A Capacitive Color-Changing Electronic Skin for Touch Sensing Applications

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Abstract— ***Robots are slowly becoming part of our civilization, or at least one of the main evolutions of the third millennium. Nowadays their integration is based on their aspects by looking more and more human. Additionally, not only considering the psychological aspects, our society will have to improve their interaction. Systems integrating a full spectrum of sensors will have to be implemented. In this framework, as a preliminary step, the implementation of a tactile robotic skin can be an interesting upgrade. To guarantee safety between robots and humans, it can be interesting to implement such robots with human-like tactile perception. In this work, we focus on the realization of innovative tactile skin model. This model allows to sense and indicate where the pressures have been applied by using a combination of a flexible polymeric capacitive skin model combined with a LED matrix.***

Keywords— Electronic Skin, Capacitance, LED matrix, Polymers

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I. INTRODUCTION

Electronic skin topic is continuously attracting more and more interest due to its wide range of applications. Such technologies can be employed for robotic skins [1, 2] or even interfaces for the forthcoming smart cities in a very close future [3]. For example, it could make the interaction of humans and robots safer in everyday life. If humans and robots share a common working space in order to relieve humans of heavy physical or monotonous works, this entails risks. Collisions between robots and humans can occur. Equipping robots with artificial tactile skin and thus a sort of sensing and even feeling will accelerate their integration and settlement in the society.

Several approaches have been used to realize a simulated tactile sensing system emulating the human skin. There is a variety of sensors based on different technologies: resistive, capacitive, optical, magnetic, with ultrasound, piezoelectric, piezoresistive, electro rheological and magneto rheological [4]. Touch-capable displays also work with some of these modes of operation. One common touch technology is based on capacitive touch system which are divided into two main different systems, the surface capacitive system and the projected capacitive system. The surface capacitive system is often designed with a conductive metal oxide coating on a glass surface. An alternating voltage is applied to this coating. As soon as a contact occurs, the position in the corners of the display can be determined by the current flow. However, this system does not work in a humid environment and can only detect a touch. Multiple touches are not possible with this system. The advantage of such a system is that it can also detect pens or hands wearing gloves [5]. The projected capacitive system works by means of a matrix of conductive wires. When the finger approaches the wires, the electric field is disturbed. As a result, a difference in capacitance can be measured on the wires that are close to the finger. From these capacitance differences, the X and Y coordinates can be determined [5].

Applications of such systems include humanoid robots, which are equipped with both capacitive systems. This allows detecting not only human touch but also the touch of objects [6], and even to determine which kinds of objects or materials by determining the permittivity [7]. Also, resistive sensors are used as robot skin by measuring the change in resistance of a pressure-sensitive rubber. This allows for example the robots to hug people and to keep their balance on one leg without hurting or falling down [8]. In a near future, prostheses will also be equipped with artificial tactile skin, which can provide the user with feedback about the curvature of the gripped object, as for example, in the following work where the use of piezoresistive and conductive tissues are illustrated [9]. The applied pressure causes a change in the electrical resistance which can be measured. Additionally, this

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approach can lead to interesting applications such as a human-machine interface as illustrated by Teyssier et al. [10], a good example of projected capacitive system. Several tactile skin models have been proposed also by considering optical sensing implementation [11-16]. An interesting matching can be considered between the optoelectronic sensing devices and their use to excite neural cells generating sort of artificial skin models for medical prosthesis.

In this work, an artificial skin model has been developed using different silicon-based materials. These materials have been selected for their ease of use and their good compliances with the mechanical properties of a human skin. A sensoristic part has been implemented under the shape of a projected capacitive system using a grid of conductive wires forming a capacitance matrix emulating the tactile perception of a human skin.

The work will describe the design and fabrication of the skin model introducing an interesting approach: the visualization of the touch localization. Indeed, based on the mimicking of our system model, the human hand, the newly introduced model is imitating its shape and texture, in particular the palm which has been simply replicated. A matrix of LEDs (light-emitting diodes) is implemented to visualize the exact position where the touch takes place directly into the skin model.

