforth called "Low Level Controller (LLC)"); (3) the development of a strategy for the stimulation of the afferent nerves in order to provide some sensory feedback to the user.

The development of the HLPRM is a typical pattern recognition problem. The HLPRM should be able to correctly identify what is the task t^* the user would like to perform among the different possible tasks. To achieve this result the HLPRM should be composed of the following subsystems:

[1] a system to increase the signal-to-noise ratio of the efferent neural signals recorded with the regeneration-type neural electrodes. It is worth noting that in this case we must consider “noise” not only the interference due to the thermal or electrical noise but also the presence of other neural signals which are not related to the task we would like to discriminate. For this reason the use of specific algorithms (such as “blind deconvolution” algorithms, principal component analysis, or cross-time-frequency representations) will be considered in order to decompose the neural signals “erasing” the noise components;

[2] a system for the extraction of different time and frequency parameters (“neural features”) from the neural signals. These features will be used for the pattern recognition;

[3] a system for the discrimination of the task desired. In this case, different architectures will be designed and tested. In particular the potentialities of the so-called soft-computing techniques (neural networks, fuzzy systems, genetic algorithms) will be analysed.

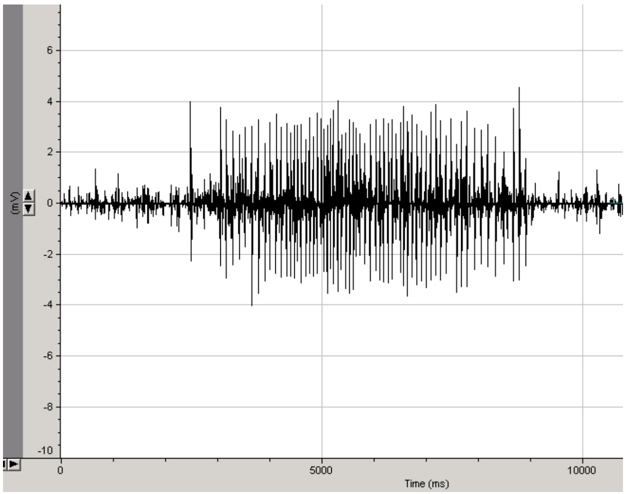

Figure 9: Example of neural signal used to test the HLPRM

Several different architectures based on statistical and soft-computing algorithms are under investigation [14,15]. These systems will be preliminary tested using some neural signals recorded using microneurography (see Figure 9).

The LLC will have to closed-loop control the actuation of the prosthesis according to the task t^* selected by the HLPRM (and the information from the sensors). Also in this case, several algorithms based on soft-computing techniques will be implemented. In preliminary experiments, the LLC was implemented as a Fuzzy Logic Controller (FLC) in order to drive the motions of the prosthetic hand according to the information extracted by the High Level Controller (HLC) in a closed-loop way. A FLC does not require an accurate model of the plant and this can be very useful in motor drive applications where the mechanical load could be non-linear or partially unknown or time-varying. In these preliminary experiments the HLC was simply a random function selecting among the different possible choices. If the command chosen by the HLC was "open the hand", the system read the present position of the hand and provided the necessary commands to the motor to reach the desired position (which was selected to be the maximum opening of the hand). If the command was "grip an object", the system acquired the force information of the hand by the communication with a microcontroller, using the parallel port, and provided the command to motors depending on the desired grip force. The hand was then closed until the contact was reached.

After this event, the thumb was stopped and the index and middle fingers were closed by the FLC commands until the difference between the actual and the desired force level was less than a tolerance threshold. The inputs to the FLC were the position error (or force depending on the implementing action) and the change in position error (force); and the output was the change in the motor voltage. The control increased or decreased the motor voltage according the position (force) error amplitude. The rule base implements a PI controller as described in [16].

The FLC was compared with a classical PID controller in the implementation of the different tasks (opening and closing the hand). The FLC outperformed the PID in both the tasks, obtaining rise times compatible with real-time applications.

Finally, in order to implement the sensory feedback the characterization of the afferent neural signals is under development [17].

5 Conclusions

In this paper, the development of a new prosthesis has been presented. This prosthesis, called RTR II hand, is based on underactuated mechanisms, which allow obtaining self-adaptive grasping capabilities without augmenting the mechanical and the control complexity, thus raising the prosthesis flexibility while maintaining the intrinsic actuation solution and implementing simple control algorithms.

This hand has also been provided with several proprioceptive and exteroceptive sensors, inspired by the analysis of natural sensors. In particular, both position sensors and force sensors have been realized and tested. The results of the first experiments with these sensors have been presented. These results are quite promising, both for the implementation of the low-level control loop of the grasping phase, and for the generation of sensory signals to be transmitted to the user through an appropriate neural interface.

Finally, the research activity for the realization of the control of the prosthesis (divided into High Level Pattern Recognition Module, Low Level Controller, and stimulation of the afferent nerves), together with the preliminary results, have been presented.

This system is the current base for the realization of a new prosthesis which could be felt by the amputee as the lost natural limb delivering her/him a natural sensory feedback (by means of the stimulation of some specific afferent nerves) and could be controlled in a very natural way by processing the efferent neural signals coming from the central nervous system (increasing the responsiveness and functionality of the current EMG-based control prosthesis) [6].

Acknowledgements

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