Chapter 8

Large Scale Capacitive Skin for Robots

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Additional information is available at the end of the chapter

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1. Introduction

In order to allow robots to share our space and chores, tactile sensing is crucial. Indeed it allows safe interaction of robots with people and objects, because it provides the most direct feedback to control contact forces both in voluntary and involuntary interactions. Furthermore, it allows improving performance in tasks that require controlled physical interactions in uncontrolled environments where the location and the characteristics of contact cannot be predicted or modeled in advance and more complex forms of interactions are required. Therefore, a tactile sensor system capable of measuring contact forces over large areas is needed. Tactile sensing in robotics has been widely investigated in the past 30 years and many examples of engineering solutions to tactile sensing have been presented in the literature [1]. Research in this field has focused largely on transduction principles and transduction technologies [2]; however, various technical issues have limited the transition from a single tactile element (or a small matrix prototype) to a large scale integrated solution: it is easy to understand that a sensitive robot skin cannot be achieved by simply aggregating a large number of single sensors. In fact, the concept of robot skin entails a number of system level problems that simply do not appear when focusing on small tactile sensors or small area arrays:

- Modularity and Conformability: the system should be modular and it should be simple to tailor it to the shape of the surface of the robot.
- Infrastructure and Networking: embedded electronics and distributed computation are necessary to facilitate the integration in the robot, otherwise a large number of wires would impede mobility and dexterity of the robot.
- Coverage: The sensors must cover the largest possible area of the robot without increasing the number of wires or the size of the ancillary electronics.
- Compliance: The sensors must be covered by a soft layer that allows safe interaction with humans and the environment and that forms a protective layer for the sensors themselves.

- Dynamic range and sensitivity: The system should be able to detect a wide range of contact pressures.
- Total Weight and installation space: In order to cover the whole robot body surface the weight of the sensors must be small as well as the required space for installation.
- Costs: The system must be as cheap as possible and off-the-shelf components should possibly be used to decrease the manufacturing cost.
- Manufacturing and deployment: the ease and speed of production have to be taken into account. The deployment procedures must be reproducible on robots with different characteristics.

Several tactile systems have been integrated into robots and described in the literature. Some of them are modular and include hierarchical data processing. Yet, the modules are usually big and cannot be installed on small robot parts. In many cases the spatial resolution is low; in others the sensory modules connectivity is cumbersome. This is clearly in contrast with the requirements above. Small sensor modules are typically necessary in order to allow the communication between them; size constraints are then very critical as not enough space typically can be found on the sensor modules to the local integration of microcontrollers or other networking electronics. One of the first examples of full-body skin for robots was proposed by Inaba et al. [3] that describes a tactile sensor system composed of a layered structure of electrically conductive fabric implementing a matrix of pressure sensitive switches. However, the complexity of the manufacturing process and the limited sensing capabilities represent the most significant limits of this approach. Force detectable surface covers have been introduced by Iwata et al. [4]. Information originating from both resistive and force sensors to correlate pressure information and exerted force is exploited. Although the presented system can be used to cover large surfaces, the actual design is strictly dependent on the actual robot surface. However, a principled discussion about design issues is not carried out. Ohmura et al. [5] proposed a conformable and truly scalable robot skin system formed by self-contained modules supported by a flexible printed circuit boards (PCBs) that can be interconnected. Each module contains 32 tactile elements consisting of a photo-reflector covered by urethane foam. In order to adjust the distance between each tactile sensor element, a band-like bendable substrate that can be easily folded (or even cut) is adopted. The system integrates a microcontroller based architecture for data acquisition and networking, however, the dimension of the system are too big for small robot parts and the spatial resolution featured is quite low [6]. The tactile system that has been developed for the robot RI-MAN also uses flexible PCBs with a tree-like shape to conform to curved surfaces [7]. The tactile elements are commercially available piezoresistive semiconductor pressure sensors, and the measurements have less hysteresis than the one shown by Ohmura et al. [5]; to reduce the number of wires, the sensor modules include multiplexers, but this approach requires to connect each module individually to a controller board. The robot ARMAR-III [8] uses skin patches based on piezoresistive sensor matrices with embedded multiplexers. The patches have a flat or a cylindrical shape and are specifically designed for the different parts of the robot; smaller patches are used for the fingers. In Kotaro [9], tactile sensing is achieved by using flexible bandages formed by two flexible PCBs with an intermediate layer of pressure sensitive conductive rubber. Each bandage has 64 taxels, but no integrated data acquisition electronics is mentioned. Piezoelectric transducers are used for the humanoid robots Robovie-IIS [10] and CB2 [11]. The transducers were placed individually on the robots and the sensitive skin has a low spatial resolution.

In Yoshikai et al. [12] the construction method for soft stretchable enclosing type tactile sensing exterior for humanoid robots is presented. A cardigan knit sensor which encloses an upper body of a small humanoid has been developed using the proposed method. The overall sensor is constituted by layers of conductive fabrics that are knitted for improved stretchability. The presented cardigan knit has, however, only 75 electrodes.

Shimojo et al. [13] have developed a mesh of tactile sensors that satisfy the requirements of a high speed and reduced number of wires and that is able to cover surfaces of arbitrary curvatures. The tactile sensors mesh is arranged as a net, where only nearby taxels are connected through wires. Since the shape of a patch must be specifically designed, modularity issues are not properly addressed, but scalability is possible thanks to the smart wiring infrastructure: only 4 wires actually exit from the patch.

