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A bio-inspired approach for the design and characterization of a tactile sensory system for a cybernetic prosthetic hand

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Abstract **– Recent research in prosthetic hands aims at developing innovative cybernetic systems able to allow users to feel an artificial hand as part of their bodies by providing the tactile sensation of a natural hand. Such prostheses must be endowed with artificial proprioceptive and exteroceptive sensory systems as well as appropriate neural interfaces able to exchange sensory-motor signals between the body and the nervous system of an amputee. Based on consideration of available neurophysiological and behavioral data in humans and on the specific sensory needs to control a prototypical grasp-and-lift task, two kinds of sensors were developed: on-off contact sensor arrays and triaxial force sensors. Both sensor types were characterized and compared with their biological counterparts. Their ability to convey critical information during a lift task was evaluated with the sensors integrated in a biomechatronic cybernetic hand.**

Index Terms – biorobotics, tactile sensors, artificial hand

I. Introduction

Our ultimate goal is to offer full functional substitution of an upper limb through a cybernetic prosthesis that their users will perceive as a natural part of their bodies [1]. A bio-inspired anthropomorphic artificial hand that mimics the biomechanical features of the human hand has therefore been developed [2].

Tactile sensor designers have often referred to the human mechanoreceptors at the glabrous (hairless) part of the hand to draw inspiration [3-8]. In most cases however, the development of tactile sensors have focused on the individual sensor components rather than on complete systems for tactile sensing, and on general but not task-specific functionalities. In this work, in contrast, the sensory system signals were related to a specific task, i.e., grasping, lifting, and replacing an object [9]. This allowed us to be guided by available human neurophysiological and behavioral data and on the specific sensory requirements of a prototypical grasp-and-lift task.

Basic human grasping and manipulation involve lifting objects and placing them back in the environment. This task has been extensively studied in neurophysiology [10, 11] and it is possible to identify the minimum requirements of a bio-inspired tactile system from this. Such a system should provide information about: contact and release between the fingertip and the object; contact between the object and the environment, and slippage between the fingertip and the object. This work demonstrates the feasibility of a tactile sensory system to be used in sensory-guided object grasping and lifting of a cybernetic prosthetic hand. We describe the fabrication of these sensors, characterize their response properties, and show preliminary data of their ability to detect phase transitions in a grasp-and-lift task.

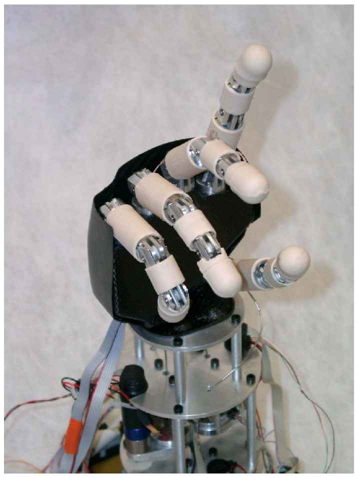

Fig. 1 The five fingered prosthetic hand.

The artificial hand and its sensory system are described in section II. Section III presents the experimental procedures on the *component level* as well as on the *system level*. Results are presented in section IV following by a discussion in section V.

II Materials

A. The prosthetic hand and sensory system

The prosthetic hand [1, 2] used in this study is shown in Fig. 1 and consists of five fingers (thumb and four fingers) with cylindrical phalanges of aluminum alloy material attached to a central palm. An underactuated mechanism that permits self-adapting grasping of the hand [12] was employed to mimic the human hand and its grasping capabilities. Each finger of this hand is underactuated so the flexion (agonistic action) of all its phalanges is obtained via a cable pulled by a DC motor. The antagonistic action is implemented by a torsional spring embedded in each finger joint. The hand has 3 DOFs for each finger and 1 DOF for thumb adduction/abduction. The motor for thumb positioning is located inside the palm while the five motors for the movement of the fingers are external and to be located in the socket worn by an amputee.

The artificial proprioceptive sensors were designed to provide information about both joint positions (by Hall effect sensors in each joint) and actuator forces (tensiometers in the cables) [2].