II. Materials and Methods

The human skin consists of three different layers [17]: the epidermis, the dermis and the subcutis (Figure 1). The epidermis is the thinnest layer (less than 0.1 mm in most places) with pigment-forming cells comprising the stratum corneum being the external interface of the human body. The dermis keeps the human skin stable and elastic at the same time. It contains the nerves for the sense of touch and the lymphatic system. The fat and connective tissue are located into the subcutis.

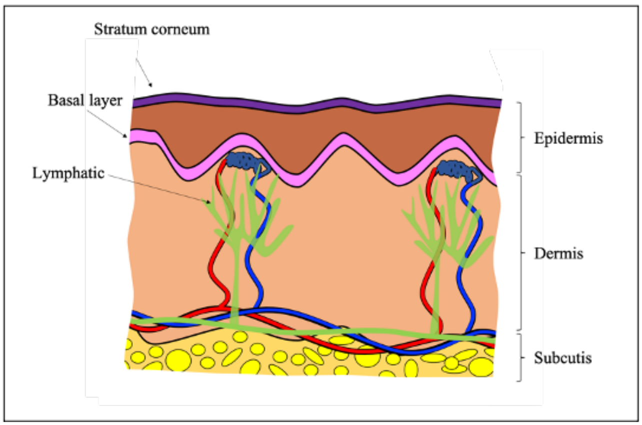

Figure 1: Structure of human skin with epidermis, dermis and subcutis.

Two different silicone-based materials have been selected to mimic these three layers. Silicones are inorganic-organic polymers. They are often used in the production of skin models as it can be used to generate different, human-like forms. It is used, among other things, for the surface reproduction of the skin and has a similar refractive index to real skin. Furthermore, silicone is durable and non-toxic once cured. Additionally, we observe that silicon-based materials have a Young's Modulus around 0,5 MPa [18] compared to a value ranging from 0,42 to 0,85 MPa for the human skin [19]. The epidermis and dermis have been reproduced by using Dragon Skin FX-pro (DS, from Smooth-On, purchased from Kaupo, Germany). This high-performance silicone has been specially developed for creating make-up prostheses and skin effects. It is soft, highly elastic and tear-resistant. Additionally, Ecoflex Gel material has been used to realize the subcutaneous tissue (EG, from Smooth-On, purchased from Kaupo, Germany). This polymer is a silicone gel and used mainly for gel-filled silicone parts, such as facial prostheses.

In order to reproduce the tactile perception of human skin, the functional principle used is based on the projected capacitive touch system, same as the one employed in touchscreen technology. In these touchscreens there are two levels with conductive wires arranged as a matrix (Figure 2). A capacitance measurement takes place at all addressable electrodes. If a finger approaches the matrix, it interferes with the electric field and thus changes the capacitance. The disturbance is higher where the contact takes place. This change in capacitance can be measured and converted into (X, Y) coordinates. Thus, the contact can be localized exactly. There are two measuring methods for detecting contact, the intrinsic capacitance and the counter capacitance method. The self-capacitance method uses the principle of the single-plate capacitor. Conductive wires represent one plate of the capacitor. This plate forms a capacitor with a virtual ground, the environment or a finger which will generate the touch [20].

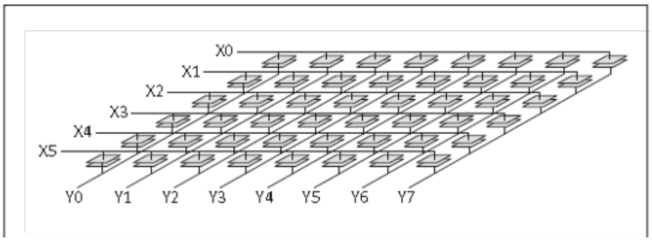

Figure 2: Two levels with conductive wires, arranged as a matrix. The change of capacitance by touching with the finger is converted into X and Y coordinates.

The single-plate capacitor generates a large electric field thanks to one plate. This allows grounded objects to be detected within a few millimeters of the sensing area. The conductive wires are arranged in a matrix, whereby all wires function as drivers and at the same time the capacitance is measured. First the capacitances are measured on all rows simultaneously and then on all columns simultaneously. Due to this measuring process, so-called ghost points can occur. Ghost points are points at which contact is erroneously detected. If a sensor surface is touched with two fingers, this results in a change in capacitance on four wires. Four points of intersection are recognized as touches, although only two points are touched. For this reason, the intrinsic capacitance method is not suitable for multiple touches [20].