Mittendorfer et al. [14] have presented a tactile sensor system made by small hexagonal PCB modules equipped with multiple discrete off-the-shelf sensors for temperature, acceleration and proximity. Each module contains a local controller that pre-processes the sensory signals and actively routes data through a network of modules towards the closest PC connection. The sensory system is embedded into a rapid prototyped elastomer skin material and redundantly connected to neighboring modules by just four ports. The functionality of some modules on a KUKA robot arm has been demonstrated, however a complete integration has not been shown.

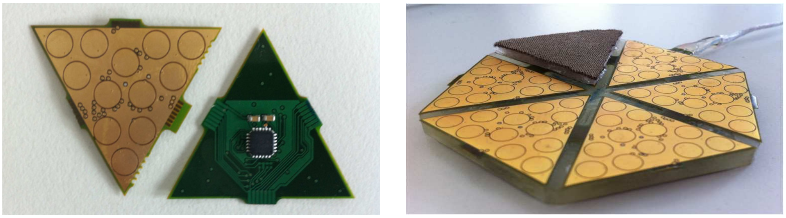
The ROBOSKIN tactile system (Patent No. I0128764) is our proposal for a skin that is able to cover large area of a robot body. It incorporates a distributed pressure sensor based on capacitive technology. The transducer consists of a soft dielectric sandwiched by electrodes. When pressure is applied to the sensor, the distance between the electrodes changes, and the capacitance changes accordingly (capacitance is a function of distance). The ROBOSKIN system is made up of a number of tactile elements (taxels) geometrically organized in interconnected modules of triangular shape. Above the flexible PCB, there is a layer of silicone foam (Soma Foama 15 from Smooth-On) that covers the 12 taxels and acts as a deformable dielectric. On top of the silicone foam is placed a deformable conductive layer made of electrically conductive lycra-like fabric. This layer is connected to ground and enables the sensor to respond to contacts with objects of any material.

As we mentioned earlier, manufacturing and deployment processes constitute an important aspect of the robot skin design since the skin has in fact to be integrated on robots with different characteristics. Flexibility in this sense is a good property for a robot skin system. In addition, it is desirable that the skin production process is reproducible so to guarantee resilience against impact and forces and the general wear and tear of the material. In particular, the ROBOSKIN tactile system has been integrated on three different types of robots: iCub [15], KASPAR [16] and NAO [17]. The three robots have different sizes and shapes, and the tactile feedback has been used for different purposes. Nevertheless, the methods that have been used to implement the skin were nearly the same, which demonstrate the portability of the sensor system technology. This chapter is organized as follows: firstly, the ROBOSKIN tactile system is presented in details in section 2; section 3 presents the methods and procedures for ROBOSKIN manufacturing and integration; in particular, section 3.1 is related to the iCub platform; section 3.1.1 presents a new implementation of iCub fingertip with experimental data related to their behavior characterization; section 3.2 is related to KASPAR and section 3.3 presents the ROBOSKIN integration on robot NAO; finally section 4 is dedicated to conclusion.

2. ROBOSKIN technology

As we told before, ROBOSKIN tactile system, incorporates a distributed pressure sensor based on capacitive technology. The transducer consists of a soft dielectric sandwiched by electrodes. When pressure is applied to the sensor, the distance between the electrodes above and below the dielectric changes, and the capacitance changes accordingly (capacitance is a function of distance).

The basis of the sensor is a flexible printed circuit board (PCB). It includes the electronics to obtain 12 measurements of capacitance and send them over a serial bus. In particular, each PCB includes 12 round pads, one for each taxel, and a capacitance to digital converter (CDC) (AD7147 from Analog Devices).

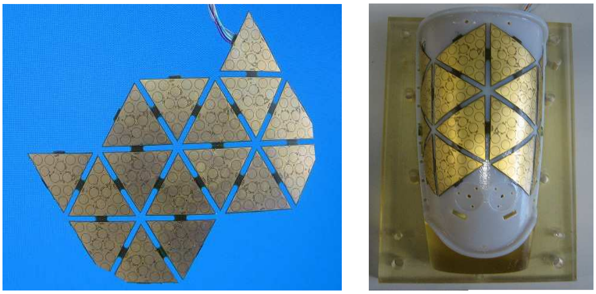


(a) (b)

Figure 1. The triangular module: (a) in the front view it is possible to see the 12 round taxels, in the back view the CDC chip from Analog Devices is shown; (b) An hexagonal patch glued on a cover with the foam elastomer and electrically conductive lycra layers.

The chip can measure the capacitance of all taxels with 16 bit resolution, but we use only 8 bit measurements, as any higher resolution is covered by noise. As a result, one measurement unit corresponds to 2.88 fF. The CDC has an I^2C serial interface and each chip can be assigned with a 2 bit address; therefore up to 4 chips can communicate over the same serial bus. The shape of the PCB is in most cases a triangle (only for the fingertips of the robot iCub we used a unique solution, which we will discuss in section 3.1.1), see figure 1(a). The triangular shape was chosen in analogy to polygonal modeling in 3D computer graphics, which uses triangles to describe the shapes of objects. The triangles can conform up to a certain degree to generic smooth curved surfaces (see figure 2(a) and figure 2(b)).

