A "Wearable" Artificial Hand for Prosthetics and Humanoid Robotics Applications

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Abstract

An "ideal" artificial hand should match the requirements of prosthetics and humanoid robotics.
It can be *wearable* by the user which means that it can be perceived as part of the natural body and should replicate sensory-motor capabilities of the natural hand. However, such an ideal bionic prosthesis is still far from reality.
This paper describes the design and fabrication of a novel artificial hand based on a "biomechatronic" and cybernetic approach. Our approach is aimed at providing "natural" sensory-motor co-ordination, by integrating biomimetic mechanisms, force and position sensors, actuators and control, and by interfacing the hand with the peripheral nervous system.

Keywords
Artificial hand, Biomechatronics, Prosthetics

1. Introduction

The objective of the work described in this paper is to develop an artificial hand which can be used for functional substitution of the natural hand (prosthetics) and for humanoid robotics applications. The artificial hand is designed for replicating sensory-motor capabilities of human hand.

The work described in this paper is started from the analysis of state of the art artificial hands designed either for prosthetics or for robotics applications. Commercially available prosthetic devices, such as Otto Bock SensorHand™, as well as multifunctional hand designs [1,2,3,4,5,6,7] are far from providing the grasping capabilities of the human hand [8]. In prosthetic hands active bending is restricted to two or three joints, which are actuated by a single motor drive acting simultaneously on the metacarpo-phalangeal (MP) joints of the thumb, of the index and of the middle finger, while other joints can bend only passively. This limitation in dexterity is mainly due to the very basic requirement of limited size and weight necessary for prosthetic applications. On the other hand robotics hands have achieved high level performance in grasping and manipulation, but they make use of large controllers which are not applicable in prosthetics or humanoid robotics where it is necessary to provide the user with a *wearable* artificial hand.

In this paper we propose a novel design methodology, for design, development and fabrication of artificial hands, aimed at balancing the two opposite requirements of high dexterity and of natural size, weight and appearance. This process can be indicated with the word *biomechatronic* design, which indicates concurrent mechatronic design with a biomimetic approach, aimed at replicating as much as possible working principles and behavior of living systems.
Starting from the considerations outlined above, we can summarize the basic specifications of the *wearable* artificial hand described in this paper:

1. natural grasping capability;
2. natural appearance (in prosthetics this is called cosmetic appearance);
3. secure grasping and sensory feedback;
4. "natural" command interface.

The first and second requirements can be addressed by optimizing the actuator system of the artificial hand. The actuator system, the hand structure and the controller module have been conceived with a biomechatronic approach. This integrated design process carries to increase the number of active and passive DOFs, and to integrate them with an appropriate mechanism aimed at replicating the movement ability of the human hand. Furthermore, the cosmetic appearance of the natural skin has to be replicated by means of a sort artificial skin which should incorporate tactile microsensors. Anyway, at present the main problems of prosthetic hands in clinical practice are related to the size, and to the kinematic architecture which are not able to provide natural appearance and natural movements. For this reason we decided to address the problems of designing novel actuation system and mechanisms inspired to obtain a "natural" movement with human-like performance during grasping tasks. These choice is also motivated by the consideration that many amputees still prefer to use passive artificial hands with cosmetic gloves which provide a natural appearance with no functionality. A possible explanation of this choice is related to the poor functionality of commercially available prosthetic hands. Artificial skin is certainly the further step towards the development of a good artificial hand really "wearable" for amputees and also for humanoid robots.
This paper is focused on the actuation system, higher number of actuators has been incorporated in the hand structure and coupled joints have been designed in order to replicate natural grasping.
The third basic issue can be addressed by introducing appropriate tactile sensors aimed at mimicking natural

perception system thanks to the possibility offered by microengineering technology.
In order to achieve the very ambitious requirement of providing a natural command, we are pursuing the objective of studying innovative interface to control the artificial hand. The core of the problem is to establish an appropriate communication between the Peripheral Nervous System (PNS) and the artificial hand (i.e., a "natural" Neural Interface (NI)) to exchange "selected" information (record and stimulate the PNS in a selective way) aimed at providing feedback and motor-sensory coordination of the artificial hand. This can be achieved by stimulating in an appropriate way afferent nerves of the human (or robotic) being who is intended *wear and control* the artificial hand.
It is important to point out that this can be done only after characterization of the afferent signals of the PNS in response to mechanical and proprioceptive stimuli. The natural control scheme of *wearable* artificial hand is illustrated in Fig. 1.