1) On-off contact sensors arrays: The design goal was to let the on-off contact sensors emulate mechanoreceptors of the human hand. Johansson and Vallbo [13] estimated that 90% of the SA-I and the FA-I mechanoreceptors get excited to a stimulus of 5 mN. This force stimulus applied through a von Frey hair with a diameter of 0.27 mm [13, 14] corresponds to 87 mN/mm^2.

Flexible contact sensors were obtained from LF9150R Pyralux (DuPont, USA) material consisting of a 127 μm thick Kapton sheet with a 35 μm layer of copper on one side. The contact sensor was composed of two layers of Pyralux with a copper electrodes obtained by photolithography. The sensors were assembled by positioning 2 mm thick strips of polyurethane foam between the two layers that allowed the top Kapton layer to return to its initial state once any external force is removed (i.e. upon the termination of contact with an object). A matrix of 8×3 contact points was designed for the fingertip, another 8×3 matrix for the middle phalange and an 8×4 matrix of sites for the proximal phalange. Each digit could thus be equipped with a total of 80 flexible on-off contacts. For assessing the functions of the sensors, contact sensors were mounted on the distal phalanges only.

Two versions of the distal phalange tactile sensor array have been implemented. In a first version (Fig. 2A, C) the squared shape electrodes (with dimensions of 1x1 mm) were connected along the columns resulting in 8 longitudinal sensitive areas. While this connection layout simplified the wiring, the design did not allow differentiation of two different objects coming into contact with the distal phalange along the vertical direction. In a second version, there were 24 1×1 mm independent tactile elements (taxels) with a minimal distance between two electrodes of 1 mm (Fig. 2B, D). Differently from the first version of the sensor array, in this case, two, instead of four, polyurethane foam strips (8×2 mm) were integrated, and the sensor array had a compliant silicone (GLS 40, Prochima s.n.c., Italy) outer layer (1 mm in thickness), that increased the size of the contact area in order to effectively provide contact information. The silicone layer also leads to good frictional properties and, thus, an increase of grasp stability, in addition to augmented artificial finger's capability to conform to object surfaces.

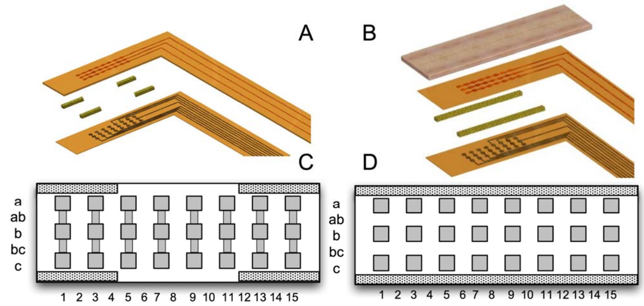

Fig. 2. Structure of the first (A) and second (B) prototypes of on-off contact sensors arrays. The two Kapton layers as well as the polyurethane foam strips and the compliant outer layer are visible. Taxels layouts: the first prototype (C) consists of 8x1 contact areas, while the second prototype (D) consists of 8x3 taxels.

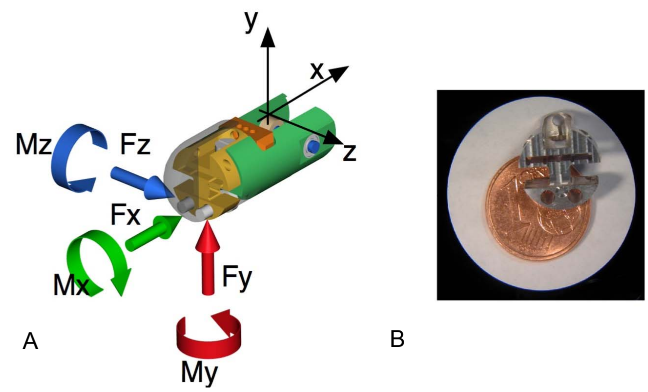

Fig. 3 The three-axis force sensor (A) reference system for the sensor; (B) fabricated aluminum sensor.