The triangular PCBs also include the electronics to communicate between themselves: three communications ports placed along the sides of the triangle (one for input and two for output) relay the signals from one triangle to the adjacent one. Up to 16 triangles can be connected in this way (4 serial buses with 4 different addresses each) and only one of them needs to be connected to a microcontroller board (MTB, see figure 3). This is a critical advantage since it reduces the amount of wires and electrical connections that are required. The MTB can also



(a) (b)

Figure 2. (a) A ROBOSKIN patch; (b) ROBOSKIN patch conformed to a curved body parts.

be used to program each CDC to either measure its 12 taxels independently at 50 Hz or an average of them at about 500 Hz.

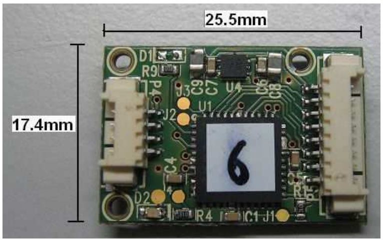
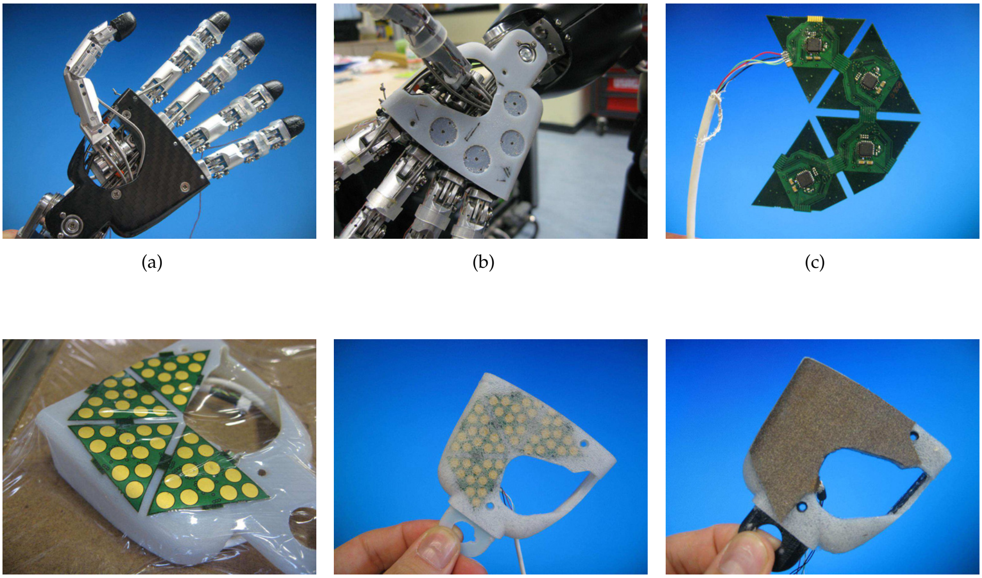


Figure 3. The microcontroller board (MTB). We designed a small microcontroller board, which collects the measurements from up to 16 CDC chips and sends the measurements over a CAN bus.

Above the flexible PCB there is a layer of silicone foam (Soma Foama 15 from Smooth-On). It is 2 mm thick for the hands of the robot iCub, and 3 mm in all other cases. It covers the 12 pads and acts as a deformable dielectric for the capacitive pressure sensor. The foam also makes the skin compliant. On top of the silicone foam there is a second conductive layer made by electrically conductive Lycra. This layer is connected to ground and enables the sensor to respond to objects irrespective of their electrical properties. It serves as the common electrode above the silicone foam for all the taxels, see figure 1(b). When pressure is applied to the sensor, this layer gets closer to the round pads on the PCB, and the sensor measures the distance. This layer also reduces the electronic noise coming from the environment, in particular the stray capacity, which can be a problem for capacitive pressure sensor systems [2]. For the KASPAR and NAO, we didn't use the conductive layer on top of the silicone foam, as in these cases the robot is intended to interact only with humans, in which case the human constitutes the ground plane (like in many consumer products, which are responsive to humans, but are not responsive to insulators, for example).

3. Integration process

In order to integrate the ROBOSKIN sensor on a robot, this general procedure must be followed:



(a) (b) (c)

(d) (e) (f)

Figure 4. The production steps for the palm of iCub. For a description of each step, please refer to the text.

- Identification of the part to be covered, see Fig 4(a). If no CAD model is available, obtain the shape with a 3D laser scanner (as for example for the hands of KASPAR).
- Manufacturing of the part (or of a cover) with a 3D printer (Eden 3D printer from *Objet*). The resulting parts look for example like in Fig. 4(b). Round holes provide space for the CDC chip and the other electronic components which are soldered on the PCB.
- Identification and wiring of the mesh of flexible PCBs that is needed to cover the part, see Fig. 4(c).
- Bonding of the PCBs on the part with bi-component glue and the help of a vacuum system, see Fig. 4(d).
- Covering the PCBs with silicone foam, see Fig. 4(e). To this aim we employ a specific purpose-built mold for each part.
- Covering of the silicone foam with a conductive lycra as ground plane, as shown in Fig. 4(f).

3.1. Implementation on iCub robot

The integration of the ROBOSKIN tactile sensor on iCub, has involved forearms, upper arms, torso and hands (palms and fingertips). The current implementation allows obtaining a number of distinguished taxels equal to 2400. In figure 5 the final result is shown.

