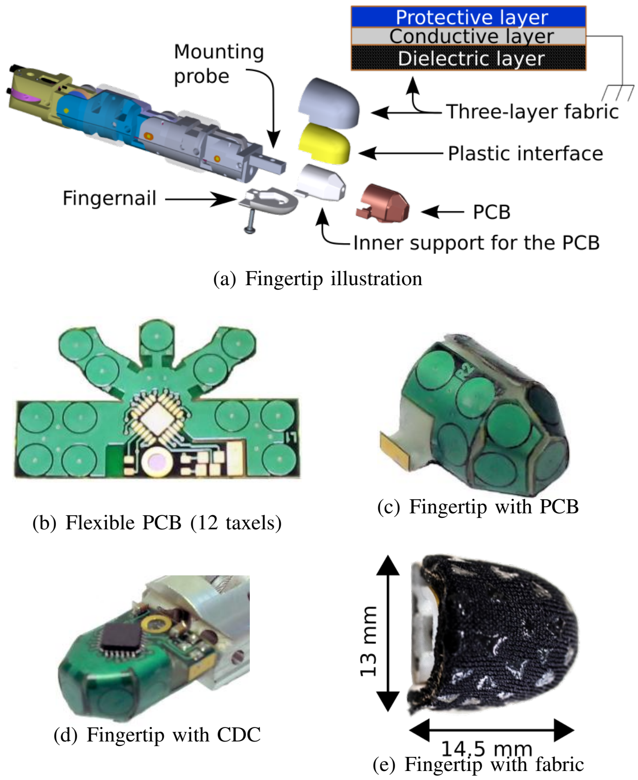
A New Design of a Fingertip for the iCub Hand

Nawid Jamali, Marco Maggiali, Francesco Giovannini, Giorgio Metta and Lorenzo Natale

***Abstract*— Tactile sensing is of fundamental importance for object manipulation and perception. Several sensors for hands have been proposed in the literature, however, only a few of them can be fully integrated with robotic hands. Typical problems preventing integration include the need for deformable sensors that can be deployed on curved surfaces, and wiring complexity. In this paper we describe a fingertip for the hands of the iCub robot, each fingertip consists of 12 sensors. Our approach builds on previous work on the iCub tactile system. The sensing elements of the fingertip are capacitive sensors made from a flexible PCB, and a multi-layer fabric that includes the dielectric material and the conductive layer. The novelty the proposed sensor lies in incorporating the multi-layer fabric technology into a small fingertip sensor that can be attached to the hands of a humanoid robot. The new sensors are more robust. The manufacturing is easier and relies on industrial techniques for the fabrication of the components, which results in higher repeatability. We performed experimental characterization of the sensor. We show that the sensor is able to detect forces as low as *0.05 N* with no cross-talk between the taxels. We identified some hysteresis in the response of the sensor which must be taken into account if the robot exerts large forces for a long period of time. The taxels have spatially overlapping receptive fields, this has been demonstrated to be a useful property that allows hyperacuity.**



(a) Fingertip illustration

(b) Flexible PCB (12 taxels)

(c) Fingertip with PCB

(d) Fingertip with CDC

(e) Fingertip with fabric

Fig. 1. The proposed fingertip: a) is a CAD drawing of the proposed fingertip mounted on the index finger of an iCub robot, b) – e) show different stages of manufacturing a prototype of the proposed fingertip. As illustrated, the finger consists of multiple layers. The PCB – hosting the CDC converter and the 12 sensors – is wrapped around an inner plastic layer, which provides support to the flexible PCB. A plastic interface is placed on top of the PCB that provides a round surface on which the fabric layer can be glued. The exterior of the fingertip is made of a three-layer fabric: a deformable fabric (dielectric) layer, a conductive layer and a protective layer. The fingertip is attached to the iCub finger through a mounting probe by screwing a fingernail at the back of the finger. The fingernail provides mechanical support with the help of a screw that links together the fingernail, the inner support and the mechanical protrusion in the finger.

