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# A Tactile Sensor for the Fingertips of the Humanoid Robot iCub

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*Abstract*— **In order to successfully perform object manipulation, humanoid robots must be equipped with tactile sensors. However, the limited space that is available in robotic fingers imposes severe design constraints. In [1] we presented a small prototype fingertip which incorporates a capacitive pressure system. This paper shows an improved version, which has been integrated on the hand of the humanoid robot iCub. The fingertip is 14.5 mm long and 13 mm wide. The capacitive pressure sensor system has 12 sensitive zones and includes the electronics to send the 12 measurements over a serial bus with only 4 wires. Each synthetic fingertip is shaped approximately like a human fingertip. Furthermore, an integral part of the capacitive sensor is soft silicone foam, and therefore the fingertip is compliant. We describe the structure of the fingertip, their integration on the humanoid robot iCub and present test results to show the characteristics of the sensor.**

## I. Introduction

Tactile sensing is a key requirement for grasping and object manipulation. If humans lose their sense of touch it is hard for them to maintain a stable grasp [2]. Like humans, humanoid robots are expected to adapt to novel objects and changes in the environment. Tactile information is essential for adapting the grasp, and in addition can be used to actively explore the object in-hand. Thus, it is possible to obtain information about objects that is hard or even impossible to acquire through other sensing modalities such as vision or sound (for example, weight, slipperiness, texture and hardness). Therefore, sensing not only aids action, but actions can be also performed to obtain "good" sensory data, enabling categorization, adaptation and learning (see for example [3][4][5]).

Many touch sensors have been described in literature, using various different methods of transduction [6]. For a recent overview of existing technologies and their implementation on humanoid robots, see [7]. Particular interest exists in developing sensors for robotic hands for object grasping and manipulation. For example, the 6-axis force sensor used in DLR-HIT hand [8], the GIFU III hand [9] and the 3-axis force sensor in the Paloma hand [10] can all measure pressure and shear forces. The GIFU III hand has 859 sensing points, however due to the nature of its sensors, the skin is not compliant and the signal conditioning happens at a distance from the sensitive area. The Obrero hand [11] has 40 contact points which embeds 4 sensors each. The Shadow hand [12] has a high number of sensors in its fingertips, based on QTC technology.

A number of groups have used capacitive technology for sensors. Miyazaki and Ishida [13] used a capacitive sensor to measure vertical foot force. In [14] a 3-axis sensor based on capacitive principle is proposed. Gray and Fearing [15] implemented an 8 x 8 capacitive tactile sensing array within 1 $mm^2$. In [16] 300dpi and 500dpi capacitive tactile imaging arrays are reported. A system using small brushes was integrated into a robot griper and was described to have high sensitivity [17]. As reported in [18] and [19], a distributed sensorized skin is under development using the same capacitive sensor technology as described later in this paper.

Commercial products incorporating sensors based on capacitive technology exist, for example the "iPod-touch" [20]. Capacitive sensors that fit on hands are available from Pressure Profile Systems [21]. Their wearable glove-like "FingerTPS" system 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 measurements are sent wireless from a module strapped on the forearm to the PC. The "RoboTouch" system, also from Pressure Profile Systems, has been included in a number of robotic hands.

Therefore, while research on tactile sensing is an active research field, there is still a lack of satisfactory tactile sensors for humanoid robots. This is because "they are too big to be used without sacrificing dexterity or because they are slow, fragile, lack elasticity, lack mechanical flexibility, and lack robustness" [7]. As such, few tactile sensors have been integrated into robots and few of them have gone beyond the prototype stage.

## II. Comparison to previous versions

In [1] we presented the first version of fingertips for the iCub humanoid robot. The most important difference was that the printed circuit board (PCB) was not flexible, but instead the sensitive zones were painted with conductive ink on the inner support and were connected to the rigid PCB via small wires. As a result, the production process was work intensive and error-prone. Moreover, the sensitive zones were rectangular instead of circular.

