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Towards a Skin-Like Embedded Tactile Sensor for Robotic Hands

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Abstract.

A novel embedded tactile sensor designed to be integrated in future robotics hands and the related production process are presented. The sensor is based on a multilayer rubber structure bound to a rigid thermoplastic support frame which encloses the embedded sensor electronics. In the project design, each sensor features up to 12 pressure sensitive tactels distributed on a phalange-like curved surface. Tactile data are read by a CDC (Capacitance-to-Digital Converter) and forwarded to a microcontroller via I2C bus. Each microcontroller module handles up to 4 sensor modules (one finger) and provides the data over CANbus.

The construction process has been designed to be as cheap and simple as possible. It is divided in four macro-steps, which relies on different technologies: elastomers for dielectric and conductive layers, thermoplastic materials and thermoforming for rigid support frame, flexible PCB for the embedded electronics and adhesive for the layers binding.

1 INTRODUCTION

Companion or Social robots represent a new class of robots specifically designed to interact and cooperate with humans not only to perform manufacturing tasks, but also for service applications even in domestic environments (e.g. house keeping, healthcare support, entertainment, etc.).

A fundamental requirement for a this type of robot is the capability of safely interact with the environment including humans. For this purpose a major feature is the capability of measuring touch information, in order to implement control strategies, for reacting to external contact stimuli.

Although in recent years, robots have become increasingly part of human life, to allow a greater diffusion of social robots (i.e. a large scale production), it is necessary to lower building costs of the robots and to make the production processes simple and repeatable.

Tactile sensing for robotic hands has been deeply studied and many types of transducers have been adopted, as widely shown in literature [3], [8].

The develpment of tactile sensors is a very hard problem involving several engineering issues and often also special processing equipment and this has limited the development of embedded solutions. Furthermore most of the solutions proposed are strongly dependent on the mechanical robot design and often specialized for a particular platform [1], [4], [5], [6], [7], [10].

In this paper a novel tactile skin-like sensor for fingertip is proposed. In particular we have focused on the study of production processes, materials and component selection issues, in order to define design guidelines for a low-cost embedded tactile sensory system. On the basis of these guidelines, we have developed some proof-of-concept prototypes.

The starting point has been the work of Maggiali et al. [9] and we have taken in account the following issues:

- Spatial Resolution: the tactile elements (tactels) number must allow the reconstruction of the contact profile all over the surface.
- Reliability: the sensor must give relaiable measures and avoid false contacts.
- Mechanical thoughness: as the sensor has to physically interact with the environment, it must be tought enough to not be easily damaged by these interactions.
- Miniaturization: as the sensor has to be deployed on a human-size like robotic hand, it must be self contained and fully embedded in a phalange-like volume.
- Production Costs: the sensor must be cheap enough to be disposable, therefore the related production process and the material used have to be optimized to have the most high-quality sensor at the lowest cost possible.

2 DESIGN CONCEPT

Capacitive sensor technology has been adopted thanks to the availability of miniature CDC (Capacitance-to-Digital Converter) used in last generation consumer electronics.

In this work a matrix of capacitors is integrated in the fingertip tactile sensor structure, and the contact pressure is detected thanks to the dielectric deformation, which results in a capacitance variation (Fig. 1). The tactile sensor elements (tactels) are, in fact, capacitive transducers distributed all over the fingertip surface.

The tactile sensor is made by 5 principal elements (Fig. 2):

- Embedded Electronics: a flexible PCB (polyimide + copper) is used to provide the tactels shape and to bring the signal to the CDC (section 3).
- Thermoplastic Support Frame: which gives the shape and the structural support to the sensor. The flexible PCB is bound to its internal surface (section 4).
- Dielectric Layers: made of a soft silicone rubber which deforms when it is subjected to the contact forces (section 5).
- Conductive Ground Layer: made of conductive silicone rubber (section 6).
- Protective Layer: made of a thin substrate of silicone rubber. It is designed both to protect the conductive layer from mechanical stress and to improve the surface grip (section 7).