I. Introduction

Robots are becoming ubiquitous. As these robots move from labs to domestic environments, they will be required to work alongside humans in unstructured, "human-centric" environments. To be able to operate in such environments, the robots must be able to dextrously manipulate objects[1], cooperating with their human counterparts. Applications of such a technology range from domestic robots that help the elderly by performing domestic chores to industrial robots that can work in unstructured environments. Dexterous manipulation is an integral part of our daily activities. We use our hands to interact with our environment. The human brain allocates a large area of the sensory cortex to process the information from the hands[2]. If robots are to work along side humans, they must be able to dextrously manipulate objects.

In this paper we present research that aims at developing artificial fingertips that can be fitted to a humanoid robot's hand, thereby, allowing the robot to dexterously manipulate objects. We use the iCub robot as our test platform. To assist dextrous manipulation, the tactile sensors in the finger must be reliable, repeatable, and have low hysteresis. The proposed fingertip uses the capacitive principle of transduction to measure applied forces. A capacitive sensor consists of a dielectric material sandwiched between two electrodes. An applied force deforms the dielectric layer, which changes the capacitance between the electrodes. The change in capacitance is proportional to the applied force. In particular, we construct a new fingertip that is more robust and easy to manufacture.

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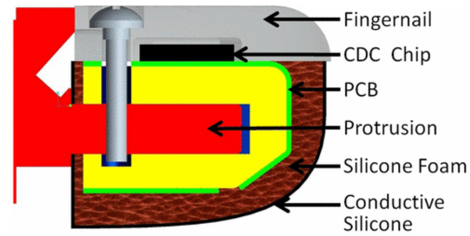
The proposed fingertip, illustrated in Figure 1, builds on previous work on the iCub tactile sensing system [3], [4]. The shape of the fingertip is based on the work by Schmitz et al. [3], which was chosen to make the fingertip compatible with the existing mounting probe on the iCub hand. We improve the fingertip design by using a novel dielectric layer proposed by Maiolino et al. [4]. Typically the dielectric layer is made of an elastomer covered by a conductive layer. This complicates the production process considerably and limits the durability of the sensor due to aging. Moreover, such systems suffer from higher hysteresis. The new fingertip uses a three-layer fabric that comprises of a deformable dielectric layer, a conductive layer and a protective layer. The three-layer fabric is manufactured using industrial techniques. As a result the fingertips are consistent, reliable, robust and easier to manufacture.

The following section gives an overview of existing work. This is followed in section III with the details of the fingertip design. Section IV describes the experimental setup. We then, in section V, present our characterization experiments and provide the results. We conclude the paper in section VI and give future directions in section VII.

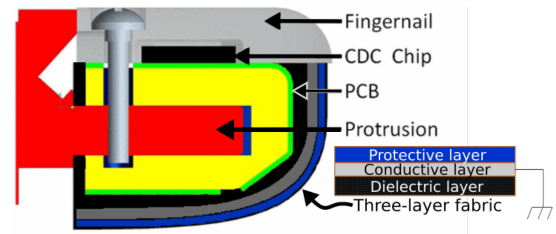
II. Background

To equip robots with human-like dexterity, the past three decades has seen increased research in the development of an artificial sense of touch. Great effort has been devoted to developing tactile sensors that can provide sufficient information for dextrous manipulation. The literature has proposed various sensing principles based on different physical phenomena. These include capacitive [5], piezo-resistive [6], [7], optical [8], [9], [10] and magnetic [11]. Knowledge of all three components of force plays a crucial role in acquiring tactile perception. Attempts have been made to build sensors which can provide all three components of force [9], [11], [12]. Using human fingers as an inspiration, soft fingers with randomly distributed receptors at different depths have been developed [13]. Researchers such as Engel et al. [14], have taken advantage of microelectromechanical systems (MEMS) to manufacture tactile sensors with the capability to provide force and temperature information. MEMS based sensors are very attractive for use in robotics because of their small size and capability to provide multiple modes of transduction. However, their development is in the early stages and their aplication still require considerable efforts.