In order to be able to correctly detect touches of more than one finger, the scanning of the rows and columns of the matrix must be carried out in the correct order. This means that the capacity of a single row to all columns is measured first. From the rows and columns where a difference in capacitance is measured, all resulting intersections are detected as touches. The wires, arranged in a matrix, contain a large number of crossing points which exhibit the behavior of a capacitor. One level is the sensor and the other the driver. In this method, the two levels of the matrix form two capacitor plates. Therefore, the electric field is smaller than in the self-capacitance method. The approach of a finger to the wire matrix changes the capacitance as the finger acts as another capacitor plate [20].

For the design of our artificial skin model, the structure shown in Figure 3 was used. The skin model consists of five silicone layers. The top layer represents the epidermis with the human skin structure, which is made of DS. Underneath is the matrix of conductive copper wires cast in DS. This layer simulates the dermis of the human skin, in which the wire matrix implements the equivalent of a tactile function.

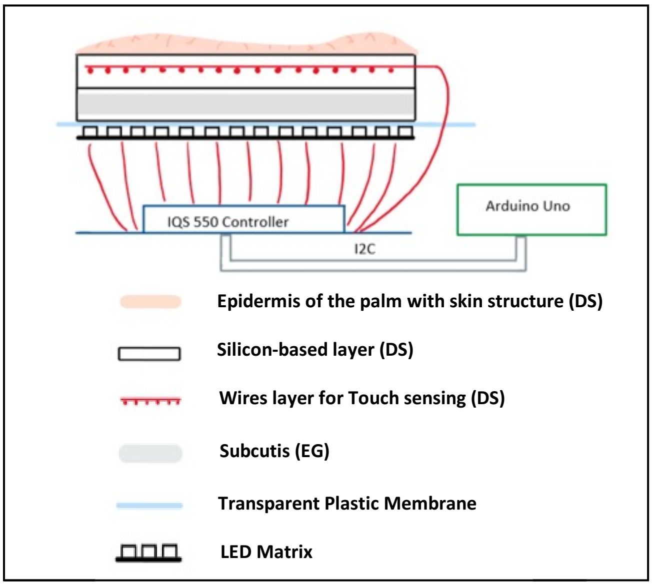

Figure 3: Sketch of the model structure, the artificial skin model, with the different skin layers, the associated electronics, hardware and material components.

For the last skin layer, the subcutis, a layer of EG was cast. It is covered on the top and bottom with a thin layer of DS as illustrated in Figure 4. The layer thickness of the subcutis is approx. 4 mm. This is within the range of a real human skin. The thickness can vary greatly depending on the region of the body, but is at least 1 mm at all points. The EG remains sticky after drying. For this reason, a further layer of DS was applied at the bottom and top. These DS layers have approximately 1 mm.

Figure 4: Detailed structure of the mimicking Subcutis layer consisting of EG layer (illuminated) wrapped in 2 DS layers.

The preparation of the different polymers is made by mixing an equivalent quantity of Part A, which contains mainly the rubber, and a quantity of Part B, which serves as a hardener (cross-linking agent), mixed together in a ratio 1:1. This preparation is then cast in a defined mold and let for drying at room temperature.

The different layers of the human skin were replicated layers by layers. The epidermis mimic had a thickness of approx. 1 mm to 2 mm made of DS. A real epidermis can be from 0.02 mm to 0.15 mm thick. In some parts of the body, such as palms and soles, it can also be slightly thicker [17]. In order to mimic the human skin color, pigments were added and mixed to the polymer preparation (Slic Pig Flesh from Smooth-On, purchased from Kaupo, Germany).