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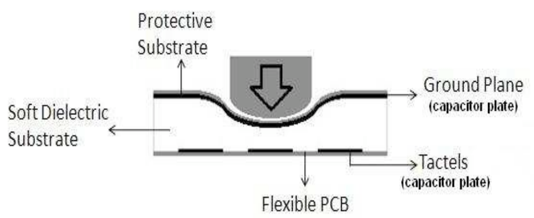

Figure 1. Layers Deformation Concept

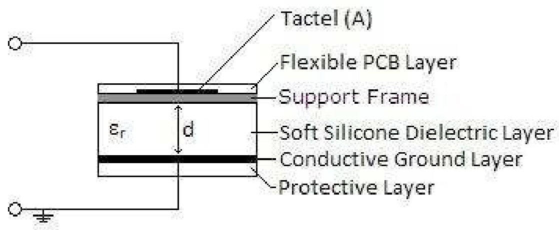

Figure 2. Tactile sensor concept

3 EMBEDDED ELECTRONICS

The embedded electronics is integrated on a flexible copper-on-polyimide (Polyimide film, Rogers Corporations) printed circuit board (PCB), capable to bend and adapt to the small and curved surfaces of the fingers. The flexible PCB can be divided in two parts:

- Tactels PCB: provides tactels shape and distribution over the surface.
- Circuitry PCB: which hosts the Capacitance-to-Digital Converter (CDC).

The fingertip sensor unit hosts 10 round tactels with a 3mm diameter and covers a human-size thumb surface, having about 2.5 tactels per square centimeter resolution (Fig. 3).

The selected CDC Analog Devices (AD7147-1, producted by Analog Devices) can read up to 12 tactels capacitance with a Femto-Farad (10^{-15F}) resolution up to 16-bits. The whole acquisition cycle is automatically completed in 20 ms.

4 THERMOPLASTIC SUPPORT FRAME

The Thermoplastic support frame gives the shape and the structural support to the sensor.

Since the flexible PCB must be supported by the support frame (flexible PCB is bound on its internal surface), various materials and manufacturing process has been investigated in order to obtain a tactile sensor structure with embedded electronic in easy and repeatable way. For this purpose the support frame consists of a mechanically thermoformed thermoplastic material sheet.

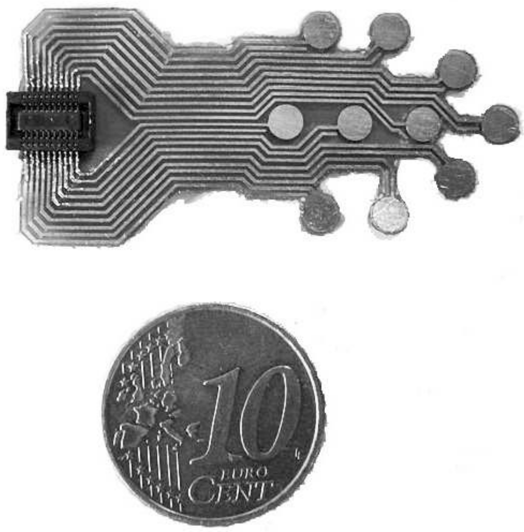

Figure 3. Tactels Pattern Flexible PCB.

Thermoforming is one of the oldest and most common methods of processing plastic materials. It is a very versatile process used to manufacture a wide range of products.

For our purposes mechanical thermoforming has been selected and performed using coupled moulds (positive and negative) which are pressed together forcing a preheated plastic sheet to the desired shape. The main advantages of this method are:

- No special thermoforming equipment needed to generate positive/negative air pressure.
- Formed material thickness can be a design parameter.
- Both the internal and external surfaces can be formed with the desired details.

The main critic part of this process is related to the mechanical stress which can damage the plastic sheet or the conductive layer attached to it.

The equipment used for thermoforming experiments and prototype frame support production was composed of:

- Electric oven with temperature regulation.
- Coupled PTFE molds.