Majority of the sensors discussed so far are rigid, that is, they don't lend themselves well to applications where the tactile sensors have to be attached to curved surfaces such as the fingertip of a humanoid robot. Ohmura et al. [10] proposed a conformable and scalable robot skin system formed by self-contained modules that can be interconnected. Each module is made of flexible printed circuit boards (FPPBs) consisting of photo-reflectors covered by urethane foam. Mukai et al. [15] have developed a tactile sensor system that uses FPCBs with a tree-like shape to conform to curved surfaces. Asfour et al. [16] use skin patches specifically designed for different body parts of the ARMAR-III robot.



(a) The existing fingertip



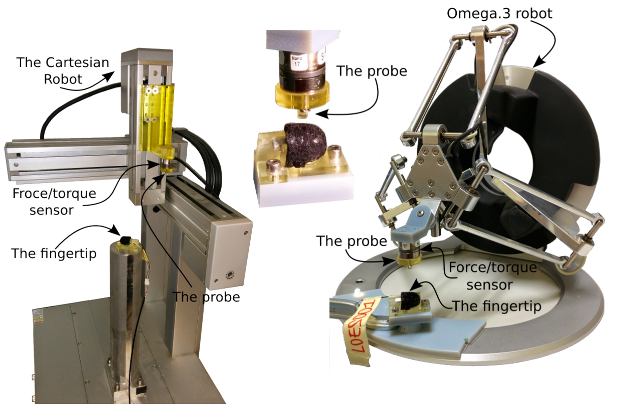
(b) The proposed fingertip

Fig. 2. Comarison of the the existing iCub fingertip (Schmitz et al. [3]) and the proposed fingertip. As illustrated the main difference between the two designs is that, in the new design the silicone foam and the conductive silicone layers are replaced by a composite three-layer fabric. This increases the robustness and repeatability of the fingertip.

III. Fingertip Design

As described in section I, the new fingertip is an extension of our previous work on the iCub tactile sensing system [3], [4]. The shape of the fingertip is based on the existing iCub fingertip [3]. This makes the fingertip compatible with the existing mounting probe on the iCub hand. The novelty of this design is that it replaces the silicone foam and the conductive silicone with a three-layer fabric inspired by the one developed for the large scale tactile sensors on the iCub's body[4]. Figure 2 illustrates the difference between the exisiting fingertip (Figure 2(a)) and the proposed fingertip (Figure 2(b)). The primary difference between the two designs is that the proposed fingertip replaces the silicone foam and the conductive silicone layers with a composite three-layer fabric. The advantage of the compiste material is that the new finger is more robust, repeatable and easier to manufacture.

As illustrated in Figure 1, the overall shape of the finger mimics the shape of a human finger. The fingertip is $14.5\,mm$ long, $13\,mm$ wide. The fingertip assembly comprises 5 layers (see Figure 1(a)). The inner support is made of plastic. The inner support is attached to the finger of the robot through a mounting probe. The flexible PCB (Figure 1(b)) is wrapped around the inner support (Figure 1(c)), the 12 sensors are deployed on locally flat planes that are cut on the inner support. The PCB hosts the chip that performs capacitance to digital conversion (CDC). A plastic surface of $1\,mm$ works as a mechanical interface: it has an inner shape that conforms to the PCB and a rounded external shape on which the three-layer fabric can be easily glued. The outer shell of the sensor is made up of a three-layer, sandwich-like, assembly that incorporates: a deformable neoprene layer, a conductive textile material (lycra) and a protective



(a) IAI Cartesian robot (b) Force Dimension Omega.3 robot

Fig. 3. The setups used for the experimental validation of the fingertip. a) an IAI Cartesian robot controls the probe in three dimensional space making contact with the fingertip at different locations to apply a force. b) A Force Dimension Omega.3 robot is used to control the probe applying and maintaining a desired force at different locations.