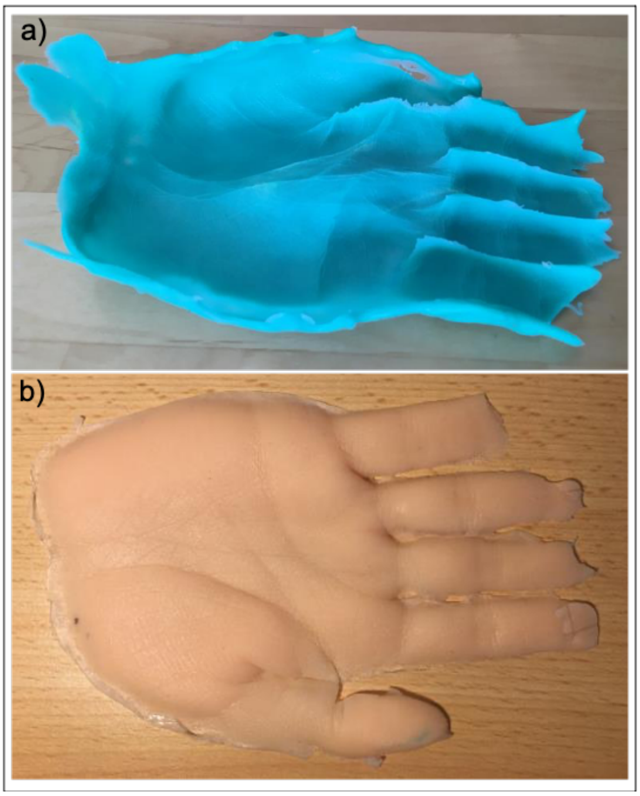

Figure 5: Real hand palm replica obtained by using Body Double polymer and then used as a mold to obtain an artificial hand palm made of DS.

In order to simulate a real human palm, in particular the shape and even the human skin texture, a replica was made with the Body Double polymer (BD, from Smooth-On, purchased from Kaupo, Germany). This material is designed to be applied directly on the human skin, harmless to the human skin and used mainly for making replica of body parts. Equal amounts of Part A and Part B of the BD polymer were also mixed together and was quickly spread on one hand and then allowed to harden for 7 minutes.

At the end of the process, a flexible mold is obtained and can be removed from the hand. The obtained mold will be used to make a hand replica made of DS. To ensure a good peeling-off between the two polymers (DS and BD), a universal mold release spray is applied in between (Universal Mold Release Spray from Smooth-On, purchased from Kaupo, Germany). By spraying the mold before applying the DS, it is possible to separate nicely the two replicas without damaging them as illustrated in Figure 5.

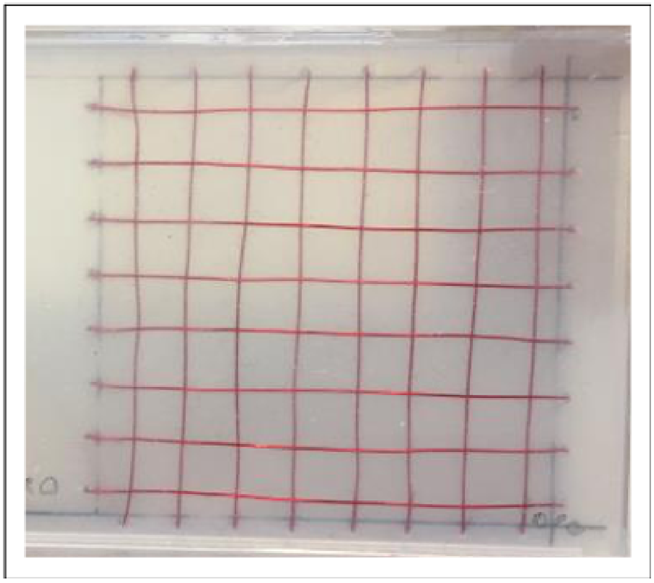

Figure 6: Wire matrix cast in DS forming the capacitive sensing layer

Then, a supplementary layer comprising the wire matrix, constituting the capacitive sensing system, is fabricated using DS to simulate the dermis. The fabrication of this capacitive layer is made by using a mold in which small holes were drilled: a total of 32 holes were drilled, 8 on each of the four sides. The hole spacing on all sides is 9.1 mm defining precisely the wire matrix.