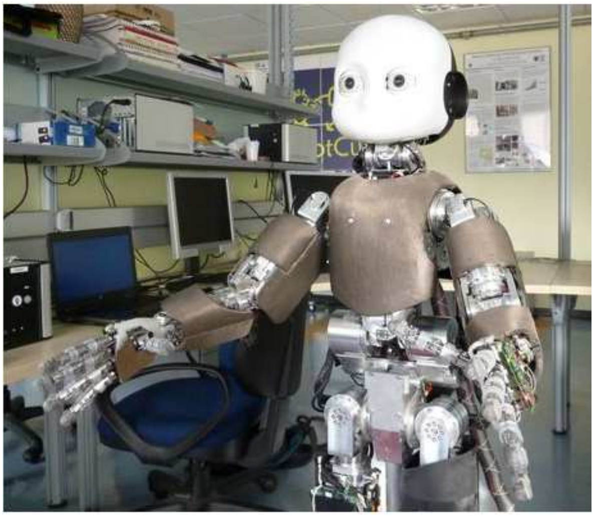


Figure 5. The iCub covered with artificial skin

3.1.1. Implementation on the iCub hands

As it is possible to see in figure 4(a), the palm of iCub is made from carbon fiber; since this is a structural part, we decided not to modify it, but instead, we added another cover above the carbon fiber part as a basis for the sensor: it has a thickness of 1.2 *mm* and provides space for the CDC chip and the other electronic components which are soldered on the PCB. The implementation steps are reported in Fig. 4. While for all the iCub parts the standard ROBOSKIN solution for the PCB has been used, for the iCub fingertips it has been necessary to design a specific solution (see figures 7(a), 7(b), 7(c)), since they have small size and round shape (each fingertip is 14.5 mm long and 13 mm wide and high and has a round shape that resembles a human fingertip).

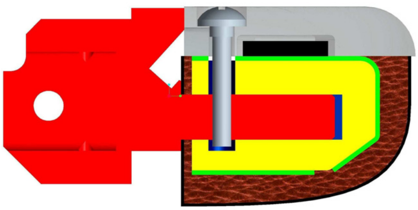
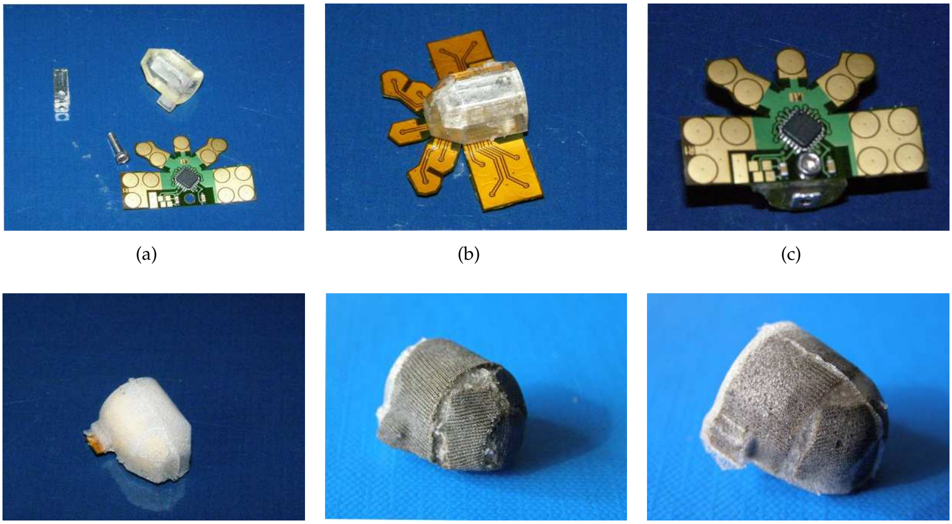


Figure 6. Crosssection of the fingertip.

The structure of the fingertip is illustrated schematically in Fig. 6: the inner support of the fingertip is shown in yellow, and the flexible PCB, that is wrapped around, is depicted in green. To mechanically attach the fingertip to the hand, the last phalanx of each digit (shown in red) has a stick that fits inside a hole in the inner support. A screw is used to secure the fingertip and, in addition, the screw fixes a fingernail on top of the fingertip that covers the

PCB. The dielectric, made of silicone rubber foam, is depicted in brown; around the foam there is the conductive lycra layer shown in black as well as the AD7147 chip.



(a) (b) (c)

(d) (e) (f)

Figure 7. The production steps for the fingertip iCub

The fingertip production protocol involves the following steps:

- The flexible PCB is wrapped around an inner support that was printed with a 3D printer. (see figures. 7(a), 7(b), 7(c)). As we are using an I^2C serial bus, only 4 wires have to be connected to the PCB (Vcc, ground, serial data line and serial clock). They travel along the side of the fingers to small boards at the back of the hand. These boards relay the data from all five fingertips (and the four triangular modules in the palm) to one microcontroller board, which is located in the forearm of iCub.
- A first layer, made with a foam elastomer (Smooth-on Soma Foama 15), is deposited over the PCB; mechanical deformation of this soft dielectric material leads to capacitance variations; therefore, it is possible to detect pressures applied on the fingertip, see figure 7(d).
- The second layer, that is made with conductive lycra, is glued over the silicone foam substrate, allowing the development of a single ground plane above all electrodes placed on the PCB thus enabling the detection of each type of object (conductive and non conductive) within noise reduction. This layer is connected to the digital ground of the CDC by one flat pad on the PCB.
- Finally the third protective layer, made again with Smooth-on Soma Foama 15, is deposited; it is used such as a protection, thus intrinsically increases the lifetime of the fingertip sensor.