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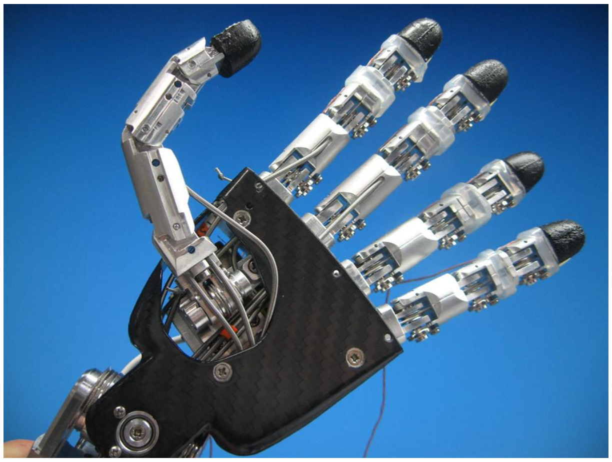

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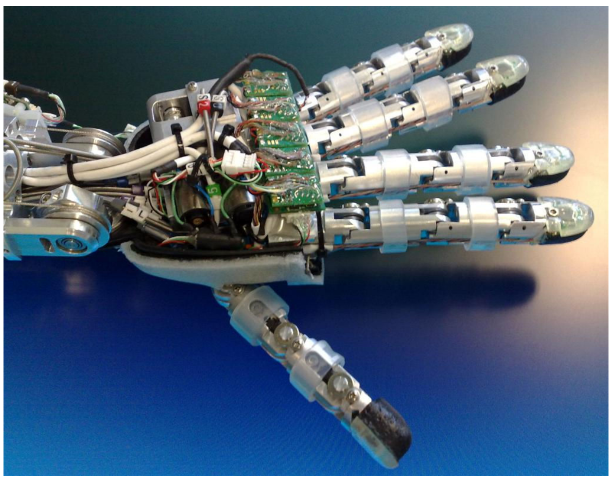


(b)

Fig. 1. **A hand of the humanoid robot iCub.** It has 9 controllable degrees of freedom, plus 3 for the wrist, and most of the actuators are located in the forearm. In the lower picture the back of the hand can be seen.

In comparison, the version presented here is easier and faster to produce, and the fingertips are more durable. In addition, the 12 sensitive zones have a circular shape. A drawback to this approach is that the silicone foam layer does not have a uniform 2 mm thickness as before, even though the differences in thickness are small.

## III. Description of the Fingertip

The fingertips were designed to fit on the hands of the humanoid robot iCub (see Figure 1). As a result each fingertip is 14.5 mm long and 13 mm wide. The fingertip has a round shape that resembles a human fingertip.

In brief, the fingertip is built up as follows (see Figure 2): A flexible PCB is wrapped around the inner support (see Figure 3). Above the flexible PCB is a layer of soft silicone foam (see also Figure 4). On top of the silicone foam is a thin layer of conductive silicone rubber, which is connected to ground.

The fingertip incorporates a capacitive pressure sensor system. Generally speaking, a capacitor consists of two conductors separated by a dielectric. The physical principle behind the sensor is that the capacitance (the ability of the capacitor to hold an electrical charge) depends on the distance of the conductors. In our case, the silicone foam acts as a soft dielectric and the conductive silicone rubber layer acts as one of the conductors. The flexible PCB includes 12 round patches, which act as the other conductor for 12 capacitors, respectively (see Figure 3 (a)). Therefore we can obtain 12 measurements of capacitance. When pressure is applied to the surface of the fingertip, the silicone foam gets compressed, and the capacitance changes accordingly. The change of capacitance is taken as an estimation of the pressure applied to the sensor.

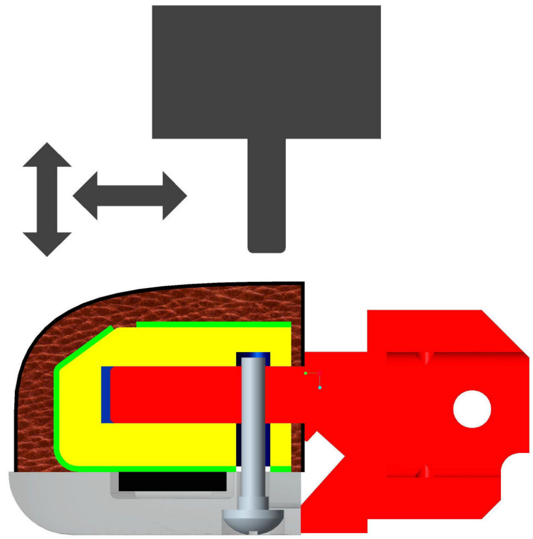


Fig. 2. **Cross-section of the fingertip and the testing probe.** Yellow: inner support. Green: flexible PCB. Blue: attachment mechanism to the rest of the finger (the last phalange of the finger, shown in red, has a stick at its end that fits inside of the fingertip and is fixated with a screw). Brown: dielectric made of silicone rubber foam. Black layer around the dielectric: the second, deformable conductor for the capacitive sensor.
In addition, the probe (2mm diameter) and the loadcell that is used to test the fingertip are depicted in dark grey. It can move up and down, left and right, backward and forward (not shown in the picture). The depiction of the components of the fingertip and the probe is proportionally correct.

