Experimental analysis of the proprioceptive and exteroceptive sensors of an underactuated prosthetic hand

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Abstract

The development of a prosthetic hand able to replicate as much as possible the grasping and sensory features of the natural hand represents an ambitious project for scientists. State of the art technology is still far to provide engineers with components with similar performance of their natural models, and active prosthetic hands can be only a pale replication of the missing natural limb.

This chapter presents the current research efforts towards the development of a self-adaptative and anthropomorphic prosthetic hand. In particular, the chapter is focused on the problem of replicating the natural sensory system of the hand with an artificial proprioceptive and exteroceptive sensory system.

Introduction

The hand is the end effector of the upper limb, which in humans serves the important function of prehension, as well as being an important organ for sensation and communication [11]. The development of a prosthetic hand able to replicate as much as possible the grasping and sensory features of the natural hand represents an ambitious project for scientists, because of its challenging characteristics and performance: a large number of Degrees of Freedom (22 DoFs), redundancy and complexity of proprioceptive and exteroceptive sensors, and advanced control [5].

State of the art technology is still far to provide engineers with components with similar performance of their natural counterparts, and prosthetic hands can be only a pale replication [2]. Commercial hand prostheses have one or two degrees of freedom (DoFs) providing finger movements and thumb opposition. Due to this lack of DoFs, such devices are characterized by a low grasping functionality [3].

In order to overcome these limitations, and to enhance the dexterity and the usability of myoelectric hand prostheses, a self-adaptative and anthropomorphic prosthetic hand has been developed [8]. In particular, this chapter is focused on the problem of replicating the natural sensory system of the hand with an artificial sensory system designed and fabricated according to a biomechatronic approach [2].

Mechanical structure

In general, cosmetics requirements force the engineers to incorporate the prosthetic device in a glove, and to keep size and mass of the entire device compatible with those of the human hand. The combination of robust design goals, cosmetics, and limitations of available components, can be matched only with a drastic reduction of DoFs, as compared to those of the natural hand [1]. Due to this, prostheses are characterized by low grasping functionality, and thus they do not allow adequate encirclement of objects in comparison to the human hand. This low flexibility and low adaptability of artificial fingers lead to an instability of the grasp in presence of an external perturbation, as illustrated in [10].

In order to enhance the dexterity of prosthetic hands by keeping an intrinsic actuation solution and a simple control algorithm, we adopted an innovative design approach based on underactuated mechanisms [4,7]. The result of these efforts is a three fingered anthropomorphic hand called RTR II hand (Fig.1) [8].

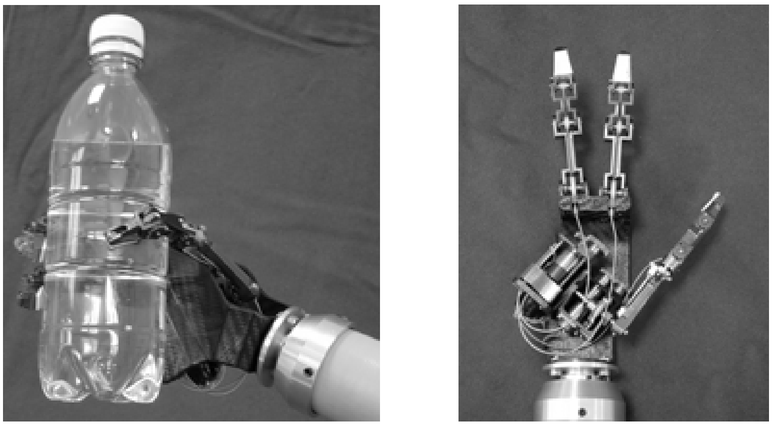

Fig. 1. The RTR II prosthetic hand (on the left) and its actuation and transmission system (on the right).

This hand weights about 320 grams, and it has nine DoFs in total, but only two motors. Index and middle fingers are identical (both have three phalanges), while the thumb has two phalanges, as in the human hand.

The hand is based on a tendon transmission system (Fig. 1). The tension of the tendons generates a 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 [4,6]. 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.