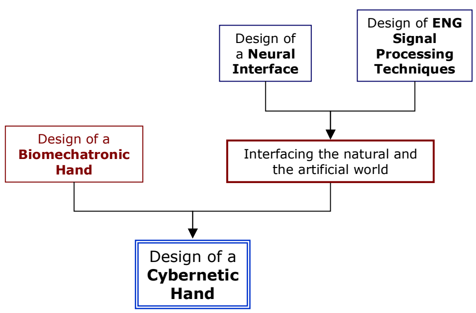


Fig. 1: The control scheme for wearable artificial hands

This paper is focused on the first and the second requirements, and we are interested in experimenting micro actuators to provide more dexterity and better mimicking of the natural appearance of artificial grasping. To address the third and fourth requirements, we developed microsensors (Hall-effect position sensors for active joints and strain gauges sensors) for force measurements and we are currently investigating a microfabricated Neural Interface for achieving a natural hand command. Both sensors and actuators have been integrated inside the structure of the prosthetic hand, keeping the natural size of the human hand.
Finally, the mechanisms of artificial joints have been designed in order to replicate the grasping trajectories typical of natural fingers after dedicated biomechanical analysis.
This paper also reports preliminary tests of a first prototype of the *wearable* artificial hand. .

2. DESIGN OF THE BIOMECHATRONIC HAND

2.1. Biomechatronic design

The main requirements to be considered since the very beginning of a artificial hand design are the following: natural appearance, controllability, noiselessness, lightness and low energy consumption. These requirements can be fulfilled by implementing an integrated design approach aimed at embedding different functions (mechanisms, actuation, sensing and control) within a housing closely replicating the shape, size and appearance of the human hand. This approach can be synthesized by the term: "*biomechatronic*" design [9].

2.2. Architecture of the biomechatronic hand

The biomechatronic hand will be equipped with three finger to provide a tripod grasp: two identical finger (index and middle finger) and the thumb (see Fig. 2).

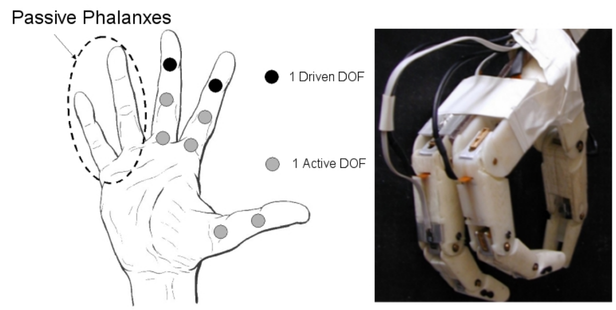


Fig. 2: Architecture of the biomechatronic hand

The finger actuator system is based on two micro-actuators, which drive the MP and the PIP joints respectively; for cosmetic reasons, both actuators are fully integrated in the hand structure: the first in the palm and the second within the proximal phalange. The DIP joint is passively driven by a four bars link connected to the PIP joint. The thumb actuator system is based on micro-actuators and is equipped with two active DOFs relative to the MP joint and the IP joint respectively.

The grasping task performed by the biomechatronic hand is divided in two subsequent phases:

1) reaching and shape-adapting phases;
2) grasping phase with thumb opposition.

In fact, in phase one the first actuator system allows the finger to adapt to the morphological characteristics of the grasped object. In phase two, the second actuator system allows the thumb opposition for the grasping task.

It is important to point out that the most critical problem of the proposed configuration is related to the torque required to micro-actuators to apply high load to the object during the grasping phase. The thumb actuator system is unable to provide a power opposition force, useful to manage critical grasps, especially in case of heavy or slippery objects.

2.3. The actuation system

The adoption of bulky and heavy actuators, in the design of commercial upper limb prosthesis, lead to an extreme reduction of DOFs. Consequently, a stable grasp can be achieved by means of high grip forces. This design technique can be represented as a loop (see Fig. 3).