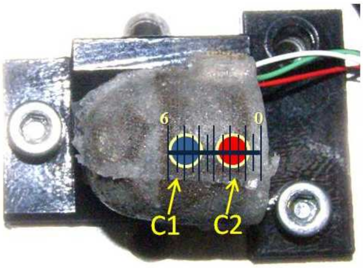


Figure 8. Fingertip sensor placed on the support used for measurements together with schematic view of the line where measurements have been taken

With respect to the first implementation of the fingertips [18], where it was used a self-made mixture of silicone (CAF4 from *Rhodia-Silicones*) and carbon-black particles (Vulcan XC72 from *Cabot*) as a ground plane, and, as protective layer, silicone glue (Sil-Poxy from *Smooth-On*) sprayed above it, the new implementation made with conductive lycra, has been chosen because it increases the durability of the fingertip to usury due to friction forces appearing during grasp tasks. In order to characterized the behavior of the new fingertip several experiments have been performed.

The characterization setup consists of a cartesian robot (TT-C3-2020 from IAI) which moves one non-conductive probe against the fingertip. The non-conductive probe is fixed at the top of an off-center load cell (AS1 form Laumas) which measures independently the force applied to the fingertip by the probe during the test. A microcontroller records the CDC output and the load cell circuit output. Therefore the Data are stored in a computer by a dedicated graphic user interface made in Matlab.

The characterization protocol was the following:

- One non-conductive probe of 4 mm diameter has been used. By the use of the Cartesian robot, the non-conductive probe applied different pressures to 13 positions, on the fingertip, separated by 0.5 mm along a 6 mm long straight line of two capacitors, indicated with C1 and C2(see figure 8).
- In each position, different pressures have been applied to the fingertip by vertical displacement of the non-conductive probe using the cartesian robot.
- Each pressure has been applied for 2 seconds, with intervals of 2 seconds. In order to investigate sensor repeatability, each pressure has been repeated fifty times. It must be observed that, along the straight line the probe was perpendicular to the fingertip.

Only the steady-state responses at external pressures of the sensor have been taken into account during post elaboration. Mean values of the fifty steady-state responses of C1 and C2, at different positions of the probe, are reported from figure 9(a) to figure 9(e). It is possible to observe a non linear trend of the capacitor variation as a function of the applied pressure. Therefore, the least squares method has been used to fit a polynomial model on each steady state response at each position. Figure 10(a) shows an example of the choice of the order of the polynomial function for CDC-C1 in the case of the position 0 mm, while, in figure 10(b), it is shown the norm of residual with respect to the polynomial order, on the basis of which,

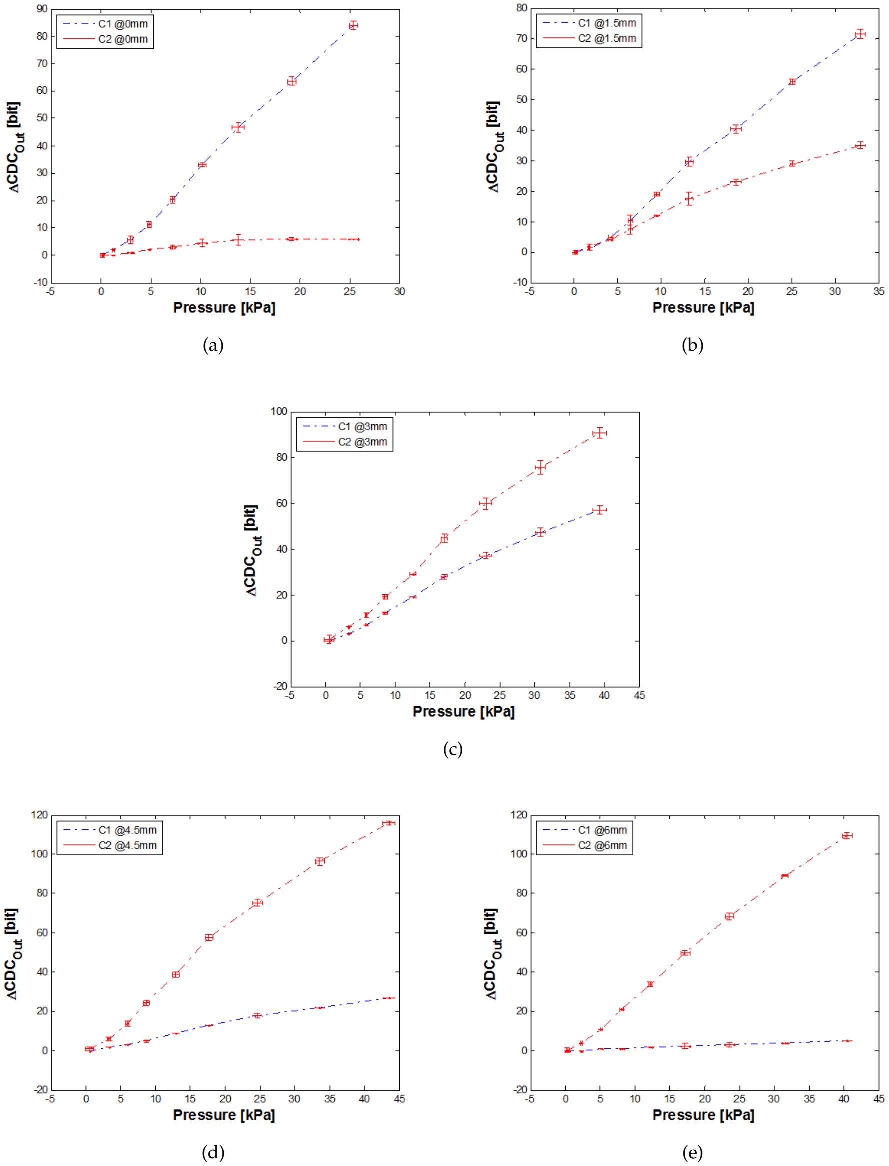
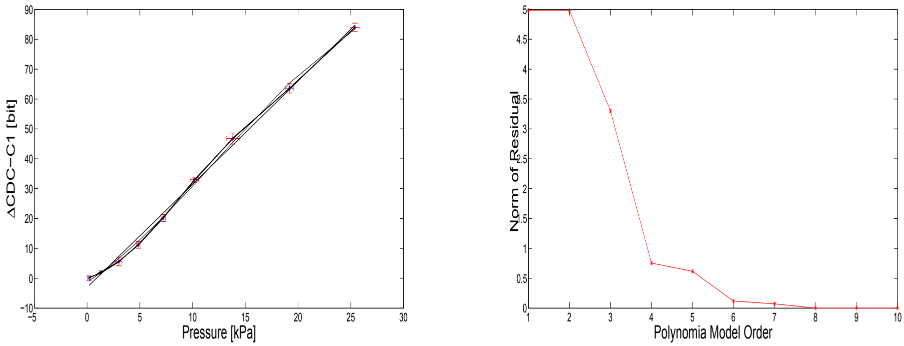