### A. Structure of the Fingertip

The structure of the fingertip is illustrated schematically in Figure 2. The flexible PCB is glued on the inner support (see Figure 3). The inner support was printed with a 3D printer (Eden 3D printer from Objet[1]). The PCB includes 12 round pads that act as conductors for the capacitive pressure sensor system. These pads are connected to a capacitance to digital converter (CDC) (AD7147 from Analog Device, [22]), which is also mounted on the PCB. The CDC is able to provide twelve 16 bits measurements of capacitance and send them, using serial bus communication, through a digital line. This is beneficial because it allows digitizing the signal as close as possible to the transducer, thus improving the signal to noise ratio, and, more importantly, it reduces the number of wires that travel from the fingertips to the hand. The AD7147

[1] www.objet.com

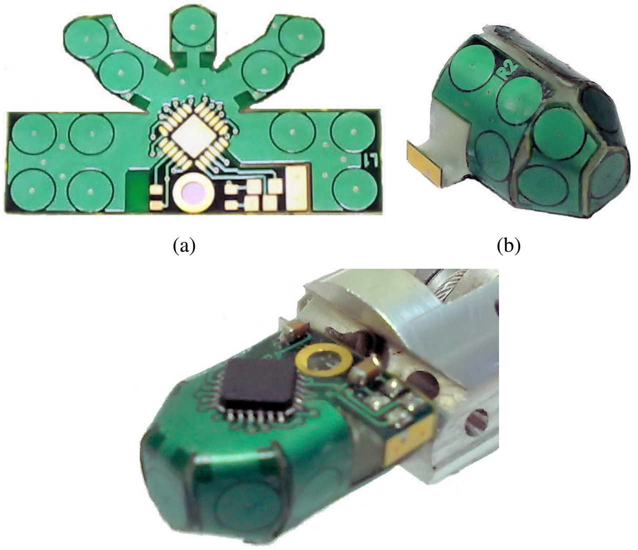

(a) (b) (c)

Fig. 3. **The flexible PCB.** 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 can be seen. The AD7147 chip and the capacitors are soldered on the PCB.

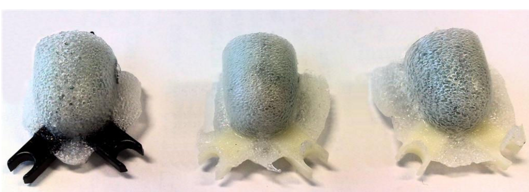


Fig. 4. **Dielectric made of silicone foam.** The dielectric for the capacitive pressure sensor is made of silicone foam (Soama Foama from Smooth-On). The foam also guarantees the compliance of the fingertips. Also visible are the holders of the fingertips in white or black, which are necessary during the production process. To produce the foam layer, the inner support with the PCB is inserted into a mold that has the shape of the final fingertip and it is fixed in the proper position with the help of the holder. The silicone foam is then poured into the remaining space between the mold and the PCB. The excessive silicone foam is removed at a later stage.

chip has on-chip environmental compensation and supports the $I^2C$ interface, so only 2 wires are necessary for the serial communication plus 2 wires for the energy supply.

The 12 pads are covered by a layer of silicone foam (Soma Foama 15 from Smooth-On[2], see Figure 4) that is roughly 2mm thick and acts as a deformable dielectric for the capacitive pressure sensor system. The foam also guarantees the compliance of the fingertips. 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. This principle has already been exploited in [23] although the scale of the air gaps was different. A similar property holds for the sensors described in [11]. The difference in this case is that the foam guarantees a homogeneous deformation that does not depend on the point of pressure.

