

# Touch Sensors for Humanoid Hands

Alexander Schmitz, Marco Maggiali, Lorenzo Natale and Giorgio Metta

**Abstract**—The sense of touch is of major importance for object handling. Nevertheless, adequate cutaneous sensors for humanoid robot hands are still missing. Designing such sensors is challenging, because they should not only give reliable measurements and integrate many sensing points into little space, but they should also be compliant and should not obstruct the other functions of the robot. This paper presents a capacitive pressure sensor system with 108 sensitive zones for the hands of the humanoid robot iCub. In particular, the palm has 48 taxels and each of the five fingertips has 12 taxels. The size and the shape of the hand are similar to that of a human child. When designing the sensors, we paid special attention to the integration on the robot. Also the ease and speed of production was an important design factor. Furthermore, the sensor incorporates silicone foam and is therefore compliant. We show the working principle of the sensor, how it has been integrated into the hands, and describe experiments that have been performed to show the characteristics of the sensor.

## I. INTRODUCTION

Tactile sensors for robotic hands are useful for a number of reasons. They provide feedback which can be used to adapt the grasp and manipulate objects. Especially when working with humans, robots need to be able to reliably detect touch and measure the forces they exert. Furthermore, cutaneous touch sensors can contribute to a rich sensory system which enables the robot to learn object properties and enhances the way it can interact with the environment.

While many different modes of transduction have been explored (for an overview see for example [1][2]), few sensors have been integrated into the hands of humanoid robots. This is because of the limited space available in such hands, which makes it difficult to preserve the other functions of the hand while integrating the sensor. While designing a sensor for robotic hands, one has to focus not only on the transducer, but also on embedded electronics, distributed computation, wiring, ease of production and robustness [2].

Several groups have included 3-axis force sensors (for example the Paloma hand [3]) or even 6-axis force sensors (for example the DLR-HIT hand [4]) into robotic hands. These sensors can localize touch only to an extent, but they

can also reliably measure shear forces. The GIFU III [5] not only has a 6-axis force sensors in its fingertips, but also 859 pressure sensing points spread all over the hand. However, due to the nature of its sensors, the skin is not compliant and the signal conditioning is located at a considerable distance from the sensitive area. The fingers of the MAC hand [6] include 8 identical modules; each module has embedded electronics and incorporates a 3-axis force sensor in addition to a pressure sensitive rubber with 64 contact points. Yet, the sensor is not compliant and too big to be included into a hand as small as the one of the iCub. The Obrero hand [7] has 40 contact points which embed 4 sensors each. An example of a hand which mounts high resolution fingertips is the Shadow hand [8]; unfortunately it is difficult to determine the quality of the sensory system since not much has been published about it.

Capacitive pressure sensors have already been explored for some time. Miyazaki and Ishida [9] used a capacitive sensor to measure vertical foot force. In [10] a 3-axis sensor based on capacitive principle is proposed. Gray and Fearing [11] implemented an 8 x 8 capacitive tactile sensing array within 1  $mm^2$ . In [12] 300dpi and 500dpi capacitive tactile imaging arrays are reported. In [13] an artificial skin based on capacitive technology with interesting characteristics like no apparent hysteresis and low noise was presented. None of these solutions has been integrated into a robotic system. A system using small brushes was integrated into a robot gripper and was described to have high sensitivity [14].

Recently a number of products like laptop trackpads, MP3 players, computer monitors and cell phones have been using capacitive technology to detect and localize human touch, for example the “iPod-touch” [15]. Therefore, small dedicated A/D converter chips have been made commercially available, for example the AD7147 [16]. Being able to digitalize the analog sensor measurements close to transducer reduces the electronic noise in the signal, and more importantly makes it possible to send the measurements over a bus, which reduces the number of necessary wires. The less wires have to be included into a robotic hand, the easier it is to install the sensor without impeding the dexterity of the hand.