Figure 9. steady-state response at 0 mm (a), 1.5 mm (b), 3 mm (c), 4.5 (d) mm and 6 mm (e) position point of the straight line of measurement

a 4th polynomial model order has been chosen. Polynomial functions thus obtained, were used to calculate the variation of capacitors C1 and C2 due to a fixed pressure as a function of position along the measurement line. Results are presented from figure 11(a) and figure 11(e), which report the variation of capacitors C1 and C2 as a function of the probe position for five different pressure values from 5kPa to 25 kPa.



(a) (b)

Figure 10. a) An example of the choice of the order of the polynomial function for CDC-C1 in the case of the position 0 mm; b) Norm of the residual with respect to polynomial order

3.1.2. Implementation on the iCub arms

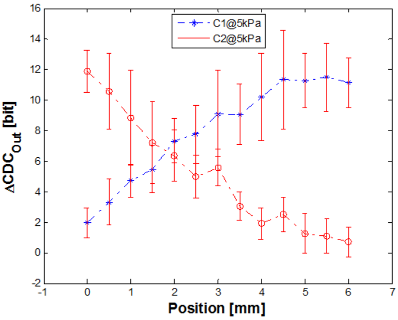
For the iCub arms, the skin was integrate directly into the covers, so new covers were designed. The production steps are the same as for the palm and the other iCub parts and are illustrated in fig. 12, for the forearm, and fig. 13, for the upper arm. On the two iCub arms we have 1464 contact points: 6 patches (61 triangular module) and 7 MTBs for each arm.

3.1.3. Implementation on the Torso of iCub

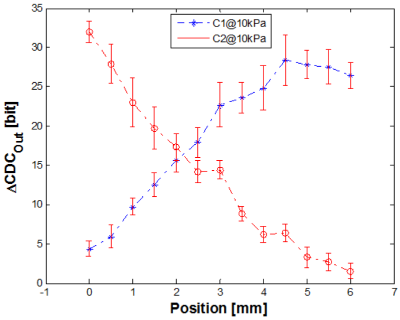
For covering the iCub Torso, five patches has been used, obtaining 528 contact points. In figure 15 it is possible to see the front of the torso covered with the glued patches and the silicone foam substrate (figure15(a)), the torso with the conductive lycra substrate on top (figure 15(b)) and finally the back of the torso cover with the 4 MTBs that are needed for the five patches (figure 15(c)).

3.2. Implementation of artificial skin on KASPAR

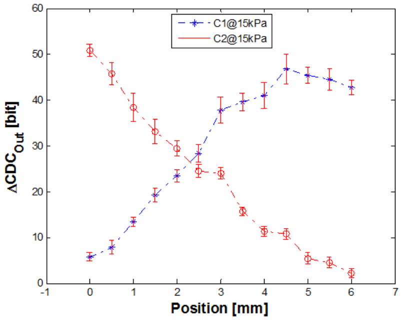
Despite the other two robot, that have an iconic appearance, KASPAR has a more human-like appearance, in fact in order to have a "natural" shape a child-sized mannequin was used as a basis and the legs, torso and the hands were kept. In order to invite children to touch the hands (which is more like touching a doll), the maintenance of human-like appearance has been an important parameter that has been kept under consideration in the covering process. For this purpose the hands have been covered with coloured foam silicone rubber (it has been