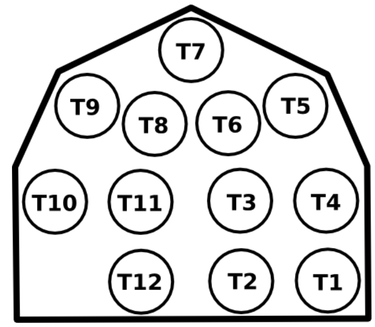


Fig. 4. A map of the texels of the fingertip used for the experimental evaluations.

textile layer (the black material visible in Figure 1(e)). The conductive lycra is connected to ground.

This assembly effectively forms a capacitive pressure sensor. A capacitor, in its simplest form, is an electrical component that comprises two conductor plates separated by a layer of dielectric material. Its capacitance, i.e., its ability to store an electrical charge, then depends on the distance between the two conductors. In our fingertip assembly, the PCB acts as one of the conductive plates and the conductive layer of the three-layered fabric acts as the other conductive plate. Sandwiched between the two are the deformable neoprene layer of the three-layer fabric and the plastic shell, which serve as the dielectric material of the capacitor. An applied force deforms the neoprene layer, changing the distance between the two conductive plates of the capacitor. Whenever a pressure is applied on the fingertip, the soft neoprene deforms thus reducing the distance between the PCB and the surface of the fingertip. Consequently, the measured capacitance value changes. It is possible to estimate the applied pressure from the capacitance value by calibrating the output of the sensor against known values. The PCB incorporates 12 round conductive pads (Figure 1(b)), acting as the plates for 12 distinct capacitors. Hence, the fingertip can sense 12 distinct pressure points. Figure 1(e) shows a complete fingertip sensor.

IV. Experimental setup

The experimental validation of the proposed fingertip was done using two setups (see Figure 3): an IAI Cartesian robot and a Force Dimension Omega.3 robot. Both setups can move the probe in 3D and measure the forces exerted by the probe. The tip allows mounting probes of different sizes to change how the sensor is stimulated. The first setup imposes a certain deformation of the sensor while measuring the force exerted by the probe on the surface. This setup allows investigating the response of the sensor to a constant displacement in terms of capacitance and reaction force (the latter corresponds to the force exerted by the deformed dielectric against the probe). The second setup was developed to perform experiments in which a predefined, constant force is applied to the sensor.

A. The Cartesian robot

Figure 3(a) shows the Cartesian robot setup. In this setup an ATI Nano-17 force/torque sensor is attached to the Z-axis joint of the robot. A probe is attached to the force/torque sensor. The robot controls the position of the probe along 3 axes to stimulate the finger. The force/torque sensor is used to measure the applied forces and torques.

B. The Omega.3 robot

In this setup a Omega.3 robot from Force Dimension is used to stimulate the finger. As depicted in Figure 3(b), this setup consists of an ATI Nano-17 force/torque sensor sandwiched between the robot and a probe. The robot applies and maintains a given force at the location of interest.

V. Characterization and Evaluation

The fingertip was characterized for various properties that are of importance to make the sensor useful for tactile sensing and dexterous manipulation. Figure 4 shows a map of the sensors on the fingertip used in our experiments. We will be referring to this map when we are evaluating the response of the finger.

A. Sensitivity

The sensitivity of a taxel was studied by applying an increasing step-force in 0.01 N increments. The experiment indicated that the fingertip can differentiate forces as low as 0.05 N. To verify our findings the taxel was stimulated by applying a step-force in the range 0.05 N and 0.50 N with 0.05 N increments. In each step, the force is applied for 5 seconds, then the probe is lifted vertically up. We wait 20 seconds for the sensors to reach their baseline value before another stimulus is applied. Each step was repeated 10 times. Figure 5 shows that the fingertip can resolve a 0.05 N force