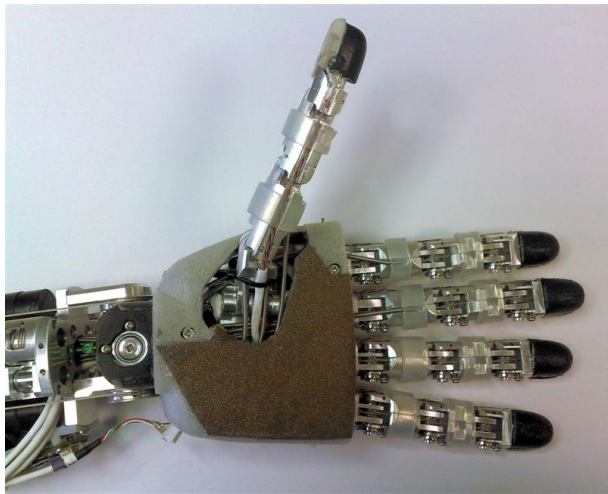
Profile Systems [17] sells capacitive pressure sensors, for example the wearable glove-like “FingerTPS” system. It supports up to 6 capacitive pressure sensors per hand. They are made of soft, conductive Lycra which conform to the finger and allow dexterous operations. The “RoboTouch” system, also from Pressure Profile Systems, has been included in the robots PR2 [17] and Twendy-One [18]. Twendy-One has 241 pressure sensing points based on capacitive technology in each of its hands, the fingertips have a round shape, the skin

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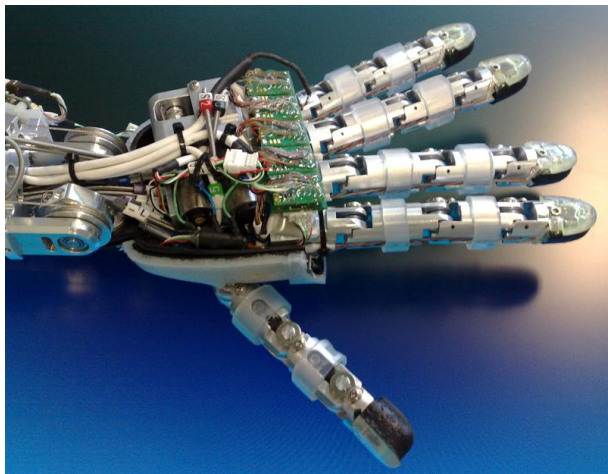
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(a)



(b)

Fig. 1. **The hand of the humanoid robot iCub.** The palm is equipped with 48 taxels, each fingertip has 12 taxels. Overall each hand has a sensory system with 108 sensors.

is compliant, and the fingertips also include a six-axis force sensor. To the best of our knowledge, however, no data has been published concerning the performance of the sensors.

In [19] we presented tactile sensors that have been integrated into the fingertips of the iCub and in [20] and [21] a "skin" based on triangular modules was described. In this work we present the integration of the triangular skin modules into the palms of the iCub to create a fully sensorized hand and compare test results of the fingertips with the palm.

## II. INTEGRATION ON THE HANDS OF THE HUMANOID ROBOT ICUB

The sensors described in this paper have been mounted on the hands of the humanoid robot iCub. iCub is 104cm tall and has 53 controllable degrees of freedom (DOF). It is equipped with digital cameras, gyroscopes and accelerometers, microphones, and force/torque sensors [22].

In particular, the hand of the iCub is roughly 14cm long and 6cm wide and has five underactuated fingers. Each hand

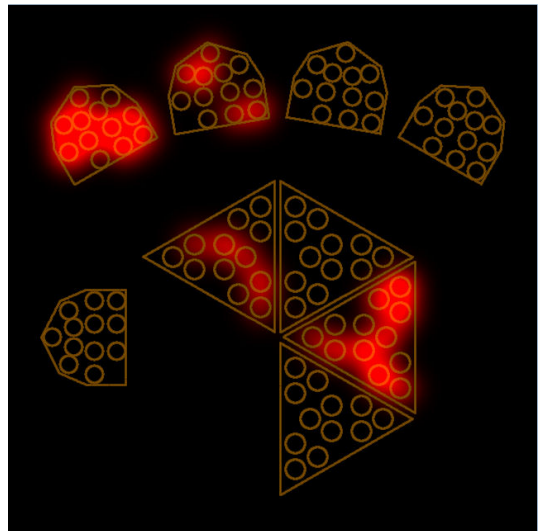


Fig. 2. Schematic representation of how the sensors are distributed on the fingers and palm.

has 9 DOF, plus three DOF for the wrist. Seven of the nine motors for the hand are located in the forearm. To measure the posture of the hand, most joints in the hand are instrumented with Hall effect sensors in addition to the incremental encoders in the motors.