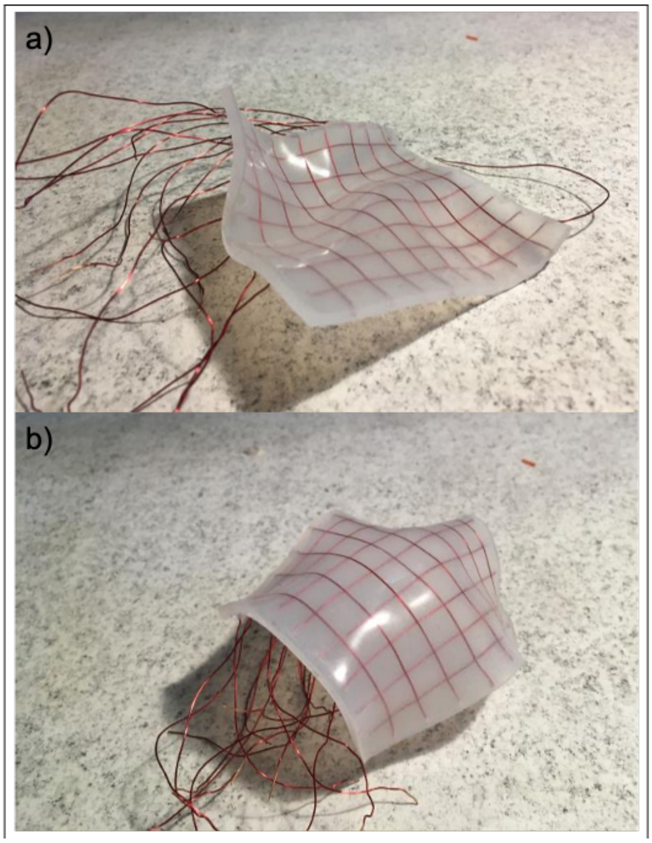

Figure 7: a) The picture illustrates that the artificial dermis, including the wire matrix, can be bent in several places at once. b) The picture shows a large curvature of the artificial dermis.

The conductive wires were threaded from one hole into the opposite hole and tightened. It was important to ensure that the rows and column were as close to each other as possible so that large gaps between the two levels could be prevented when pouring in the silicone and these gaps would not affect the capacitance measurement. The generated dermis layer, including the wire matrix, has a thickness of 1.6 mm. This layer thickness is in the range of a real dermis, which can be from 1 mm to 4 mm depending on the body region [12].

To detect and localize a touch on the artificial skin model, some electronics and hardware components are required. These include a wire matrix as sensor, a controller and a microcontroller board. A LED matrix was used for the visualization of the data. Concerning the design of the electronic skin, copper wires insulated with a polyamide coating and a diameter of 0.4 mm were used. A voltage was applied between the rows and columns. The applied voltage and the insulation of the wires are necessary to generate a capacitors function and accordingly a difference in capacitance can be measured. When touching, the contact area becomes larger and the distance between the finger and the wire matrix smaller. The wire matrix is based on the functional principle of projected capacitive system using the counter-capacitance method. The horizontal distance between the wires in the wire matrix is the same as the LED distance in the LED matrix. This means that each crossing point of the wire matrix is directly above an LED (Figure 8a).

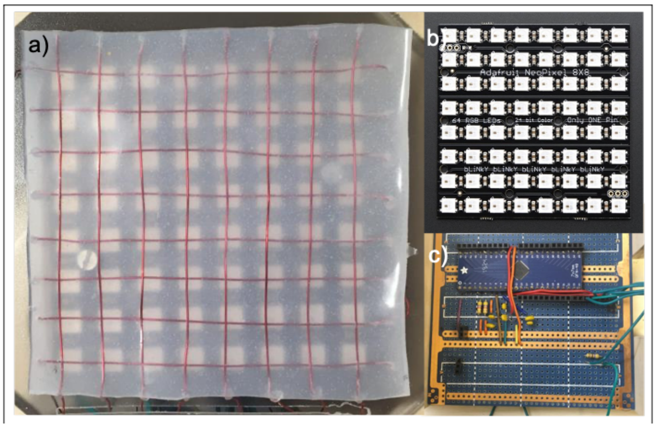

Figure 8: a) LED matrix shown with the capacitive wire matrix. b) Adafruit 8 by 8 RGB LED Matrix, with 64 individually addressable LEDs. c) IQS550 controller with PCB adapter on a soldering board.