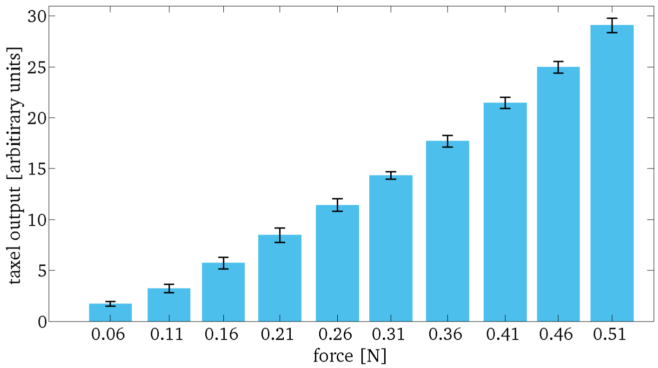


Fig. 5. Taxel sensivity: taxel outputs are averaged over 10 sampler per force step (force step = 0.05 N). The error bars represent one standard deviation.

with statistical significance[1]. The reported sensitivity is based on the stimulus being applied at the center of a taxel. It is expected as the stimulus moves away from the center of the taxel, the stimulus will not excite the taxel to its maximum value, hence reducing its sensitivity. However, as we will show later, the taxels have overlapping receptive fields. This property can be exploited to retain a high sensitivity by combining the output of multiple taxels to reconstruct the applied force.

B. Hysteresis

The hysteresis exhibited by the sensor depends on the amount of the deformation of the dielectric layer of the three-layer fabric, that is, the neoprene fabric. In Figure 6 we notice that hysteresis appears when large forces, approximately 1 N, are applied.

It is known that the hysteresis depends on the duration and magnitude of the applied force. We devised another set of experiments to investigate the effect of the duration of an applied force on the hysteresis of the fingertip. In these experiments, a taxel on the fingertip was repetitively stimulated. The probe started from an initial position in which it did not touch the sensor, i.e., zero force, it applied a constant deformation and then it retracted back to the initial position. This step was repeated consecutively for 10 minutes. Figure 7 reports the response of the sensor (left) and the force measured by the probe (right) in two conditions corresponding to steps of different amplitudes. These plots show that the hysteresis also depends on the duration of the stimulation. Overall these experiments demonstrate that the sensor exhibit hysteresis which must be taken into account or compensated.

C. Crosstalk

We also investigated the presence of cross-talk between taxels. For this experiment we applied an incrementally increasing force to the fingertip. The force was applied in 8 steps reaching a maximum force of 10 N over a circular area of 4 mm in diameter. The location of the stimulus was

[1]Note that the values for the applied force in the x-axis are averaged over 10 samples. Hence, due to rounding, it does not start exactly from 0.05 N.