The actuators system consists of 2 DC motors with different characteristics and functions:

- the first motor (Minimotor S. A., mod. 1727 006 C, with 20/1 Minimotor S.A gearhead) acts on a slider providing all the fingers with the flexion/extension movements for power grasp (a detailed view of the slider is shown in Fig. 4);
- the second motor (Minimotor S. A., mod. 1219 006 C, with 10/1 Minimotor S.A gearhead) allows the adduction and abduction movements of the thumb (positioning grasp with less power).

Sensory system

The hand sensory system is the core of the prosthetic device. It is necessary to enable automatic control of grasping tasks without requiring special attention and efforts to the user. In addition, the sensory system is studied with the idea of providing the amputee with cognitive feedback about the grasping task that is performed [9].

For these reasons, according to a biomechatronic approach [2], the artificial sensory system is inspired at replicating the natural sensory system providing both proprioceptive and exteroceptive sensing abilities.

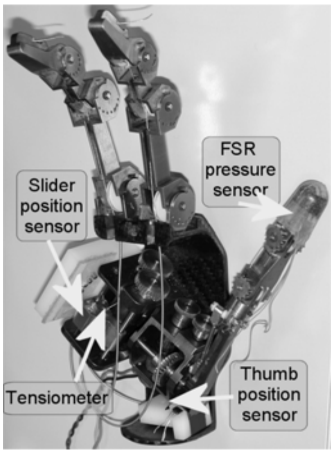

Fig. 2. Photograph of the prototype of the RTR II hand.

In synthesis, the sensory system is composed of different sensors (Fig. 2):

- proprioceptive position sensors - the position of the slider actuating the tendon transmission is monitored by a Hall-effect sensor, which detects the position of the slider along his stroke during the flexion/extension movements of the fingers, like the physiological angular sensors in the joint capsules [5,13];
- proprioceptive joint angular position sensors - the thumb angular displacement when performing adduction/abduction movements is measured by a Hall effect sensor embedded in the joint structure, like the physiological angular joint sensors in the joint capsules [5,13];
- proprioceptive tendon force sensors - a tension sensor has been fabricated in order to continuously monitor the cable tension applied by the motors, as the Golgi tendon organ in series with the muscle [5,13];
- exteroceptive force sensors - an artificial mechanoreceptor is obtained by means of a FSR sensor embedded in a silicone cap at the thumb tip. This sensor behaves like the physiological skin mechanoreceptors [5,13]. The force sensor has been applied only on the thumb tip that is significantly involved in all the functional grasping tasks [12].

The following subsections describe in detail the sensory system and its performance.

Materials and methods

The calibration of the tensiometer and of the FSR pressure sensor have been done using an INSTRON R4464 testing machine (Instron Corporation, Canton, Massachusetts, USA) with a static load. The calibration of the two position sensors have been done manually with a Rupac digital Caliper 1165.

The data have been pre-processed with custom-made electronic boards. All the signals have been acquired using an acquisition board (National Instruments™ DAQ Card 1200), and processed by a custom LabVIEW™ interface to visualize in real time the output (in Volts) versus the applied load or displacement. All data have been saved on a PC for post-processing and further reference.

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. Twelve magnets (model 103MG5, Honeywell Inc, Freeport, Il, USA) have been mounted in front of the slider in order to generate a monotonic magnetic field (Fig. 2). Thanks to a Finite Elements (FE) simulation, a configuration of magnets able to generate an appropriate distribution of magnetic field has been established

The experimental analysis (Fig. 3) has assessed the simulation and the final calibration on board has provided good linearity and repeatability (enhanced by reducing the machining and assembling tolerances) [8]. With a power supply of 5V, the output of the sensor could be approximated by:

$$V_{out} = 0.0643 \cdot X_{slider} + 1.8371, \qquad R^2 = 0.9901 \tag{1}$$

where R^2 is defined as:

$$R^2 = 1 - \frac{\sum \left(y_j - \hat{y}_j\right)^2}{\sum \left(y_j\right)^2 - \sum \left(\hat{y}_j\right)^2} \tag{2}$$