This simplifies writing the software for controlling the corresponding LEDs. The capacitance values at the crossing points of the wire matrix are obtained by means of a IQS550 controller and an Arduino microcontroller board (Arduino Uno). The microcontroller board has 14 digital inputs and outputs, an I2C interface (pin assignment Arduino Uno). Under the skin model there is a transparent plastic sheet on which the skin model lies. This plastic plate separates the skin model and the underlying electronic components. It is transparent, so that the light of the underlying LED matrix can shine through the skin layers. The user of the model thus receives visual feedback on the position and intensity of the touch.

The IQS550 controller is located at the bottom of the model structure. The wires of the matrix are led to the controller. In addition, next to the model there is an Arduino Uno, which communicates with the controller via the serial data bus I2C (Inter-Integrated Circuit). In addition, in order to avoid any limitations in the number of touches, the selected capacitive system was designed to be a projected capacitive system.
The software is loaded directly in the Arduino, the Arduino being the link between the software and the IQS550 controller which has a number of capabilities including measuring differences in capacitance and identifying the corresponding intersection points. Recognition of gestures, such as scrolling and zooming can be realized. The detection of multiple touches can reach 5 touches simultaneously. All connections of the Arduino Uno to the IQS550 controller and the LED Matrix have been defined for multitouch localization (Figure 8b and 8c). For the visualization of the touch localization, an Adafruit 8 by 8 RGB LED matrix is used. On this matrix, there are 8 times 8 RGB (R = red, G = green, B = blue) LEDs, each one individually addressable. The brightness of the LEDs can be adjusted on a scale from 0 (off) to 255 (maximum brightness). Even with a low number (e.g., 50) the light can penetrate all silicone layers. The LED matrix is squared with side lengths of 71.12 mm.

III. RESULTS AND DISCUSSION

The whole artificial skin model is illustrated in Figure 9. All the different components were implemented in a compact wood housing in which are installed the different skin layers, the projected capacitive sensing layer and the LED matrix connected to the electronical components. The three artificial skin layers designed a flexible skin model. This is achieved by the silicone-based materials used and the flexible copper wires in the dermis. The model can be bent at will without major restrictions without losing elasticity or suffering damage. A variety of different touches can be performed on the flexible tactile skin model and visualized with LEDs (Figure 9a and 9b). The model recognizes not only touches with one, but also with several fingers. The skin model also distinguishes between gentle and normal touches. This is also differentiated by color with the help of the LEDs. Gentle touching of the epidermis or a very small distance between the skin layer and a finger results in orange shining LEDs (Figure 9a). With normal to strong contact with the skin model, the affected LEDs light up red (Figure 9b). The thickness of the epidermal layer is not constant due to the shape of the palm, it varies between 0.6 mm and 2.5 mm. For this reason, more pressure is needed at thicker epidermal areas to make the LEDs light up red.

It was shown that the concept of an artificial tactile skin model can be successfully produced. By inserting a wire matrix into the artificial dermis, the function of the mechanoreceptors in the skin can be simulated in a simplified way. For this purpose, the capacitive behavior between the wires and their change when touching the model was used. Thus, the model is able to recognize the required touches at varying intensity.