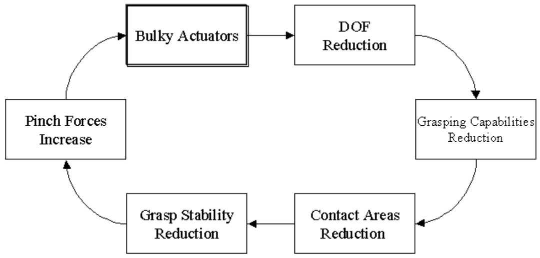


Fig. 3: Standard approach loop

The above schematization shows how this approach led to design hands with a maximum of two DOFs able to provide a pinch force of about 100 N.

The aim of he proposed approach (see Fig. 4) is to invert the previous one by using micro-actuators, focusing on the increase of DOFs.

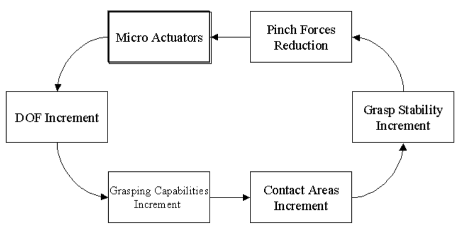


Fig. 4: Novel approach loop

Starting from this viewpoint we are developing an artificial hand actuated by micro-drives. Due to its enhanced mobility our hand will be able to increase the contact areas between phalanxes and grasped object. Following this basic idea we can accept a reduction in power actuation increasing contact areas in order to augment grip stability.

3. DESIGN OF THE HAND PROTOTYPE

In order to demonstrate the feasibility of the described biomechatronic approach, we have developed a three fingered hand prototype by developing two finger (index and middle) and the thumb. Actuators, position sensors and 2D force sensors have been integrated in the hand structure.

4. INDEX/MIDDLE FINGER DESIGN

The two prototypes have been designed by reproducing, as closely as possible, the size and kinematics of a human finger. They consist of three phalanxes and of palm housing, which is the part of the palm needed to house the proximal actuator (see Fig. 5).

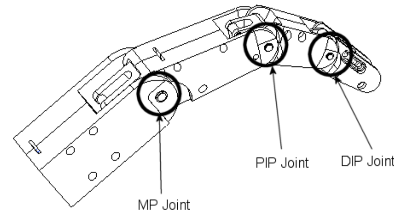


Fig. 5: Index/Middle finger

4.1. Actuator system architecture

In order to match the size of a human finger, two micro-motors have been integrated , respectively, within the palm and the proximal phalange.

The actuator system is based on Smoovy™ (RMB, Eckweg, CH) micro-drivers (5 mm diameter) high precision linear actuators based on DC brushless motors with planetary gears. The rotary motion of the shaft is converted to linear motion using lead screw transmission.

The main mechanical characteristics of the linear actuators are listed below (see Table 1).

Gear stages	3
Transmission rate	1:125
Maximum load radial	25 N
Maximum load axial	40 N
Maximum speed	200 mm/min
Nominal force	12 N
Weight	3.2 g

Table 1: Summary of the main characteristics of the Smoovy™ (RMB, Eckweg, CH) micro drivers (5 mm diameter).

The selected actuator fulfils almost all the specifications for application in the prosthetic finger: small size, low weight and high bandwidth. The main problem encountered is related to noise, which in present implementation turns out to be relatively high. Despite of this limitation, we decided to proceed with the application of the linear actuator in order to investigate integration problems and global performance. One possible solution for reducing noise caused by motors activation is to adjust the acoustical impedance of the motors housing and of the external palm/finger structure.

The output force resulting from motor activation is sufficient to move the phalanxes for achieving adaptive grasp. In addition, the shell housing provides mechanical resistance of the shaft to both axial and radial loads. This turns out to be essential during grasping tasks, where loads, derived from the thumb opposition, act on the whole finger structure.

4.2. *Kinematics architecture*

The kinematics of each finger joint is described in the following subsections.

4.2.1. MP Joint

The proximal actuator is integrated in the palm and transmits the movement through a slider-crank mechanism to the proximal phalange providing flexion/extension movement. The slider is driven by the lead screw transmission directly mounted on the motor shaft.