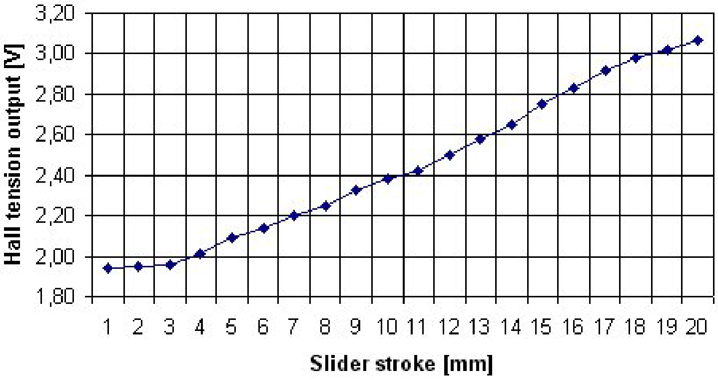

Fig. 3. Hall tension versus linear slider's stroke.

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 (Fig. 4). 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 a mechanical component acting as a mechanical stop for the cable and able to strain itself under the tension of a grasping cable.

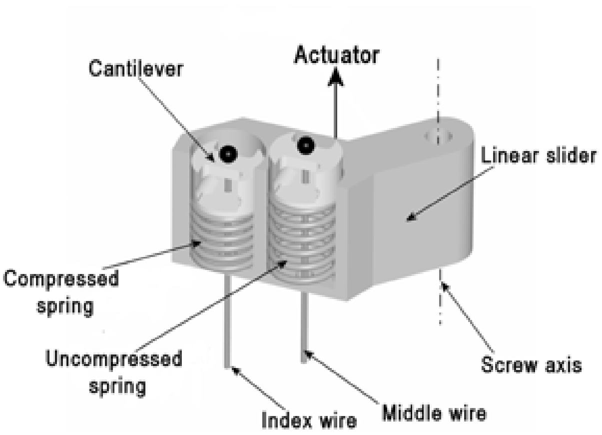

Fig. 4. Cross section of the linear slider.

In order to obtain an elastic strain of the component and an appropriate mechanical strength, a classic structural analysis with FE methods (using two symmetry planes and linearity assumption) has been used to optimize the dimension of the cantilever in the design phase.

The tendon tensiometer is based on two strain gauges sensors (model ESU-025-1000, Entran Device Inc, Fairfield, NJ, USA). The micromechanical structure has been fabricated to obtain a deformable cantilever (Fig. 4), in order to continuously monitor the cable tension applied by the motors, as the Golgi tendon organ in series with the muscle [5,13].

A cone-shaped tip, fixed to the load cell, has been used to apply the load. A Wheatstone bridge, followed by a signal amplifier and a low pass RC filter with f_t=100 Hz, has been used to detect the variation of the resistance of the two strain gauges. The output of the tensiometer Vout is related to the applied tension T_{cable} by the following equation:

$$V_{out} = 26.349 \bullet T_{cable} - 0.3732, \qquad R^2 = 0.9996 \tag{3}$$

The sensing device has shown good dynamic, sensitivity and repeatability performance (Fig. 5); a little hysteresis and time delay have been detected due to the differential mechanism of the hand (there is a spring under the strained component) [8].

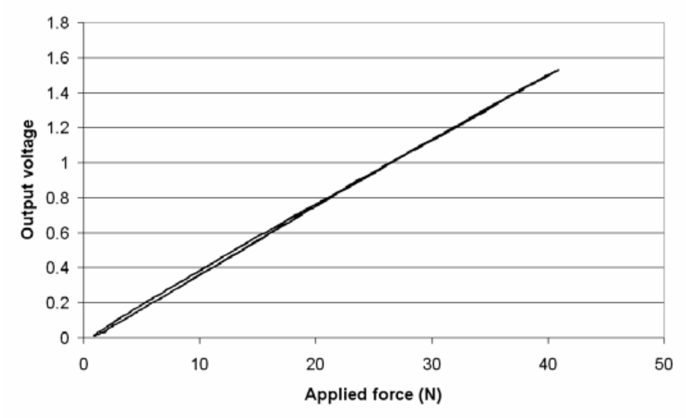

Fig. 5. Output response of the tensiometer.