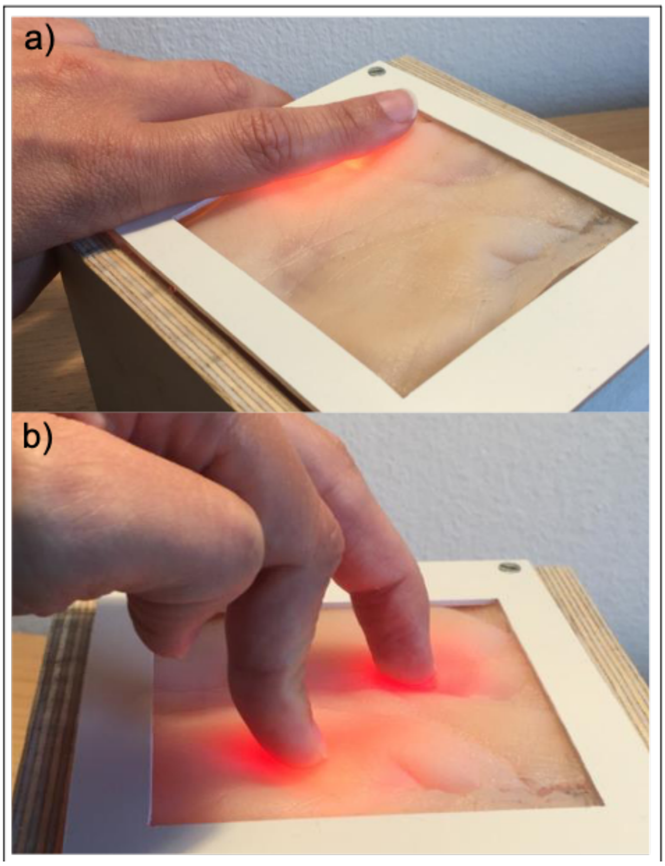

Figure 9: a) The finger surface gently touches the epidermis. Several LEDs are activated and recognize the gentle touch with orange light. b) Two fingers make a normal to strong touch on the epidermis. The LEDs react to this with red light.

Furthermore, an exact replica of the palm of the hand with the silicone papillary ridges could be simulated. This makes the prototype looking like a real palm. However, the artificial tactile skin model still has some points that could be improved. By building the prototype, the flexibility of the skin model is limited. The design was mainly influenced by the LED matrix and the electronics. To make the whole setup flexible, flexible electronics must be used. In a first step, the position indicator could be integrated flexibly in the skin itself (for example in the subcutis). For this purpose, it is possible to replace the rigid LED matrix by a flexible one. The disadvantage of this solution, however, is that the LED matrix always has a certain size and the LEDs are placed at fixed distances. This, in turn, brings with its restrictions regarding the size of the artificial skin. To avoid these disadvantages, individual LEDs or Micro LEDs could be used instead of a matrix.
Another point that can be optimized is the tactile perception. Tactile perception of the skin includes not only the mechanoreceptors, which perceive touch and pressure, but also thermal and pain receptors. In this work only the mechanoreceptors were simulated. To make tactile perception more realistic, sensors for temperature measurement and pain perception could be implemented. Additionally, there is the possibility to make the skin model

even more realistic. For example, sweat glands or fine hairs could be integrated, which control the heat regulation. It is important to ensure that the moisture produced by the sweat glands does not affect the capacitance. These observations will be integrated in the forthcoming skin models already in development in our laboratory. All these further developments and approaches may be used for preventing collisions and damages in between robots and humans in working spaces since the robot can perceive and react to contact safely. The regaining of tactile perception is also important in prosthetics and for burn victims. This can be achieved with tactile sensors integrated in an artificial skin and its data processing.

CONCLUSION

The aim of this work was to create and fabricate a functional prototype: an artificial skin model that perceives applied touch has been done. The three skin layers (epidermis, dermis and subcutis) of the artificial skin were made of silicone-based materials. To imitate the tactile perception of a real human skin, the functional principle of projected capacitive touchscreen has been applied. For this purpose, a matrix of copper wires was integrated into the artificial dermis layer. By touching the tactile dermis layer, capacitance changes take place between the wires of the matrix. These capacitance changes are measured and localized. The position of the pressure is then indicated by an LED matrix integrated into the artificial skin model.

The prototype, which perceives pressure in the dermis through an integrated, flexible 8 by 8 matrix can display the position of the touch. In order to make the artificial tactile skin mimic human skin, there are some enhancements that can be made. To keep the flexibility of the whole model, flexible electronics must be used, which can be integrated into the artificial skin. Next steps will concern the design and implementation of flexible electronics to generate a self-standing functional artificial tactile skin model. In a near future innovative developments will concern the reproduction of human skin prototypes according to a very high spatial resolution identical to the sensitivity of the human skin.

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