4.2.2. PIP joint

The same mechanism used for the MP moves the PIP joint. Only the geometrical features are varied in order to fit within the space available according to the specifications of the biomechatronic hand.
High friction forces occur, during the mechanism movement, because of low pitch of the threaded shafts. For this reason the two lead screw transmissions are non backdrivable; but this turns out to be useful for ensuring grasping forces maintenance without power supplying.

4.2.3. DIP joint

A four bars link has been adopted for the DIP joint and its geometrical features have been designed in order to reproduce as closely as possible natural DIP joint flexion. The mechanism has been synthesized according to the three prescribed positions method [10].

5. THUMB DESIGN

A thumb has been designed in order to complete the hand prototype and to perform grasping tasks with thumb opposition. The thumb has been designed by simply removing the distal phalanx from the index/middle finger (see Fig. 6)

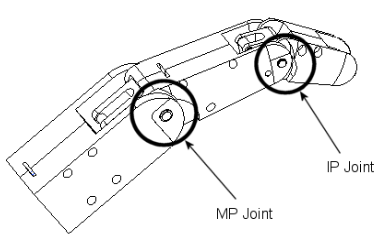


Fig. 6: Thumb

6. HAND ASSEMBLING AND FABRICATION

A first prototype of the hand has been developed incorporating two fingers and thumb. In fact, at least three hard-fingers (nonrolling, and nonsliding contact) are necessary to completely restrain an object [11].
The assembling process allows the hand prototype to perform two grasping tasks (see Fig. 7):

1. Cylindrical grasp
2. Tripod pinch grasp

The hand prototype has been fabricated using the Fused Deposition Modeling [FDM] process.

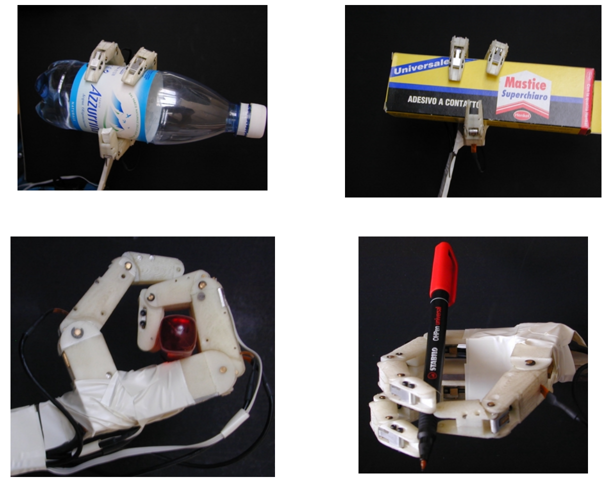


Fig. 7: Pictures of cylindrical and tripod grasps

7. FINGERTIP FORCE CHARACTERIZATION

A first set of experimental tests has been performed in order to evaluate the force that the index/middle finger is able to exert on an external object [12]. To this aim we have measured the force resulting when the finger is pressing directly on a force sensor (3-axial piezoelectric load cell 9251 A, Piezo-Instrumentation KISTLER, Kiwag, CH), corresponding to different configurations of the joints.
Two “pressing” tasks were identified in order to evaluate separately and independently force obtained by the two actuators incorporated in the finger:

- TASK 1: the pushing action was exerted only by the distal actuator.
- TASK 2: the pushing action was exerted only by the proximal actuator.

During the force characterization the fingertip pushed on the force sensor. The Z force component was recorded, the X and Y outputs of the load cell were monitored. This was obtained by adjusting the finger position for obtaining a force parallel to the Z-axis of the load cell. A first set of experimental tests was done on the finger prototype, with the aim of evaluating how much force the finger is able to apply on an object.

7.1. *Results and discussion*

Ten tests were performed for each subtask. The obtained results are illustrated in Fig. 8. These force values are comparable with force exerted by “natural” human finger during fine manipulation, thus demonstrating the feasibility of the biomechatronic approach, at least for this class of manipulation tasks. The output force resulting from motor activation is sufficient to move the phalanxes for achieving adaptive grasp [13].