2) *Triaxial Force Sensor:* The force sensor was designed to detect the three components of the contact force occurring at the finger-object interface. Moreover, the sensor was designed to detect the contact between the object and the environment and to be sufficiently sensitive to sudden surface tangential force changes in order to detect slippage. The force sensor was dimensioned by means of FEA tools (ANSYS 5.7) in order to identify the maximum strain levels and to choose the strain gauge elements accordingly. The calculated maximum loads were 4.5, 6, and 4.5 N along the x, y and z axis, respectively (Fig. 3). Moreover, the triaxial force sensor was calculated to sufficient bandwidth (DC-400 Hz, cf. [15]). The mechanical structure of the sensor (Fig. 3) was made of an elastic aluminum alloy. In order to detect the three components of an applied force, a strain gauge (N3K-06-S022H-50C, Vishay Micro-Measurements, Vishay Intertechnology Inc., USA) was attached located to the root of each of the three tethers of the sensor (Fig. 3). Three additional strain gauges were used for temperature compensation.

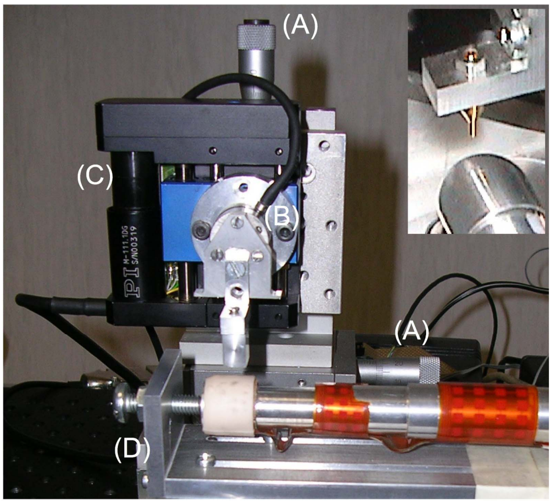

Fig. 4 Characterization apparatus featuring three micrometric translation stages (A), the ATI 6-axis load cell (B), the PI nanometric translation stage (C). (D) shows the contact sensors array mounted on an artificial fingertip mock up. The inset shows the end probe used to perform static characterization of the triaxial force sensor embedded at the hand fingertip (also shown).

III. Methods

A. On-off contact sensors

Static characterization of the contact sensors arrays was obtained by an experimental apparatus composed of three micrometric translation stages with crossed roller bearing (Fig. 4A) (M-105.10, PI, Karlsruhe, Germany), that allowed the positioning of the loading structure on the sensor under test. The contact sensors array was mounted on a cylindrical aluminum structure whose radius was the same as the distal phalange of the artificial hand (i.e., Ø 12 mm). Load was applied to the sensor through a six-components load cell (Fig. 4B) (ATI NANO 17 F/T, Apex, NC, USA) interfaced to a nanometric translation stage (Fig. 4C) (111-1DG, PI, Karlsruhe, Germany) which is servo-controlled with a DC servomotor connected to a controller (PI Mercury C-860.10) that was interfaced to a PC workstation. Signals coming from the contact sensors array were acquired at the rate of 10 kHz and stored digitally; the acquisition board was a National Instruments PC-6032E and the software interface was developed in LabView 7. The force required to activate individual taxels was measured (threshold tests) as well as the force when the probe was retracted and the taxels again were deactivated. Hysteresis was defined as the difference between the on-set and off-set forces. Threshold experiments were performed by means of the end effector composed of an aluminum block having a small positive curvature (Ø 30 mm) similar to the curvature of objects commonly used in activities of daily living.

B. Triaxial force sensor

Static characterization of the triaxial force sensor integrated in the hand fingertip (Fig. 3), was performed by means of the same experimental apparatus as was used for the contact sensor tests. The end effector in this case was a 1 mm diameter sphere at the end of a cylindrical brass (Fig. 4, inset). To detect torque components that could arise due to misalignments between the loading structure and the sensor, the ATI six-components load cell was used. Sensor signals were detected through a typical Wheatstone-bridge configuration electronics with temperature compensation. Strain gauge signal conditioning included three precision instrumentation amplifiers for accurate, low noise differential signal acquisition with low offset voltage drift and excellent common-mode rejection (INA 126PA Burr-Brown, Texas Instruments, TX, USA). The acquisition system was the same as described above.