We have integrated a capacitive pressure sensor system with 108 sensitive zones into the hand of iCub, i.e. into the palm and all fingertips, see Fig. 1 and Fig. 2. The palm consists of four triangular modules, which can be used to cover generic curved surfaces and will be used to cover also other parts of the robot body in the future [3]. On the contrary, the small size and round shape of the fingertips made it necessary to design a specific solution that fits on the fingers of the iCub. As a result each fingertip is 14.5 mm long and 13 mm wide and high. It has a round shape that resembles a human fingertip.

## III. CAPACITIVE PRESSURE SENSOR TECHNOLOGY

Each triangular module and each fingertip incorporate a flexible PCB with the electronics to obtain 12 capacitive pressure measurements and send them over a serial bus. In particular, each PCB includes 12 round pads for the capacitive pressure sensor and a capacitance to digital converter (CDC) (AD7147 from Analog Device, [16]). The CDC chip has on-chip environmental compensation and is able to measure either all 12 taxels independently at 50 Hz or an average of the 12 taxels at about 500 Hz. The CDC can provide twelve 16 bits measurements of capacitance and send them over an I<sup>2</sup>C serial bus. As a result, for the fingertips, only 4 wires travel along the side of the fingers to small boards at the back of the hand. In the case of the palm, the triangles also include the electronics to communicate between themselves over a serial bus, therefore only one of them is connected to the boards in the back of the hand. These boards relay the data from all five fingertips and the

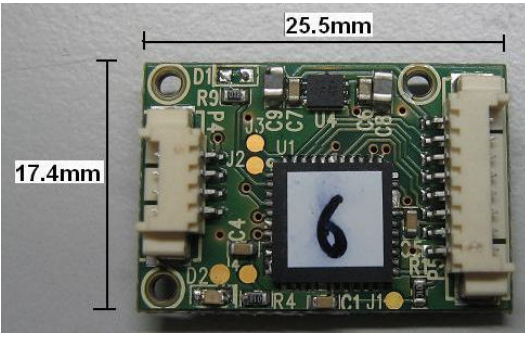


Fig. 3. **The microcontroller board.** It receives all the measurements and sends them over the CAN bus to the PC104 in the iCub head.

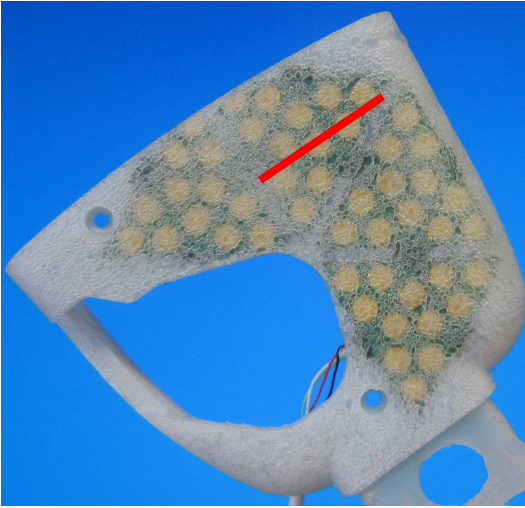


Fig. 4. **Dielectric made of silicone foam above the triangular modules in the palm.** The silicone foam (Soama Foama from Smooth-On) covers the triangular modules in the palm. The foam acts as a deformable dielectric for the capacitive pressure sensor and guarantees the compliance of the sensor. Also visible are the round pads on the triangular modules. The sensor delivers one capacitance measurements for each round pad. The red line shows the taxels that we tested in the experiment reported in Fig. 13 (see text).

four modules in the palm to a microcontroller board, which is small enough to be included into the forearm of iCub (see Fig. 3). The microcontroller unit collects the measurements from all the CDC chips and sends the measurements through a CAN bus to the PC104 in the iCub head.

A layer of silicone foam (Soma Foama 15 from Smooth-On<sup>1</sup>) covers the 12 pads, see Fig. 4. It is roughly 2mm thick and acts as a deformable dielectric for the capacitive pressure sensor system. The foam also guarantees the compliance of the sensor. It compresses easily after the first contact and this makes the sensor sensitive to light touch. The foam contains air bubbles that when compressed enough make the whole structure somewhat stiffer. This non-linearity is useful to enhance the range of measurable forces.

In the case of the palm, we have glued electrically conductive Lycra fabric on top of the silicone foam. The fabric is electrically connected to ground and acts as the

other conductor for the capacitive sensor system. This is necessary to guarantee the same response of the sensor to objects with different electrical conductivity (unlike many consumer products, which are not responsive to insulators, for example). The grounded Lycra also reduces the electronic noise coming from the environment, in particular the stray capacity, which is usually a problem for capacitive pressure sensor systems [2].