The mechanical thermoforming process is made of 3 steps:

1. Mold Assembly preparation: the plastic sheet is blocked within aluminum clamps and placed on the female mold, using the guides to have the best alignment. Then the male mold is placed on the sheet and everything is blocked on the support aluminum bar (Fig. 4).
2. Heating and Forming: the Mold Assembly is introduced into the oven at the desired temperature (within the material thermoforming range). Material glass transition temperature is reached when its edges start to bend. When the central part of the plastic sheet starts flexing, the sample is ready to be formed. The male mold is

pressed (manually or using a weight) into the female mold and the mold assembly is extracted from the oven.

3. Cooling: mold assembly is placed into a clamp which continues to press male and female molds together. When the mold is cold, it is possible to disassembly it and extract the formed plastic sheet (Fig.5).

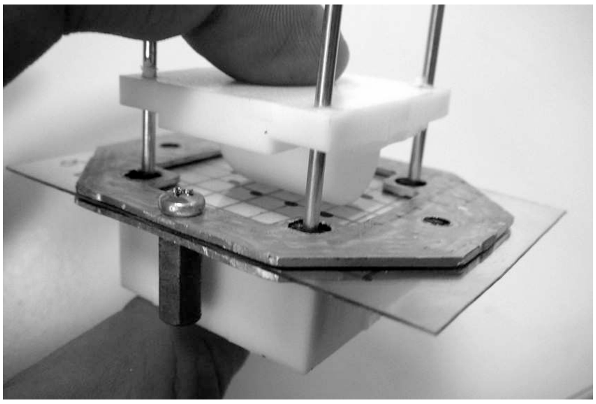

Figure 4. Mold assembly.

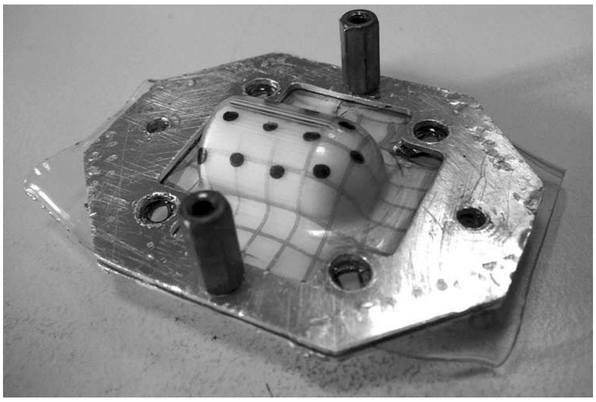

Figure 5. Thermoformed fingertip chassis.

We investigated on various type of thermoplastic materials and in particular: ABS (Acrylonitrile-Butadiene-Styrene), PETG (Polyethylene terephthalate glicole), PETGAG (3-layer structure of PETG-PETA-PETG), Acetate, White Styrene and Polypropylene.

The first issue, that has influenced the material choice, was related to the thermoforming temperature range, since the flexible PCB, and then the electronic, was bound to the thermoplastic sheet before the thermoforming process. The second issue was related to the commercial available thickness of the thermoplastic sheets, since thermoplastic support frame is part of the dielectric layer of the equivalent capacitor, and it is not thinned by the forces applied on the sensor surface.

On basis of this analysis we have decided for PETGAG that has a large thermoforming range: between $100°C$ and $160°C$), and it has been avalaible in sheets with thickness of 0.150 mm, which was the smallest provided by suppliers. Furthermore, during the material investigation which led to the selection of PETGAG, we tried to empirically assess the locations predictability of the tactels and the sheet deformation repeatability. The former aspect refers to the needing to know where each tactel will be located after the thermoforming process, while the latter refers to the needing of produce small series of identical sensor units.

Experiments where done by manually drawing a 5x5 mm grid and the planar tactels pattern over the plastic sheet and then visually inspecting the formed part.

These experiments where conducted for all the materials investigated (ABS, PETG, PETGAG, Acetate, White Styrene and Polypropylene) with different results. In particular PETGAG showed very good deformation repeatability.