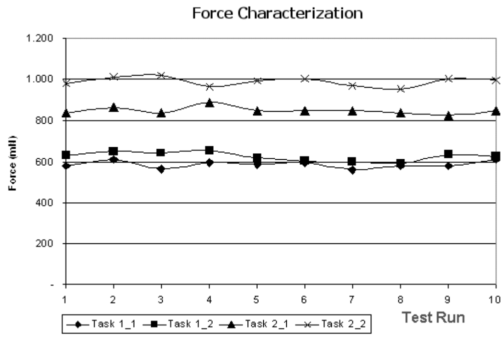


Fig. 8: Experimental results.

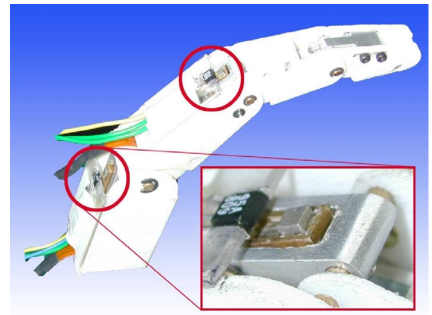


Fig. 10: The first prototype with the 2 integrated sensors.

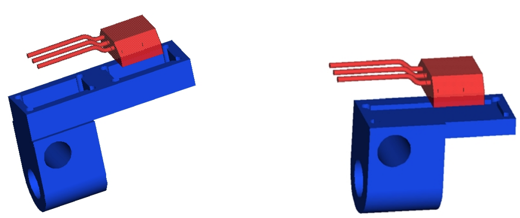
8. SENSORY FEEDBACK

In order to control the hand prototype a force/position feedback has been integrated within the device.

8.1. Position sensors

Six position sensors, based on Hall-effect sensors (SS495A, Honeywell, USA), has been integrated in the hand structure in order to measure the angular position of the six active joints. The main advantages of Hall-effect sensors are their small size and their contactless working principle, which allow us to avoid friction forces.

The sensors are fixed respectively to the palm and to the proximal phalanxes and the magnets are directly mounted on the sliders of the six joints (see Fig. 9).



(a) Slider for the MP joint. (b) Slider for the DIP joint.

Fig. 9: Drawings of the two position sensors (the dimensions of (a) are 12x4x8 mm^3, and the dimensions of (b) are 8.7x4x6 mm^3).

In this configuration the sensor measures the linear movement of the slider, that is related to the angular position of the joint. In the MP joints, the sensor measure a linear movement of 5.2mm; in the PIP joints, the linear movement is 8mm.

Using a micrometric translator stage we have found two optimal configurations. In the first one two magnets are used at a distance of 3.5mm. This configuration showed an output range of 3.78V with a covered range of 5.4mm, and its linearity was 5.34%. They can be used for the PIP joints.

The second configuration uses 6 magnets placed as in. The covered range is 8.4 mm with a linearity of 3.81%. So this configuration is suitable to be mounted in the MP joints.
A picture of a finger prototype with the integrated sensors is showed in Fig. 10.

8.1.1. Characterization of the sensors

The best and simplest way to characterize these sensors is to use an optical method. We used a Nikon Coolpix 950 digital camera posed on a tripod in order to obtain a stable position perpendicular to the plane of movement of the finger, which was fixed in vertical position. The movement of each Smoovy actuator was driven by a CCS00001 Controller (RMB, CH). Each controller has a power supply of 11V, while each sensor was supplied with 6V.

For each active joint, 100 different frames were acquired, 50 for the flexion and 50 for the extension. For each frame the output value of the sensor was measured with a digital multimeter and recorded, and the relative position of the joint was measured using the module Measure Tool of Adobe PhotoShop 5.5, with a precision of 0.1°.

8.1.2. Results and discussion

Results are presented in Fig. 11and in Fig. 12, respectively for the sensor in the MP joints and in the PIP joints. The flexion phase is indicated with small light circles, while the extension is indicated with small dark squares.