Thumb position sensor

In order to sense the position of the thumb, a round-shaped cap with two magnets (model 103MG5, Honeywell Inc, Freeport, Il, USA) has been assembled at its base, at the center of rotation of the four bar link mechanism providing abduction/adduction capabilities to the thumb (Fig. 2). A Hall effect sensor (model SS496B, Honeywell Inc, Freeport, Il, USA), located in front of the cap, determines the angle displacement of thumb metacarpus.

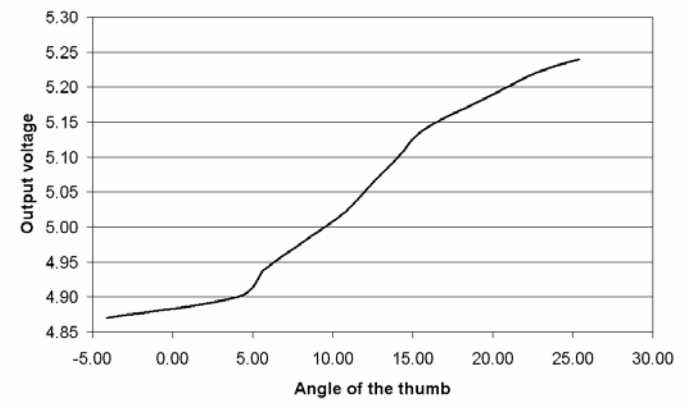

Fig. 6. Response of the thumb position sensor.

The output of the position sensor V_{out} is related to the angular position of the thumb θ_{thumb} by the following equation:

$$V_{out} = 131.1 \bullet \theta_{thumb} - 319.76, \qquad R^2 = 0.9575 \qquad (4))$$

The sensor has an operative range of 30° and has shown good sensitivity, and repeatability performance (Fig. 6).

Force sensor

A FSR pressure sensor (part #400, Interlink Electronics, Camarillo, Ca, USA), 5 mm in diameter and 0.3 mm of nominal thickness, has been 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 hand was locked with the force sensor facing upwards, and a cylinder (5 mm in diameter), fixed to the load cell of the testing machine, has been used to apply the load. The output of the FSR force sensor V_{out} is related to the applied force F_{FSR} by the following equation:

$$V_{out} = - 0.2887 \bullet \mathrm{Ln}(F_{FSR}) + 1.2867, \qquad R^2 = 0.9754 \qquad (5)$$

Preliminary experiments have shown a low hysteresis, and high repeatability (Fig. 7). 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 [5,13].

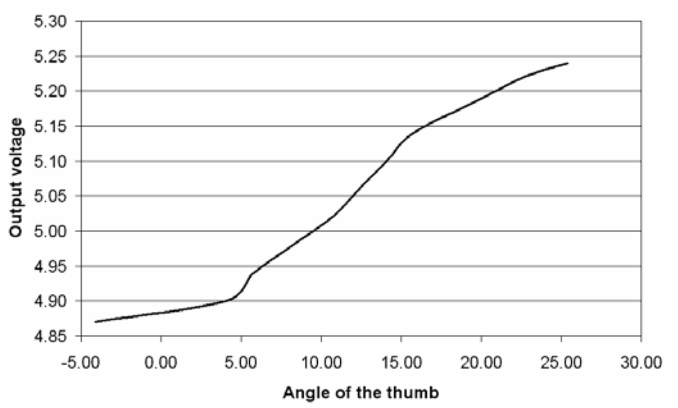

Fig. 7. Output response of the thumb force sensor.

Conclusions

Commercial hand prostheses have just one or two degrees of freedom (DoFs) providing finger movements and thumb opposition. Due to this lack of DoFs, such devices are characterized by a low grasping functionality.

In order to overcome these limitation, and to enhance the dexterity and the usability of myoelectric hand prostheses, a self-adaptative and anthropomorphic prosthetic hand has been developed.

In this chapter the sensory system of this hand, called RTR II hand, has been described. The proprioceptive and exteroceptive sensory structure has shown good performance in terms of operative range, repeatability and linearity.

At present some experiments on the control of the hand by means of the Electromyographic signals are carried out, to exploit the force and position sensors for implementing a closed-loop control of the grasping hand in order to limit the user involvement just in identifying the initial parameters of the grasping task (the required grasping force level and the grasping type). The expected result is the increasing of the prosthesis usability.

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