5 DIELECTRIC LAYER

The main part of the dielectric layer (dielectric layer is composed of silicone rubber substrate plus thermoformed frame support) is made of commercial soft silicone rubber platinum-catalyzed RTV (Room Temperature Vulcanization), with shore hardness A 00-30 and available as a two components (A, B) product (Ecoflex Series 00-30, Smooth-On, U.S.A).

To produce the fingertip-unit prototype we used the thermoformed frame support as male mould to have the best possible coupling, and a calibrated negative mould to obtain an even 2 mm layer. The material was processed according to the manufacturer specifications (curing agent B was added to the component A at the ratio 1:1 by volume), then the Ecoflex compound has been placed inside the moulds and cured at room temperature for 24 hours.

5.1 Improvement of Dielectric constant of Silicon Rubber

The thickness of dielectric layer is a trade-off between the deformation needed to have detectable capacitance variations (more the deformation, more the capacitance variation) and the capacitance needed to work in the CDC linear zone (20pF).

According to the capacitor law:

$$C = \epsilon_0 \cdot \epsilon_r \cdot \frac{A}{d} \quad (1)$$

and taking into account that, due to design requirements, pads area is fixed ($A = 6\pi \times 10^-6mm$), we performed various experiments in order to increase the dielectric permittivity of the silicone rubber matrix in order to get higher thickness (more deformation) and capacitance value under 20 pF (linear zone of CDC).

The performed experiments has been made on the basis of Carpi et al. [2] work. In particular a ceramic filler with high dielectric permittivity ($\epsilon_r \approxeq 110$), 99%-pure rutile-type titanium dioxide TiO_2 (Titanio biossido - code 488257, Carlo Erba, Italy) has been dispersed into the silicone rubber matrix Ecoflex 00-30 in order to increase its dielectric permittivity ($\epsilon_r \approxeq 3$).

Samples having 10%, 20%, 30% and 40% in weight dispersion ratio were separately fabricated. We got the same results as reported in [2]: an increase of 30% at low frequency in the composite resulting

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from a dispersione of 30% in weight TiO_2, and worst mechanical properties in composite samples with TiO_2 dispersion ratio of 40% in weight; at our work frequences (250 KHz) the increase of silicone rubber dielectric permittivity is under 30% and also we noticed a loss of elasticity of the compound.

On basis of these considerations we discarded this ceramic filler and we performed the same experiments with another ceramic filler powder, 99% strontium titanate S_rTiO_3 (Strontium titanate - code 396141-500G, sigma-aldrich).

With this filler we got better results, but not enough satisfying for our application. Others fillers and methods to increase dielectric permittivity of elastomers are under analysis, but for this prototype of fingertip tactile sensor we decided to use pure silicone rubber substrate as dielectric layer.

6 CONDUCTIVE GROUND LAYER

The conductive ground layer acts as common plate for all the tactels. We investigated on several conductive silicone rubbers, inks and adhesives in order to obtain a perfect binding between the dielectric layer and the conductive one.

On basis of this investigation we chosen a two components (A, B) black conductive silicone rubber (Silopren 2345, Momentive, U.S.A).

The material was processed as follow: curing agent B was added to the component A at ratio 1:1 by volume, then in order to obtain a thin layer, the compound was deposited on the base rubber by dip-coating; Finally the layer was vulcanized in oven at 120°C for 2 hours.

Momentive Silopren 2345 has eletric surface resistance of 370 ω for $50\mu m$ layer thickness. The surface resistance limits the sensor bandwidth, but in our application the sensor bandwidth is wide enough to let it work properly.

7 PROTECTIVE LAYER

The protective layer has the function of to separate and to insulate the ground plane from the touched objects, protecting it from wears; furthermore it provides good grip to the surfaces.

The protective layer has been made by a thin layer of Smooth-On Ecoflex Series 00-30 silicone rubber deposited by dip-coating on the tactile sensor surface.

8 LAYERS BINDING

In order to obtain a one-piece sensor all the layers must be bound together. We investigated several adhesives. In order to minimally affect the capacitance value, thin films of adhesives are required.