The knowledge of the dynamic behavior of the sensor was essential for the correct acquisition and interpretation of the input signals. To measure the frequency response of the triaxial force sensor we excited the sensor by means of an impulsive stimulus because it would excite all the vibrational modes of the structure. The impulse stimulus was obtained by means of a steel sphere (Ø 6 mm) dropped from a height of 29 cm above the sensor along the x direction (cf., Fig. 3A). The signals from the sensor's three strain gauges were acquired by means of the same system used for the static measurements described above, except that the sampling rate was 40 kHz. Signal characterization was carried out using Matlab Signal Processing and System Identification toolboxes.

C. Detecting phase transitions

The sensory system was expected to provide a control system with information sufficient to recognize and isolate the mechanical events that separate the main *phases* of the lifting task as described elsewhere [10, 11]. These are the phases prior to object lift-off from the table (*preload* and *load*); the object-lift off (*lift* and *static)*; and finally, the object touch-down (*unloading* and *release*).

The contact sensors array was particularly suited to sense contact information between the fingers and the object, while the triaxial force sensor in addition was supposed to detect contact information between the object and the environment. Contact information was obtained by a logical OR operation of the signals of all the taxels. In this way, the detection of any contact between the hand and the object was guaranteed, without extracting contact patterns. Information on object-table contact was obtained from the low-pass filtered first derivative of the data coming from the central strain gauge of the triaxial force sensor. While a classical "filtered derivatives" approach was followed in this study, there are more advanced solutions available [16]. The artificial hand was mounted on a humanoid robot arm [17], programmed to perform the grasping, lifting and replacing task using the thumb and index fingers of the artificial hand. The test objects were plastic cylindrical boxes, whose weight were 100, 200, 400 g. Signals coming from the contact sensors array and the triaxial force sensor were sampled and acquired at the rate of 1 kHz, and stored digitally. The acquisition board was a

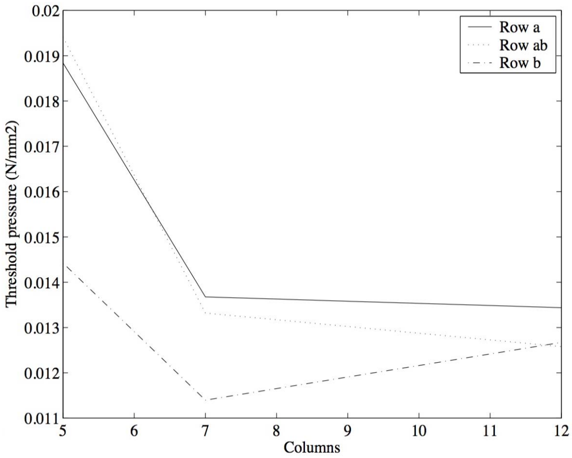

Fig. 5 Threshold forces of the second prototype (cf. Fig 3B, D) of the on-off contact sensor array of the fingertip.

National Instruments PC-6032E and the software interface was developed in LabView7.1.

IV. Experimental results

A. On-off contact sensors

Threshold estimations were obtained for both types of contact sensor arrays designed for the fingertip (Fig. 2). The pressure required to activate at least one of the contacts of the second prototype of the sensor was <15 mN/mm^2 in most of the contact surface. The value was lower where the distance from the two foam strips was higher (row b in Fig. 5).

Hysteresis was computed for three locations (i.e. 1a, 7a and 7c in Fig 3C, D). It averaged 0.73±0.071 mN/mm^2 (mean ± SD). The results were the same whether the force was applied for 2 or for 5 seconds.