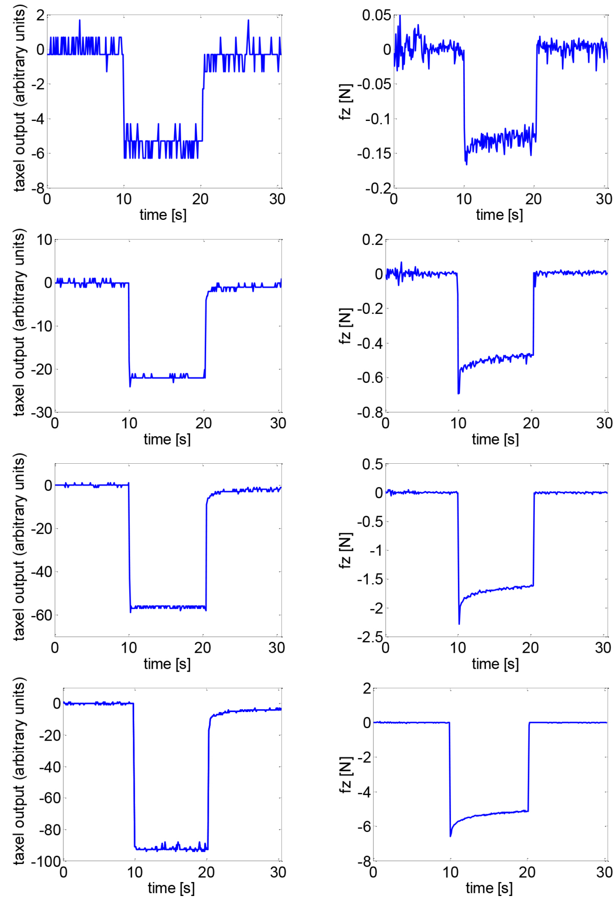


Fig. 6. Hysteresis: response of a taxel to different forces. In this experiment the probe remained in the starting position for 10 seconds, then it pushed one of the taxels for 10 seconds and returned to the initial position. Left plots show the response of the taxels, while right plots show the applied force. The probe is position controlled so it maintains a fixed deformation of the sensor. The applied force changes with time as the elastic fabric deforms. When the force is large the sensor shows hysteresis due to the fact that a certain amount of deformation remains when the probe returns to the starting position. The deformation slowly disappears and the response of the sensor returns to the baseline.

roughly above taxel number 2 (Figure 4 reports a map that illustrates the location of the taxels on the fingertip). The idea in this case was to rule out the possibility that a large force applied on the top of the fingertip deforms the sensor and produces spurious activation of the taxels on the sides. We determined that during the experiment only the taxels close to the stimulus were activated significantly above the baseline. As this is a natural effect due to the size of the probe and the spatial sensitivity of the taxels we concluded that there is no cross-talk between the taxels in the fingertip. Figure 8 reports the response of all the taxels that were activated during the stimulation.

D. Spatial resolution

To test the spatial resolution of the fingertip, we used the Omega.3 setup to apply an stimulus of 4 N at multiple locations on the fingertip. The starting position was at the back of the fingertip, between taxel-12 and taxel-2 (see Figure 4). The stimulus was applied, in 0.1 mm intervals,

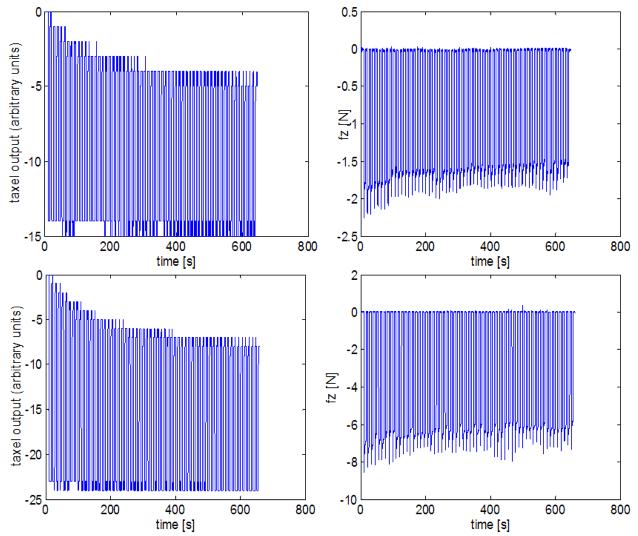


Fig. 7. Hysteresis: response of a taxel to repetitive stimulations. In this experiment the probe applied a series of steps of constant amplitude for about 10 minutes. The probe started from an initial position in which it did not touch the sensor (zero force) and then moved a predetermined position in which it applied a certain deformation (maintained constant during each trial). The figure reports two experiments with different amplitudes (top: small amplitude, force in the range of 1.5–2 N, bottom: larger amplitudes, force in the range of 6–8 N). The plots on the left represent the response of the sensor, the plots on the right represent the measured force. In both cases it can be noticed that the response of the sensor when the pressure is released changes with time because the fabric deforms with time.