Thermoformed support frame (section 4) and silicone rubber layers (section 5) have been bound together using a one-component silicone adhesive specifically made for bonding RTV silicone rubber to other silicone rubber or other materials (Smooth-on, Sil-Poxy, U.S.A). This adhesive has similar consistency as other silicone adhesives, but it is possible to obtain thin films by spreading it with a squeege.

Flexible PCB (section 3) has been bound to the thermoformed support frame (section 4) using a cyanoacrylate istantaneous elastomeric adhesive (Loctite, Loctite 480). It has good elasticity after curing thanks to its native silicone addition. Its glass transition temperature is 150°C, therefore it is suitable to be used during the thermoforming process (section 4). Finally, thanks to its liquid consistency it is easy to obtain thin adhesive films.

Silicone Rubber dielectric substrate (section 5) and Conductive silicone (section 6) perfectly bind together, furthermore they show excellent deformation and elongation characteristics (Fig. 6).

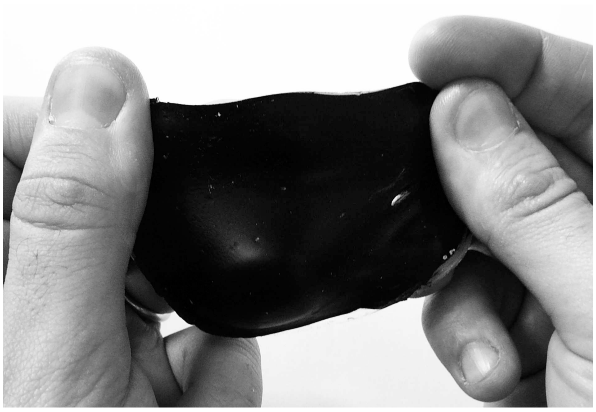

Figure 6. Ecoflex and Silopren binding

9 EXPERIMENTAL RESULTS

In order to validate the functioning of the system we performed experiments on three intermediate phases of implementation process of the tactile sensor, and in particular in the first experiments we tested the sensor response in the case of planar flexible PCB covered by the dielectric and conductive silicone substates (Fig. 9.1). In the second experiments we tested the sensor responce in the case of planar flexible PCB bound to a PETGAG sheet and covered by dielectric and conductive silicone substrate (Fig. 9.2). The third experiments is about the functioning of the fingertip prototype (Fig. 9.3).

Data acquisition has been done using MATLAB RTW (Real-Time Workshop): the sensor has been connected via CANbus to an XPC-target (with a CAN-PCI card), then sent over LAN to a Host PC.

In order to avoid spurious data, due to inappropriate bending of flexible PCB, the sensor has been fixed on a rigid support in order to obtain reliable and repeatable measurements

9.1 Planar Version Operative Test (rubber only)

In this first experiments we tested the sensor response in the case of planar flexible PCB covered by the dielectric and conductive silicone substates. we activated a zone of the sensor using an indenter loaded with a known weight (45g, 95g, 250g, 500g).

In this phase the sensor pads were covered with a pure Ecoflex 00-30 layer of 2mm thickness. This test aims to understand which is the sensor response to external forces without the rigid support frame.

Test results are shown in Fig. 7: each line refers to a tactel signal; when a load is applied, the 8-bit output stabilizes around a value between 0 and 255. More is the force applired to the tactel, more tha line will fall to 0. As the indenter round contact area was about 4mm diameter we have a force distribution which excite more a small group of three tactels and less the other perihperal ones. Each rectangle corresponds to the application of the different loads. Sensor saturation is over 500g.