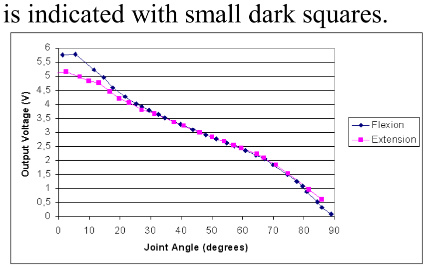


Fig. 11: Response curve for the MP joint.

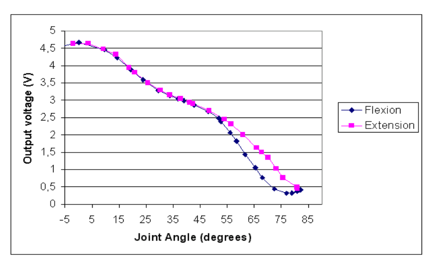


Fig. 12: Response curve for the PIP joint.

It is important to point out that both curves for both sensors generally present a low hysteresis. The difference between the flexion and the extension curve is mainly due to the mechanical clearance of the sensorized slider.

8.2. 2D force sensor

A 2D force sensor, based on strain gages technology, has been developed in order to sensorize the distal phalanx of the fingers (index and middle). The force sensor can measure normal and tangential forces.
The sensor design has been optimized using the Pro/Mechanica Structure software (see Fig. 13).

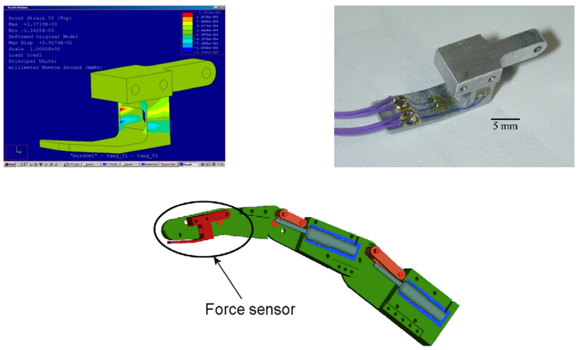


Fig. 13: Sensor simulation, development and positioning

8.2.1. Characterization of the sensor

The force sensor has been characterized using an INSTRON 4464 testing machine.
For each direction one traction-compression loading cycle (0 N – 10 N – 0 N) has been performed.

8.2.2. Results and discussion

Results are presented in Fig. 14 and Fig. 15, for the normal loading direction and the tangential loading direction respectively.

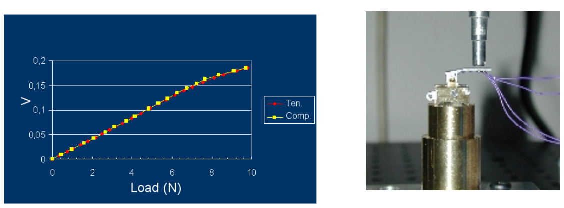


Fig. 14: Response curve for normal direction

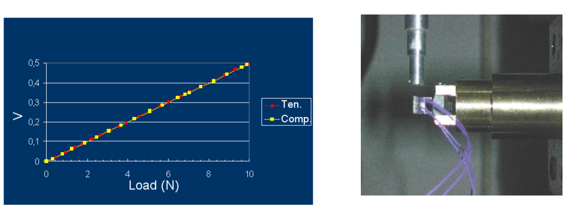


Fig. 15: Response curve for tangential direction

9. Future improvements

The experimental tests showed promising results, but there is still room for improvement. First of all, natural fingers movements during grasping activities will be further investigated in order to achieve a truly "human-like" behaviour of the artificial finger. The force sensor measurements will be further investigated in order to sense incipient slippage and to obtain force sensing abilities. Finally, suitable control strategies will be investigated and applied in order to develop a natural control of the *wearable* hand.

10. Conclusions

A novel approach to the design and fabrication of innovative prosthetic hands, called biomechatronic design, has been presented. It is based on integrating together multiple degrees of freedom, multi-sensing capabilities, and distributed control in order to obtain "elegant" human-like appearance, simple and direct controllability, low weight, low energy consumption and noiselessness.
Following this type of approach a first hand prototype with six DOFs has been designed and fabricated. In this paper we focused our attention on the design and development of a first implementation of an innovative hand, and in particular on the biomechatronic approach and on the integration of the position and force sensors.

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