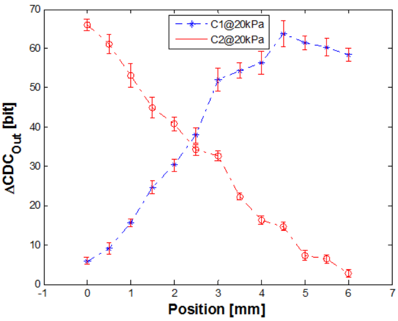
(a)



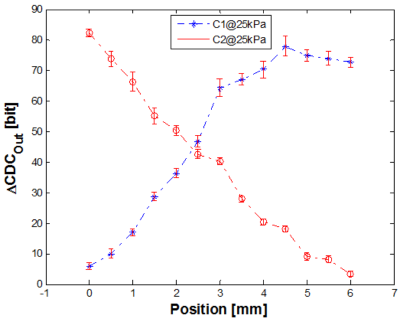
(b)



(c)

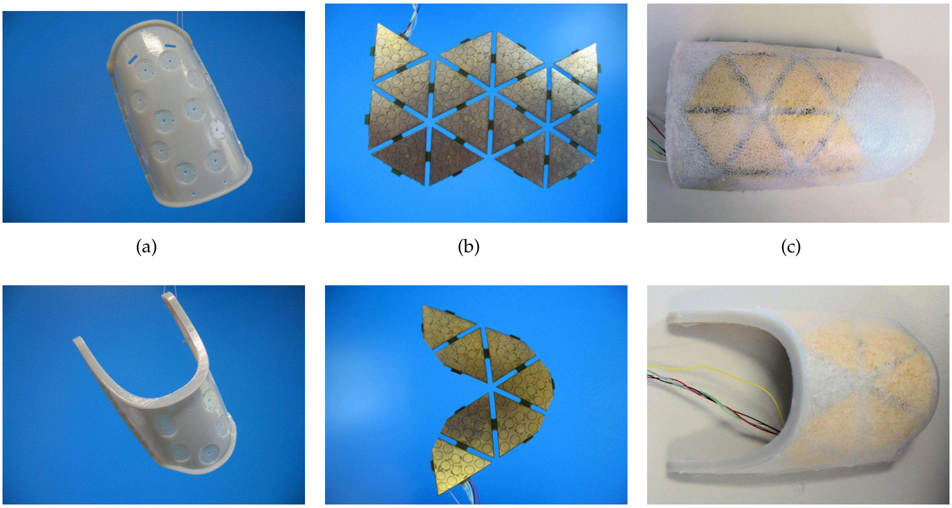


(d)



(e)

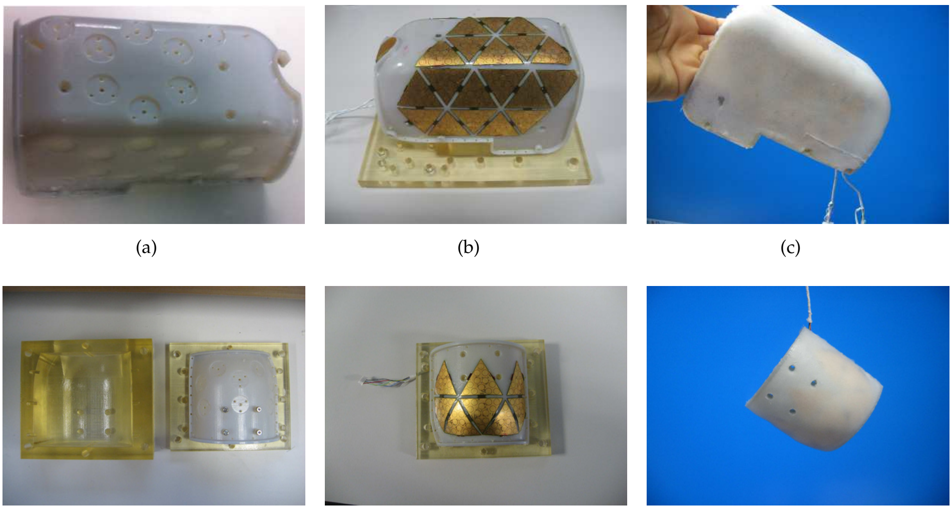
Figure 11. Calculated variations of C1 and C2 due to a fixed pressure applied by the probe along different positions of the straight line of measurement



(a) (b) (c)

(d) (e) (f)

Figure 12. The process steps for iCub forearm: two covers are needed which are mounted together on the robot forearm.



(a) (b) (c)

(d) (e) (f)

Figure 13. The process steps for iCub upper arm: two covers are needed which are mounted together on the robot upper arm.