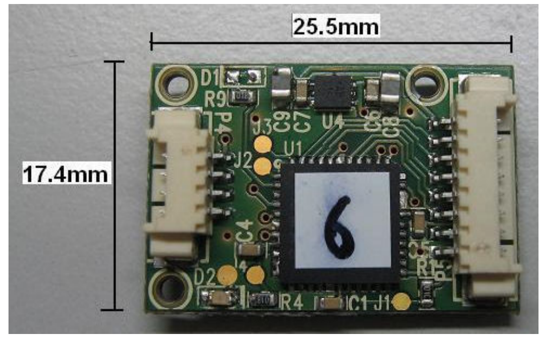



Fig. 5. **The microcontroller board.** The board reads the 5 fingertips and sends the measurements via the CAN bus to the PC104 in the iCub head.

On top of the silicone foam we spray a thin layer of conductive silicone, which acts as the other conductor for the capacitive sensor system. This layer is connected to ground and reduces the electronic noise coming from the environment. In particular, stray capacity is usually a problem for capacitive pressure sensor systems [7]. The conductive silicone is a self-made mixture of silicone CAF4 from Rhodia-Silicones and carbon-black particles Vulcan XC72 from Cabot[3]. This layer is highly elastic, adhesive to silicone and sufficiently electrically conductive (about 10k$\Omega$ measured between two points at the maximum distance found on the fingertips). To spray this material we used the solvent tetrahydrofuran.

In addition, we spray a thin layer of silicone glue above the conductive silicone layer to protect the conductive layer.

## IV. Integration on the Hands of the Humanoid Robot iCub

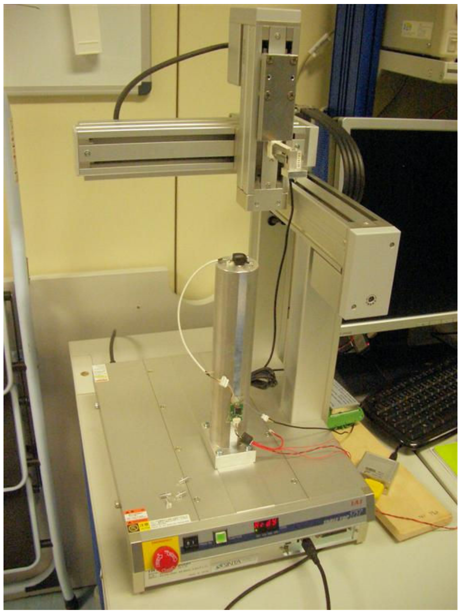
The fingertip described in this paper has been designed to be mounted on the hands of the humanoid robot iCub. iCub is 104cm tall and has 53 controllable degrees of freedom (DOF). It is equipped with digital cameras, gyroscopes and accelerometers, microphones, and force/torque sensors [24]. A distributed sensorized skin is under development using the same capacitive sensor technology described in this paper [18][19].

The hand of the iCub is roughly 14cm long and 6cm wide and has five underactuated fingers (see Figure 1). In particular, each hand has 9 DOF, plus three DOF for the wrist. Seven of the nine motors for the hand are located in the forearm. To obtain 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.

To mechanically attach the fingertip to the hand, the last phalange of each digit has a stick that fits precisely inside a hole in the inner support of the fingertip (see Figure 2). 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.

[2]www.smooth-on.com

[3]www.cabot-corp.com



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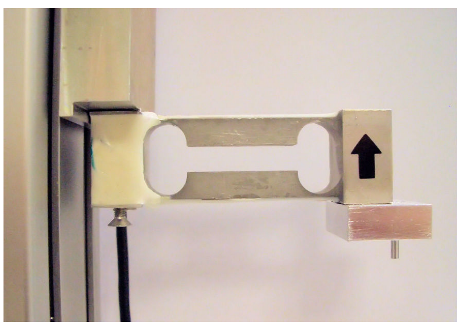


(b)

Fig. 6. **Test setup.** The test setup that is used to test the characteristics of the fingertip is shown. The fingertip is mounted on a platform. A Cartesian robot (TT-C3-2020 from IAI) moves an off-center loadcell (1 kg AL series, from Laumas). In (b) the probe that is used to push the fingertip can be seen. It is cylindrical with a diameter of 2mm.

As discussed earlier, the fingertip includes the electronics to send the 12 capacitance measurements over an $I^2C$ serial bus. Therefore, only 4 wires 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 to a microcontroller board, which is small enough to be included in the forearm of the iCub; it is 25.5 mm long and 17.4 mm wide (see Figure 5). Each microcontroller unit can collect the measurements from up to 16 CDC chips and send the measurements through a CAN bus to the PC104 in the iCub head. The microcontroller unit can also program the CDC chips for different behaviors. The CDC chips are able to measure either all 12 taxels independently at 50 Hz or an average of the 12 taxels at a higher frequency (about 500 Hz). Each fingertip can therefore be used adaptively to either detect contacts at high frequency with low accuracy or at a lower frequency with higher precision.