For the fingertips we use a different material as a conductor on top of the silicone foam, which conforms more easily to the round shape of the fingertip. Specifically, we spray a thin layer of conductive silicone on top of the silicone foam, which is a self-made mixture of silicone CAF4 from Rhodia-Silicones and carbon-black particles Vulcan XC72 from Cabot<sup>2</sup>. This layer is elastic, adhesive to silicone and sufficiently electrically conductive for the fingertips (about  $10k\Omega$  measured between two points at the maximum distance found on the fingertips). To spray this material we used the solvent tetrahydrofuran. We also spray a thin layer of silicone glue (Sil-Poxy from Smooth-On) above the conductive silicone layer to protect the conductive layer.

The physical transduction principle behind the sensor is that the capacitance depends on the distance between the 12 round patches on the flexible PCB and the conductive material on top of the silicone foam (either the conductive lycra or the conductive silicone rubber layer). The silicone foam acts as a soft dielectric. When pressure is applied to the surface of the sensor, the conductor on top of the foam gets closer to the flexible PCB and the capacitance changes accordingly. The change of capacitance is taken as an estimation of the pressure applied to the sensor.

#### IV. THE PALM

The palm consists of four triangular modules (see Fig. 4 and 5). Each is based on a flexible PCB, which can conform to generic smooth curved surfaces and can therefore be used to cover also other parts of the robot [20][21]. Each module provides 12 capacitive measurements and can send them over a serial bus. Three communications ports placed along the sides of the triangle (one for input and two for output) allow relaying the signals from one triangle to the adjacent one. Up to 16 triangles can be connected in such a way, and only one of them needs to be connected to the microcontroller board. This is a critical advantage since it reduces the amount of wires and electrical connections that are required.

#### V. THE FINGERTIPS

The fingertips have a shape that resembles human fingertips and are 14.5 mm long and 13mm wide and high. The fingertip has a round shape that resembles a human fingertip. The structure of the fingertip is illustrated schematically in Fig. 6. In the fingertips the flexible PCB is wrapped around an inner support (see Fig. 7). The inner support was printed with a 3D printer (Eden 3D printer from Objet<sup>3</sup>). To mechanically attach the fingertip to the hand, the last

<sup>1</sup>www.smooth-on.com

<sup>2</sup>www.cabot-corp.com

<sup>3</sup>www.objet.com

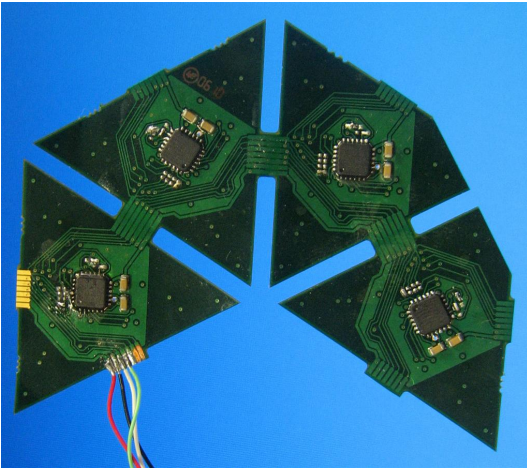


Fig. 5. **Triangular PCBs.** Each triangular module includes an AD7147 chip. The modules are connected to each other, and therefore only one of them needs to be connected with wires to the microcontroller board.

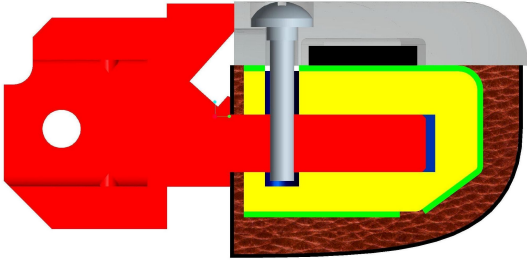


Fig. 6. **Cross-section of the fingertip.** Yellow: inner support. Green: flexible PCB. Blue: attachment mechanism to the rest of the finger (the last phalange of the finger, shown in red, has a stick at its end that fits inside of the fingertip and is fixated with a screw). Brown: dielectric made of silicone rubber foam. Black layer around the dielectric: the second, deformable conductor for the capacitive sensor. The depiction of the components of the fingertip is proportionally correct.

phalange of each digit has a stick that fits precisely inside a hole in the inner support of the fingertip. A screw is used to hold the fingertip in place. The screw also fixes a fingernail on top of the fingertip that covers the PCB.