Figure 14. The covers of iCub arms covered with conductive lycra

(a) (b) (c)

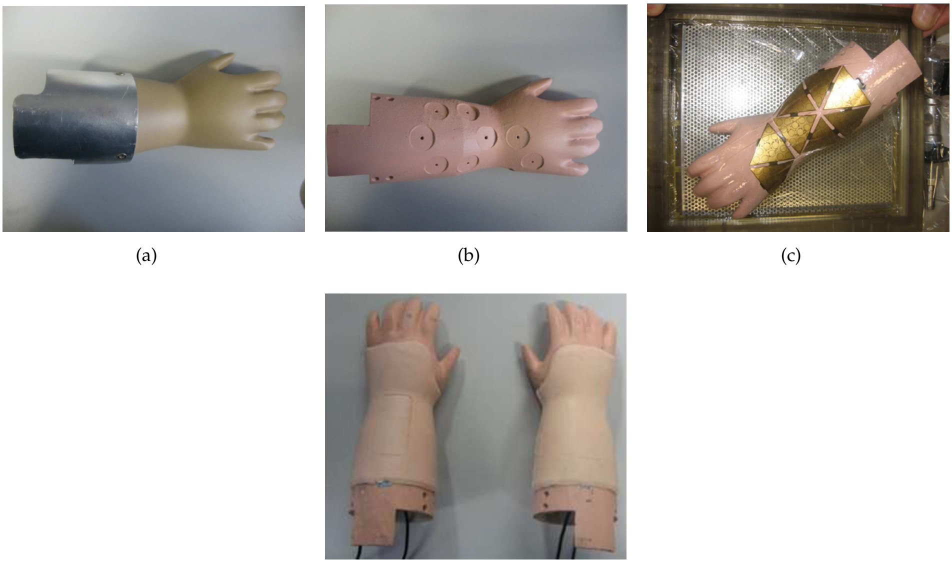
Figure 15. The process steps for iCub Torso

obtained adding color pigments to the rubber mixture). Furthermore it has been decided to not cover the silicone rubber substrate with ground plane (the KASPAR parts come in contact only with human being that constitute the ground plane during tactile contact). The hands have been scanned with a laser scanner and completely rebuild by a 3D printer in order to have the housing for the electronics (see figures 16(a) and 16(b)); The procedure used was the same explained before for the iCub parts. In figure 16(d) the final result for KASPAR hands is shown. For the other parts (cheeks, torso, upperarms and feet) we didn't take in consideration the human-like appearance because this parts, in the final setup of KASPAR, are covered by clothes. For the upper arms a cover with the housing for the electronics was build by a 3D printer and the patch was covered by a neoprene substrate. For the cheeks, torso and the feet it has not been possible to rebuild the part with the 3D printer (more expensive), so Artificial Skin patches have been applied on the puppet surfaces by glue. In total on KASPAR there are 12 MTB boards and 68 triangles that corresponds to 1128 contact point.

3.3. Implementation on NAO

For NAO the goal was to sensorize the forearms and the upper arms. Therefore, we designed 6 covers (2 for each forearm and 1 for each upper arm) to mount over the robot structural covers as for the iCub palm.

Fig. 18 shows the steps to cover NAO's forearm with skin. In total NAO has 18 triangles that correspond to 216 contact points for each lower arm and 9 triangles that correspond to 108 contact points for each upper arm.

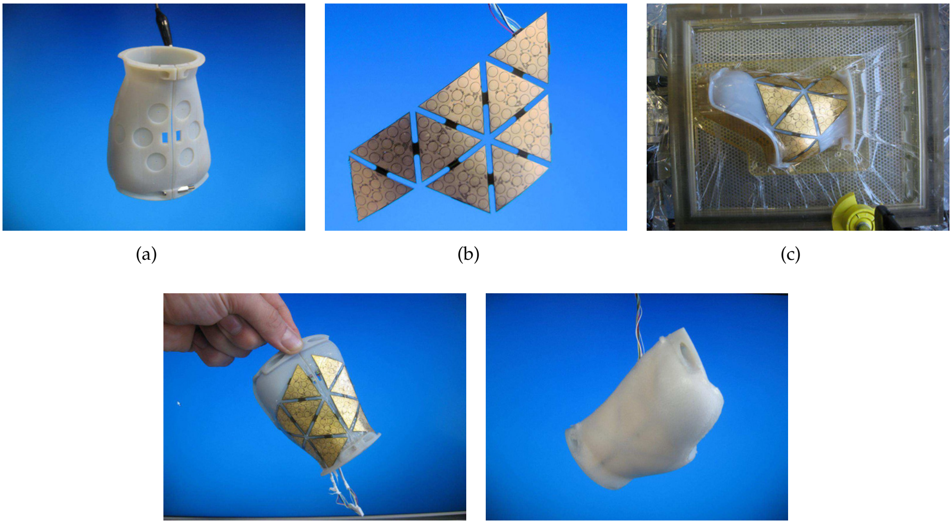


(a) (b) (c)

(d)

Figure 16. The process steps for KASPAR hands

Figure 17. NAO with his forearms covered with the artificial skin.



(a) (b) (c)

(d) (e)

Figure 18. The steps for implementing the skin on NAO's hands. (a) The two parts of the cover for NAO's forearm. (b) The triangles for one half of the forearm. (c) The PCBs are glued to the cover. (d) The cover with the PCBs. (e) The silicone foam has been molded onto the forearm. (e) The final result.

4. Conclusion

In the chapter the ROBOSKIN tactile system has been presented; in particular the procedures and methods for its integration in three different robotic platforms have been shown, proving its portability and its capability to cover large area of the robots body. Indeed the three robots have very different characteristics, but the integration steps were the same. A new implementation for the iCub fingertips has been shown and behavior characterization data have been presented. The new implementation allows to have a better robustness increasing the durability of the fingertip during grasp operations.

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