## V. Testing the Fingertip

### A. Test Setup

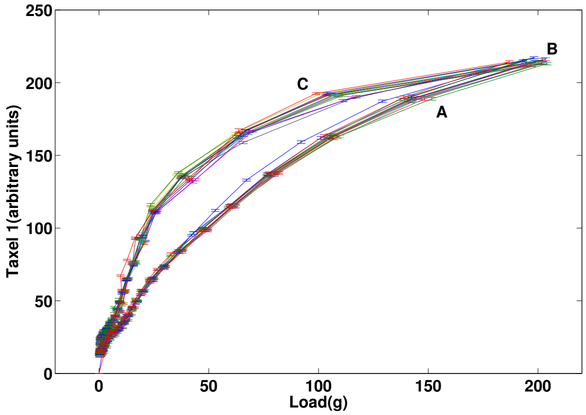
To test the capacitive pressure sensor we use a cartesian robot (TT-C3-2020 from IAI[4]). The robot moves an off-center load cell (AS1 from Laumas[5]). At the end of the loadcell a probe is mounted (see Figure 6), which is moved during the tests against the fingertip. The signal from the loadcell is amplified by an AT-10 from Precise Instruments[6], and to digitalize the signal we use the same microcontroller board that we also use to send the measurements of the fingertip to the PC. Therefore, we get synchronized data from the capacitive pressure sensor system and the loadcell. The loadcell was calibrated with 0, 1, 10, 100 and 500 g weights. Metal probes of varying diameter can be attached to the loadcell. For the tests shown here we used a probe with 2mm diameter, therefore the contact area between the probe and the fingertip is about $12.6mm^2$. 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 on the sensor. When the probe moves downward, it applies pressure to the fingertip. The robot also provides information about the position of the probe. The maximum frequency the cartesian robot can reach for a 2mm z-movement is 10 Hz.

### B. Experimental Results and Discussion

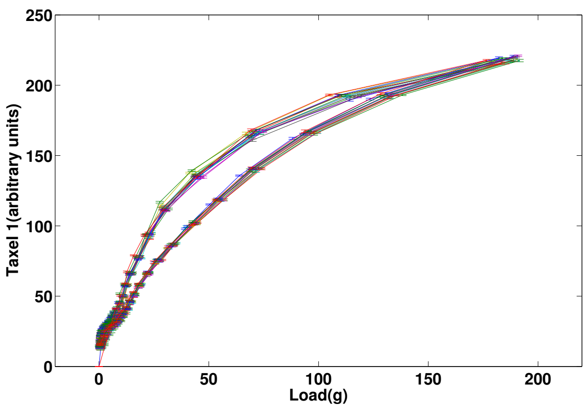
In the first experiment we tested the response of the sensor to different pressures. The probe was placed above one of the taxels of the sensor system and was then moved up and down several times. We moved the probe in small steps of $0.1mm$ each, to cover the available range. In each step we collected data from the fingertip and the load cell and then changed the position of the probe after 60 seconds. Figure 7 (a) shows the average and standard deviation of the sensor measurements collected in the first second immediately after moving the probe, while Figure 7 (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 $12.6mm^2$ (0.16 $N/mm^2$). 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).

To determine whether the hysteresis disappears over time we conducted another experiment in which the probe remained stationary for longer time. In this experiment the probe changed its position only every 720 seconds, and remained even 1440 seconds at the position where it applied

[4]www.intelligentactuator.com
[5]www.laumas.com
[6]www.preciseinstrument.com




(a)




(b)

Fig. 7. **Response of a taxel of the capacitive sensor 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 most pressure to the fingertip. In Figure 8 we show the time series of measurements when the probe is in its second deepest position (phase A), then moved to the position where it applied the most pressure (phase B), and then again moved the second deepest position (phase C). These phases correspond also to the phases shown in Figure 7. 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. This shows that the sensor gives a good measurement of displacement. However, we are interested in measuring pressure and not displacement. The pressure varies between phase A and C and this explains the hysteresis seen in Figure 7. The pressure also varies while the probe is stationary and this explicates the differences between Figure 7 (a) and (b). Even after 720 seconds the pressure in A and C are still different and therefore there is still hysteresis. These effects are probably due to the silicone foam.