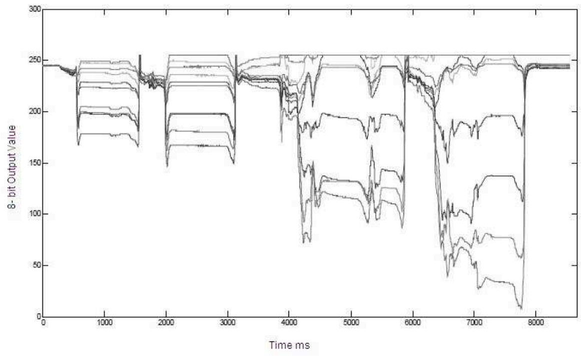

Figure 7. Planar sensor covered with rubber layer

9.2 Planar Version Operative Test (planar PETGAG + rubber)

In this second experiments we tested the sensor responce in the case of planar flexible PCB bound to a PETGAG sheet and covered by dielectric and conductive silicone substrate. This intermediate test consists in activating a zone of the sensor using a indenter loaded with a known weight (45g, 95g, 250g, 500g). In this phase a 0.150 mm PETGAG sheet was interposed between the sensor pads and a pure Ecoflex 00-30 layer of 2mm thickness with. This test aims to understand how the chassis affects the sensor behavior. Test results are shown in Fig. 8 from the comparison between this experiment and the prevoius one, we notice that the measures are only slightly affected by the PEGAG layer introduction.

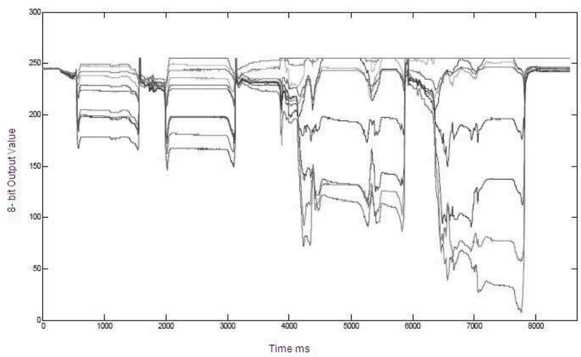

Figure 8. Planar sensor covered with PETGAG and rubber layers

9.3 Fingertip Sensor Operative Test

In this final test the sensor was in its final fingertip shape. The fingertip has been placed over the positive fingertip mold and fixed in order to perform the measurements. The sensor has been activated using a pen as indenter to qualitatively compare the sensor response to prevoius tests. Test results are shown in Fig. 9; when the fingertip is pressed it has a fast and suitable response to the exerted force.

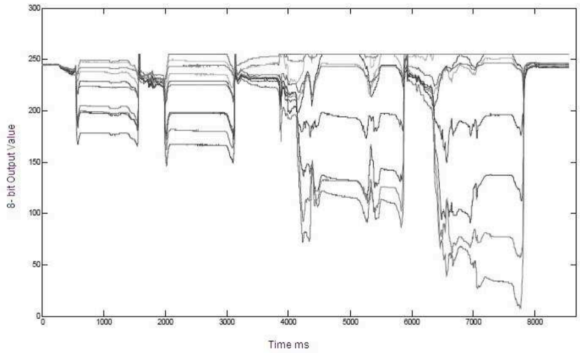

Figure 9. Fingertip sensor qualitative test

10 CONCLUSION AND FUTURE WORK

The fingertip-sensor prototype was produced and tested succesfully. It is important to notice that it has not shown any hysteresis due to material deformation. Planned future tests will be performed using a load cell based equipment, in order to better characterize sensor response.

Miniaturization will be taken into account also for embedded electronic circuit which will be manufactured on flexible ciruit in order to have a sensor effectively embeddeddable onto a robotic hand.

The capacitance augmentation did not give the desired results, actually we have not planned to perform experiments with other materials.

Finally the production process can be improved by adopting the vacuum forming technique, using a vacuum forming machine and proper designed molds because the flexible circuit related to the tactels pattern will be attached to the internal support frame before the thermoforming process and mechanical thermoforming could in some case to damage the flexible PCB. In this way the only external intervention at the end of the production will be the binding of rubber layers and the sensor frame support.

This will be the foundation of a process capable of produce small series of sensor units, such as the sensors for a complete robotic hand, using a single customized female mold.

ACKNOWLEDGEMENTS

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