## VI. TESTING

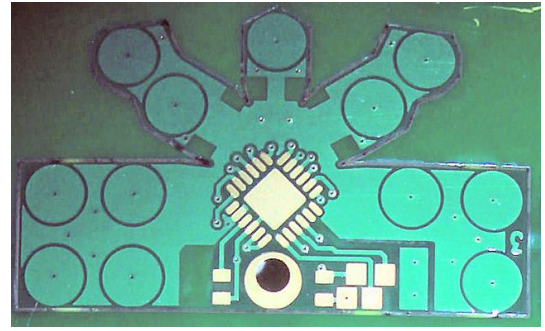
### A. Test Setup

To test the capacitive pressure sensor we use a Cartesian robot (TT-C3-2020 from IAI<sup>4</sup>). The robot moves an off-center load cell (AS kg 1 for the fingertips, AS kg 0.5 for the palm, from Laumas<sup>5</sup>). At the end of the loadcell a probe is mounted (see Fig. 8), which is moved during the tests against the fingertips or palm, respectively. The signal from the loadcell is amplified by an AT-10 from Precise Instruments<sup>6</sup>, and to digitalize the signal we use the same microcontroller board that we also use to send the measurements of the capacitive pressure sensor system to the PC. Therefore, we get synchronized data from the capacitive

<sup>4</sup>www.intelligentactuator.com

<sup>5</sup>www.laumas.com

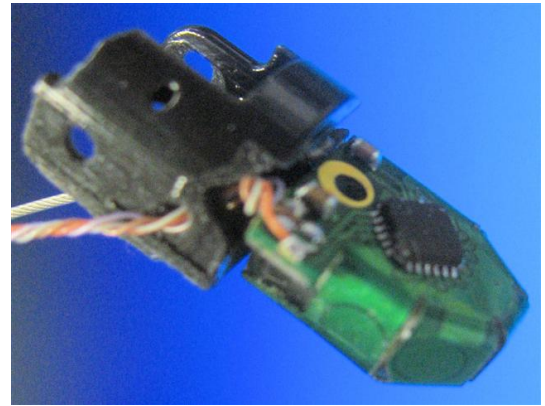
<sup>6</sup>www.preciseinstrument.com



(a)



(b)



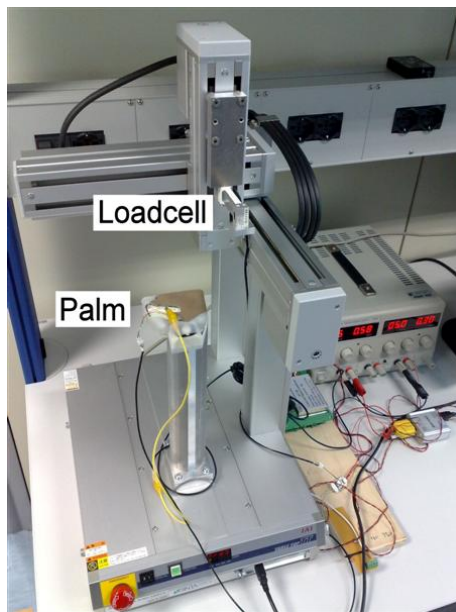
(c)

Fig. 7. **The flexible PCB for the fingertips.** In (a) the 12 pads for the capacitive pressure sensor system and the soldering points for the CDC chip, for the 2 capacitors and for the connector cables for the digital output are visible. In (b) the flexible PCB wrapped around the inner support can be seen. The inner support is produced with a 3D printer. In (c) the flexible PCB wrapped around the inner support and mounted to the last phalange of the finger (here in black) can be seen. The AD7147 chip, the capacitors, and the wires are soldered on the PCB.

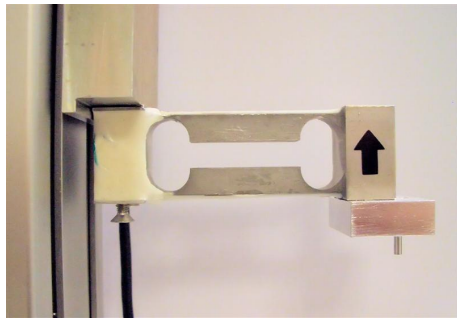
pressure sensor system and the loadcell. Cylindrical metal probes of varying diameter can be attached to the loadcell. The Cartesian robot moves the loadcell with the metal probe in x, y and z direction and can therefore push the metal probe vertically against the sensor at different locations. When the probe moves downward, it applies pressure.