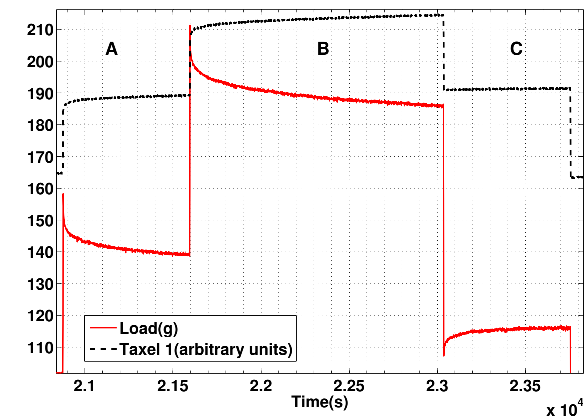



Fig. 8. **Hysteresis.** The probe (2mm diameter) remained for 720 seconds in one position (phase A), then pushed 0.1 mm down (thereby increasing the pressure), remained there for 1440 seconds (phase B), moved 0.1 mm up (thereby releasing pressure and returning to its original position), and remained 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.

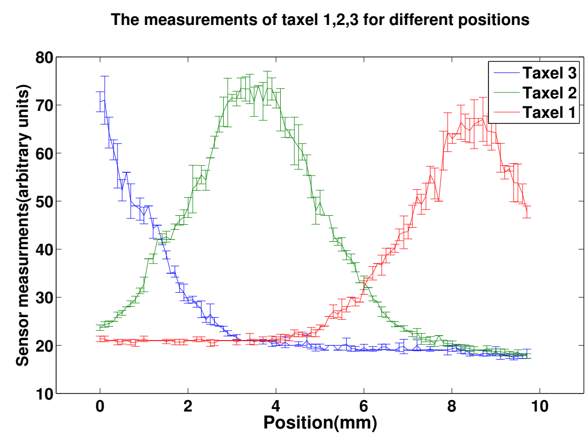



Fig. 9. **Spatial resolution.** The probe (2 mm diameter) is pushing the fingertip at different positions (0.1 mm distance to each other), along a straight line from the back to the front of the fingertip. Along this line the surface of the fingertip is nearly perpendicular to the probe. For each position 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.

Furthermore, 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 we filtered the data offline and plot only those values which correspond to a force of 28-32g. The results presented in Figure 9 show that there is little cross-talk between the taxels and that the fingertip can be used to localize where pressure is applied to it.

## VI. Conclusions and Future Works

### A. Conclusions

We presented a fingertip with a capacitive pressure sensor system that was installed on a humanoid robot. While designing the fingertip special attention was given to the integration on the robot. The fingertip embeds the PCB with the electronics to perform the digitalization: this reduces the number of wires required to connect to the fingertip. Furthermore, the sensor has a shape similar to a human fingertip, is small, provides 12 pressure measurements and is intrinsically compliant. Also the ease and speed of production was an important design factor. The fingertip is more durable than the last version of fingertips designed for the humanoid robot iCub [1].

Our results show that the sensor can be used to measure the pressure applied to the fingertip, but the sensor also shows hysteresis. This is not surprising, as in general severe hysteresis is the main drawback of capacitive sensors, as discussed in [7]. Furthermore, there is little cross-talk between the taxels and the fingertip can be used to localize where pressure is applied to it.

### B. Future Works

We would like to further test the fingertip, 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.

## References


[1] A. Schmitz, M. Maggiali, M. Randazzo, L, Natale and G. Metta, "A Prototype Fingertip with High Spatial Resolution Pressure Sensing for the Robot iCub," in *Proc. 8th IEEE-RAS Int. Conf. on Humanoid Robots*, 2008.