B. Triaxial force sensors

Due to the mechanical structure of the sensor it was possible to obtain separate estimates of the Fx, Fy and Mx components of the applied loads. The preliminary calibration measurements sensor evidently indicates highly linear static responses from all three strain gauges (Fig. 6). Virtually the same frequency response curves were obtained from all three strain gauges with a bandwidth of 700 Hz. The responses showed two main resonance peaks: the first at 388Hz and the second at 2,700Hz, the former was related to the dynamic properties of the strain gauges and the latter was close the mechanical resonance frequency predicted from the FEA (2.5 kHz).

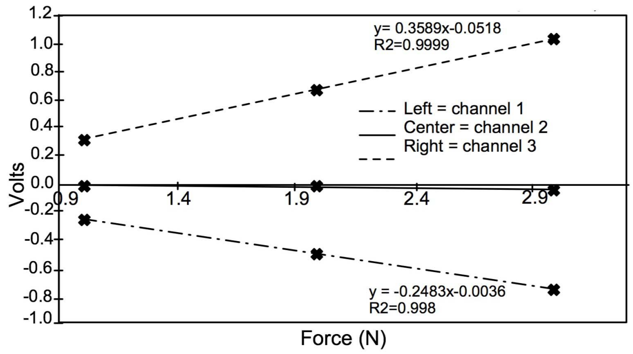

Fig. 6 Response of the sensor for loading along the z axis.

C. Detecting phase transitions

Figure 7 (upper panel) shows the continuous signal from the on-off contact sensor (the thick solid line) indicating object-finger contact and the raw signal of the load force (the thin solid line) as a 100 g object was lifted and replaced on the table. Figure 7 (lower panel) shows the same on-off contact sensor signals but with the corresponding first time derivative of the load force signal. The derivated signal highlighted the location of the peaks to identify the object lift-off and touch-down.

V. Discussion

In this work it has been demonstrated that the implemented tactile system was able to functionally provide the same information as provided by the biological mechanoreceptors during a prototypical lifting task. We accomplished this by following a bio-inspired functional design approach wherein only the key principles of a biological function were copied, an approach that obviously simplified the design.

Both the on-off contact sensors and the triaxial force sensors showed sensitivities and frequency responses, respectively, comparable to those observed in human mechanoreceptors.

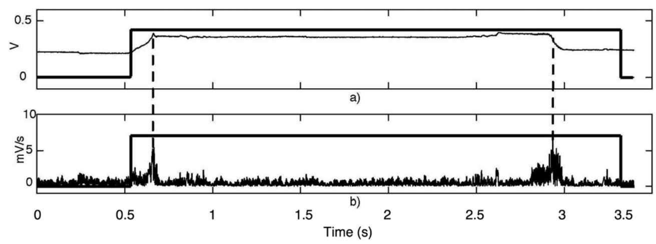

Fig. 7 Result of the phase separation algorithm. Upper panel: triaxial force sensor output (thin solid line) and contact sensor output (thick solid line); Lower panel: filtered derivative signal, whose peaks indicate phase transitions (solid line) and contact sensor output (thick solid line). The two vertical dashed lines between plots a) and b) indicate the instants at which a phase transition is detected. The on-set and off-set of the dashed line indicate contact detection.

Indeed the contact sensor design with a skin covering reach the design goals with a big margin and the frequency response of the force sensor was broader than has been reported for the Pacini corpuscle (0-700 Hz vs 60-400 Hz). In short, we expect the embedded force sensor to be able to detect tiny vibrations at the finger surfaces.

Previous studies in robotic grasping and manipulation have shown that breaking the task into phases simplifies its control by limiting the context and scope for each phase [18-20]. Our preliminary studies of the grasp-and-lift task indicate that the sensors will enable detection of such phases of an evolving manipulation task.

To avoid cognitive overload it is important that amputees with prosthetic devices are provided with sensory feedback congruent with physiological signals. If detecting discrete events – as would be possible with the proposed artificial sensory system – is indeed crucial for the control of the grasp-and-lift task in humans as proposed in literature [9] remains to be shown in future studies. Likewise, further studies are required to explore the possibility to exploit these sensors in the development of autonomous systems for the control of manipulation.

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