### B. Experimental Results and Discussion

In the first experiment we tested the response of the fingertip to different pressures. The probe was placed above one of the taxels of the sensor system and was then moved up and down several times. We moved the probe in small steps of 0.1mm each, to cover the available range. In each step we collected data from the fingertip and the load cell and then changed the position of the probe after 60 seconds. Fig.



(a)

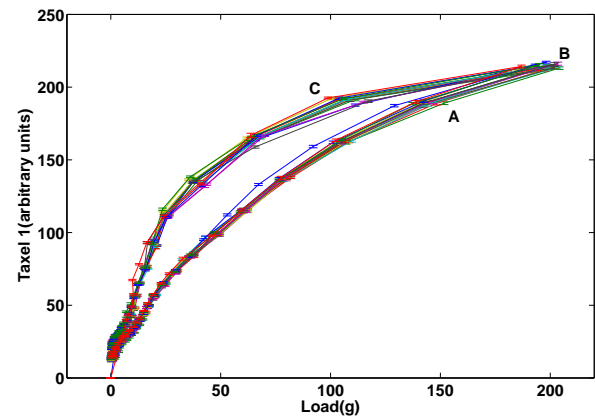


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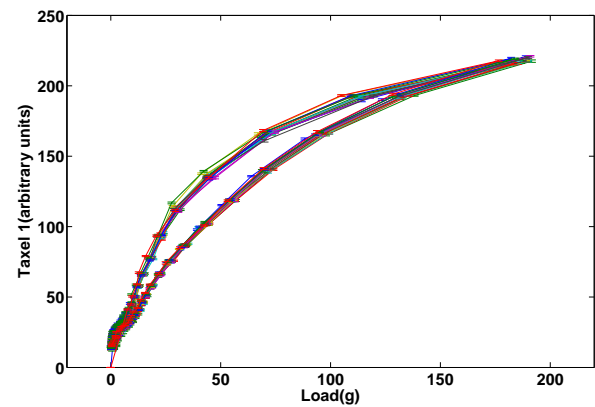
Fig. 8. **Test setup.** The test setup that is used to test the characteristics of the sensor is shown. In this picture, the palm is mounted on a platform. On the same platform also the fingertip can be mounted. A Cartesian robot (TT-C3-2020 from IAI) moves an off-center loadcell (AL series, from Laumas). In (b) the probe that is used to push the palm or fingertip, respectively, can be seen.

9 (a) shows the average and standard deviation of the sensor measurements collected in the first second immediately after moving the probe, while Fig. 9 (b) reports the data that was collected in the last second before moving the probe again. In both plots, when increasing the pressure we could observe the nonlinear response we expected due to the characteristics of the silicone foam as discussed previously. Indeed, this property might be useful as it makes the sensor particularly sensitive to low pressures and still able to measure forces as large as about 2 Newton over an area of  $12.6\text{mm}^2$  ( $0.16\text{ N/mm}^2$ ). The result also shows that there is low noise in the measurements, as the standard deviations as well as the differences between the repetitions are low. Unfortunately, we could also clearly observe hysteresis in the sensor system. The hysteresis was clearly higher in (a) than in (b).

We performed a similar experiment with the palm (see Fig. 10). The response looks more linear and less hysteresis is visible: this is because the maximum pressure is lower and



(a)



(b)

Fig. 9. **Response of a taxel of the fingertip to different pressures.** Every 60 seconds we moved the probe (2 mm diameter) up and down in steps of 0.1 mm. In (a) we show the average and standard deviation of the first second of measurements, in (b) of the last second. Clearly visible is the nonlinear response of the capacitive sensor, with a higher sensitivity for lower pressures. Also visible is the hysteresis of the sensor, which is higher in (a) than in (b).

the robot remained only 2 seconds in every position. When we pushed harder and stayed 60 seconds in every position like with the fingertip, also the nonlinearity and hysteresis looked similar to the one in the fingertips (results not shown for space reasons). Concerning hysteresis, the experiments with the fingertips represent the worst case scenario (pushing the foam hard for an extended period of time), while the results in Fig. 10 show that if the forces stay in a lower range and are not maintained for extended periods of time, the hysteresis of the sensor is considerably reduced.