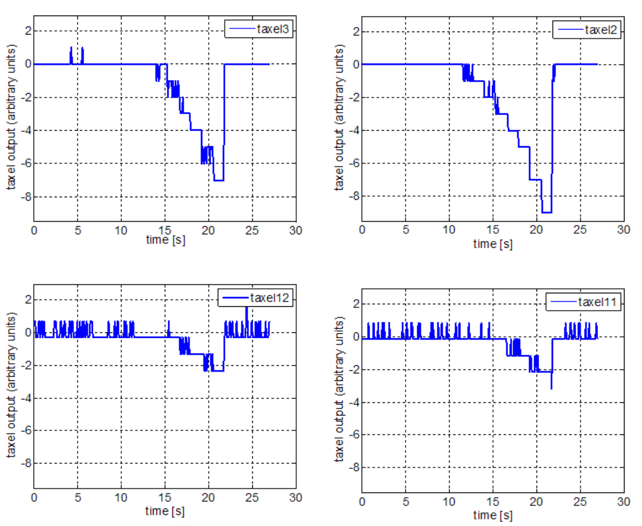


Fig. 8. Crosstalk: Response of a taxel to a 10 N force applied using a probe with a 4 mm diameter. The probe was positioned approximately over

along a straight line that ended at the midpoint between taxel-8 and taxel-6. At each location the 4 N stimulus is maintained for 2 seconds, then the probe is lifted vertically up, we wait 5 seconds to allow the sensors to reach their baseline value before another stimulus is applied.

Figure 9 shows the response of the sensors in the finger tip. The figure reports the sensors values, averaged over 10 samples, just before the probe is lifted up. At the starting point taxel 2 and taxel 12 have the highest response levels.

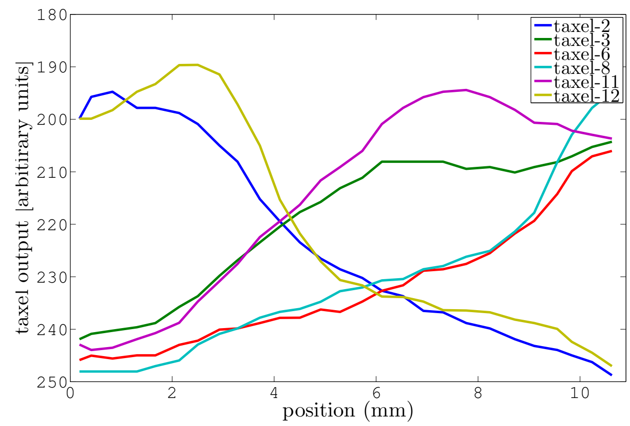


Fig. 9. Response of the fingertip to a 4 mm probe applying 4 N force. The force was applied at 0.1 mm intervals starting from the edge of the finger, running across the middle of the finger towards the tip. Only the taxels that were activated by the stimulus are shown.

As we move away, taxel 3 and taxel 11 start to respond to the stimulus. Finally, as we approach the tip of the finger, taxel 6 and taxel 8 respond. Not surprisingly, it matches the taxel map of Figure 4. We also notice that not all sensors respond at the same level. This can be explained by the fact that the probe placement is approximately in the middle of the taxels in question.

VI. Conclusions

We have presented the design a robotic fingertip that can be fitted to the hands of a humanoid robot. The proposed fingertip uses capacitive sensors to determine the applied force. The novelty of the presented fingertip is that it replaces previously used silicone foam and conductive silicone with a three-layer fabric. The advantage of using a three-layer fabric is that there are well developed industrial processes for manufacturing such materials.This leads to a consistent, robust and easy to manufacture tactile sensors. We also characterized the sensor to evaluate it. We showed that the sensors can sense forces as little as 0.05 N, there is little cross-talk between sensors and it has a good spatial resolution.

VII. Future Work

In future we would like to investigate methods that can reduce the effect of hysteresis. We would also like to add other sensing modalities such as thermal sensors and vibrations sensors. Further tests will be carried out to evaluate the utility of the sensors in manipulating everyday objects.

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