[2] G. Westling and R. S. Johannson, "Factors influencing the force control during precision grip," *Exp. Brain Res.*, vol. 53, pp. 277284, 1984

[3] J. J. Gibson, "The theory of affordances," in R. Shaw and J. Bransford (eds), *Perceiving, acting, and knowing: Toward an ecological psychology,* Hillsdale, NJ, USA: Erlbaum, pp 67-82, 1977

[4] P. Cisek, "Beyond the computer metaphor: Behaviour as interaction," *Journal of Consciousness Studies*, 6(11), pp 125-142, 1999

[5] G. Metta and P. Fitzpatrick, "Better Vision Through Manipulation" in *Proc. 2nd Int. Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems,* pp 97-104, 2002

[6] H. Nicholls and M. Lee, "Tactile sensing for mechatronics - a state of the art survey," *Mechatronics*, vol. 9, 1999

[7] R.S. Dahiya, G. Metta, M. Valle and G. Sandini, "Tactile Sensing: From Humans to Humanoids," *IEEE Transactions on Robotics,* vol. 26, no. 1, 2010

[8] H. Liu, P. Meusel, N. Seitz, B. Willberg, G. Hirzinger, M. H. Jin, Y. W. Liu, R. Wei and Z. W. Xie, "The modular multisensory DLR-HIT-Hand," *Mechanism and Machine Theory,* vol. 42, no. 5, pp 612-625, 2007

[9] T. Mouri, H. Kawasaki, K. Yoshikawa, J. Takai and S. Ito, "Anthropomorphic Robot Hand: Gifu Hand III," in *Proc. Int. Conf. ICCAS*, pp 1288-1293, 2002

[10] P. Dario, C. Laschi, A. Menciassi, E. Guglielmelli, M. C. Carrozza, M. Zecca, L. Zollo, G. Teti, L. Beccai, F. Vecchi, S. Roccella "A Human-like Robotic Manipulation System Implementing Human Models of Sensory-Motor Coordination," in *Proc. 3rd IEEE-RAS Int. Conf. on Humanoid Robots,* 2003

[11] L. Natale and E. Torres-Jara, "A sensitive approach to grasping," in *Proc. 6th Int. Conf. on Epigenetic Robotics,* 2006

[12] Shadow Hand Company, Shadow dexterous hand (2008) [Online]. Available: http://www.shadowrobot.com/hand/

[13] S. Miyazaki and A. Ishida, "Capacitive transducer for continuous measurement of vertical foot force," *Med. Biol. Eng. Comput.*, vol. 22, pp. 309316, 1984

[14] Z. Chu, P. M. Sarro, and S. Middelhoek, "Silicon three-axial tactile sensor," *Sens. Actuators A*, vol. 54, pp. 505-510, 1996

[15] B. L. Gray, and R. S. Fearing, "A surface micromachined microtactile sensor array," in *Proc. Int. Conf. on Robotic Automation*, 1996

[16] R. J. D. Souza and K. D. Wise, "A very high density bulkmicromachined capacitive tactile imager," in *Proc. Int. Conf. Solid-State Sens. Actuators, Transducers*, pp. 1473-1476, 1997

[17] P. A. Schmidt, E. Mael, and R. P. Wurtz, "A sensor for dynamic tactile information with applications in human-robot interaction & object exploration," *Robot. Autonomous Syst.*, vol. 54, pp. 1005-1014, 2006

[18] M. Maggiali, G. Cannata, P. Maiolino, G. Metta, M. Randazzo, and G. Sandini, "Embedded tactile sensor modules," presented at the 11th Mechatron. Forum Biennial Int. Conf., 2008

[19] G. Cannata, R. S. Dahiya, M. Maggiali, F. Mastrogiovanni, G. Metta and M. Valle, "Modular Skin for Humanoid Robot Systems," in *4th Int. Conf. on Cognitive Systems*, 2010

[20] Apple Inc., iPod Touch Technology (2009). [Online]. Available: http://www.apple.com/ipodtouch/features/technology.html

[21] Pressure Profile Systems Inc., PPS-Products (2007). [Online]. Available: http://www.pressureprofile.com/products.php

[22] Analog Devices Inc., CapTouch Programmable Controller for Single-Electrode Capacitance Sensors - AD7147 (2007). [Online]. Available: http://www.analog.com/static/imported-files/Data_Sheets/AD7147.pdf

[23] L. Jamone, G. Metta, F. Nori and G. Sandini, "A Humanoid Robot Acting over an Unstructured World," in *Proc. of 6th IEEE-RAS Int. Conf. on Humanoid Robots,* 2006

[24] G. Metta, D. Vernon, L. Natale, F. Nori and G. Sandini, "The iCub humanoid robot: an open platform for research in embodied cognition," in IEEE Workshop on Performance Metrics for Intelligent Systems Workshop, 2008