The results above are probably due to the viscoelastic properties of the silicone foam. To further analyze the viscoelasticity of the foam, we conducted another experiment in which the probe remained stationary for longer time. We were using again the fingertip, and in this experiment the probe changed its position only every 720 seconds, and remained even 1440 seconds at the position where it applied the highest pressure to the fingertip. In Fig. 11 we show the time series of measurements when the probe is in

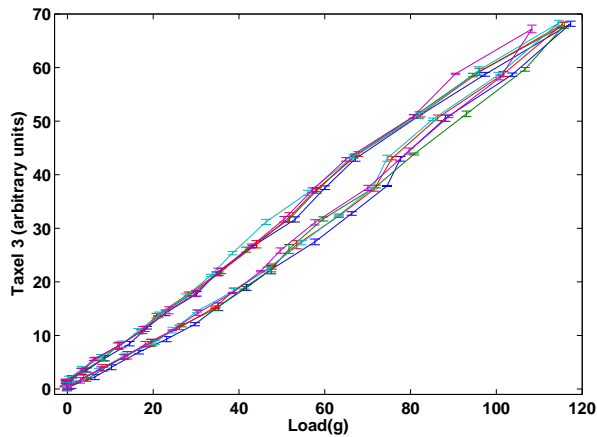


Fig. 10. **Response of a taxel of the palm to different pressures.** Every 2 seconds we moved the probe (3 mm diameter) up and down in steps of 0.1 mm. We show the average and standard deviation of the first second of measurements.

its second deepest position (phase A), then moved to the position where it applied the most pressure (phase B), and then again moved to the second deepest position (phase C). These phases correspond also to the phases shown in Fig. 9. We present the data of both the capacitive pressure sensor and the force as measured by the loadcell. The capacitive sensor has a relatively stable output during each phase and similar measurements during phase A and C.<sup>7</sup> It can be concluded that the sensor gives a good measurement of displacement<sup>8</sup>. However, the viscoelastic properties of the foam are clearly visible. As we keep the strain constant in each phase, the stress changes: the pressure varies while the probe is stationary and this explicates the differences between Fig. 9 (a) and (b). The differences between phase A and C show up as hysteresis in Fig. 9.

The initial response of the capacitive sensor to a change of displacement of the probe was very fast: There was no delay between the initial change of the measurements of the capacitive sensor and the loadcell. Of course, this does not take into account the delay due to the microcontroller board and the subsequent CAN-bus (this delay is difficult to quantify in our setup).

Finally, we tested the spatial resolution of the sensor. The probe applied pressure to the fingertip at different positions, along a straight line from the back of the fingertip to the front. Along this line the surface of the fingertip is nearly perpendicular to the probe. For each position, the probe moved up and down several times, before moving towards the front of the fingertip, in steps of 0.1 mm each. We show the measurements of the 3 taxels that the probe traverses while going from the back to the front. In this plot we show the response of the sensor to a constant pressure; to do this

<sup>7</sup>The small changes are probably due to the off-center loadcell, which bends when force is applied to it. Therefore, even though the robot does not move, the position of the probe changes a bit as the force changes.

<sup>8</sup>Indeed, the capacitive sensor has a linear relationship to displacement, the results are not shown because of limited space.

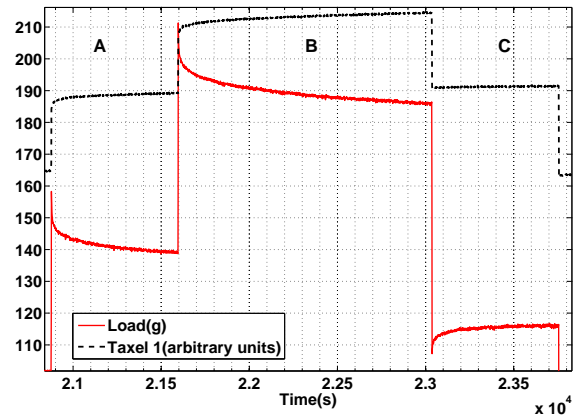


Fig. 11. **Hysteresis.** The probe (2mm diameter) remained for 720 seconds in one position (phase A), then pushed 0.1 mm down (thereby increasing the pressure), remained there for 1440 seconds (phase B), moved 0.1 mm up (thereby releasing pressure and returning to its original position), and remained there for another 720 seconds (phase C). The capacitive sensor has a relatively stable output during each phase and similar measurements during phase A and C. However, the pressure changes while the probe is stationary and varies between phase A and C.

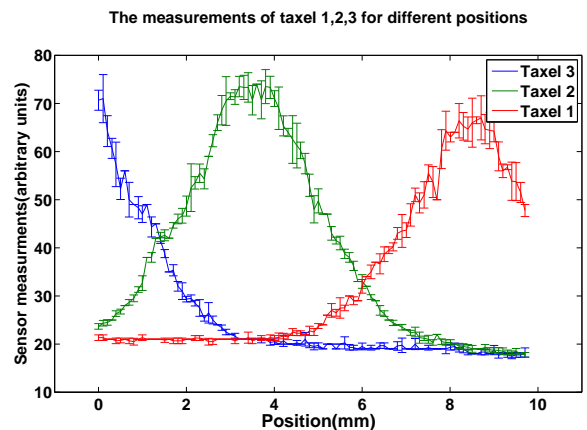


Fig. 12. **Spatial resolution of the fingertip.** The probe (2 mm diameter) is pushing the fingertip at different positions (0.1 mm distance to each other), along a straight line from the back to the front of the fingertip. Along this line the surface of the fingertip is nearly perpendicular to the probe. For each position the probe moves up and down several times. We show the average measurement and standard deviation for 3 different taxels when the loadcell measures 28-32g.

we filtered the data offline and plot only those values which correspond to a force of 28-32g. The results presented in Fig. 12 show that there is little cross-talk between the taxels and that the fingertip can be used to localize where pressure is applied. We conducted a similar experiment for the palm. The results in Fig. 13 are similar to the one of the previous experiment. The different response of the 5 taxels we tested can be explained by the fact that the probe was not placed exactly at the center of the sensors (the red line in Fig. 4 shows the locations that were tested with the probe, the probe moved from left to right).

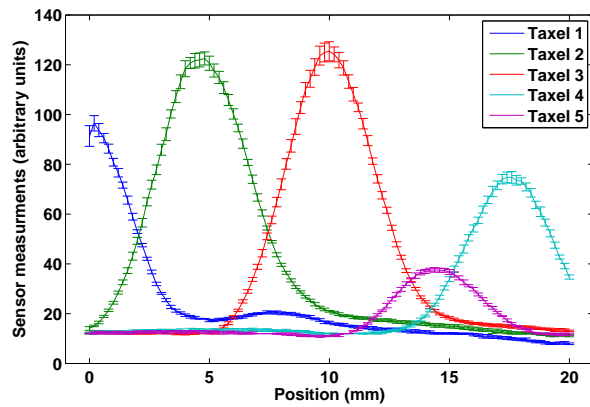


Fig. 13. **Spatial resolution of the palm.** The probe (3 mm diameter) is pushing the palm at different positions (0.2 mm distance to each other), along a straight line, as can be seen in Fig. 4, starting at the right side of the palm. For each position the probe moves up and down 15 times. We show the average measurement and standard deviation for 5 different taxels.

## VII. CONCLUSIONS AND FUTURE WORKS

### A. Conclusions

We presented a robotic hand with a capacitive pressure sensor system. While designing the sensor special attention was given to the integration on the robot. Also the ease and speed of production was an important design factor. The fingertips and the palm incorporate a PCB with the electronics to perform the digitalization: this reduces the number of wires required to connect the fingertip and the palm. Furthermore, the fingertip has a shape similar to a human fingertip, is small, provides 12 pressure measurements and is intrinsically compliant. The palm is based on a modular system that can be used also for other parts of the robot. Our results show that the sensor can be used to determine where and (although to a lesser extent) how much pressure is applied to the sensor.

### B. Future Works

We would like to further test the sensor, especially its endurance, its step response, the minimal measurable pressure, and the response to probes of different diameter and shape. Also its ability to aid grasping and object manipulation has to be proven. We are planning to test different dielectrics to reduce the hysteresis and make the sensor more sensitive. Along the same line, the flexible PCB can be also wrapped around an inner support made of silicone, which increases the compliance of the fingertip. The number of taxels could be increased from 12 to 24 by using the PGA version of the AD7147 chip and decreasing the size of the taxels. In addition, it would be beneficial to include other sensor modalities in the fingertip. As the general principle described in this paper is easily applicable to other shapes, capacitive sensor systems could be also included in the other phalanges of the fingers of the humanoid robot iCub.

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