 Ionic liquid based distributed touch sensor using electrical impedance tomography

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Abstract

Inspired by the human skin sensory mechanism, there are growing interests in creating a sense of touch in robotics. This work describes a new impedance based design to create an artificial tactile sensing skin. It has demonstrated that the electrical impedance tomography imaging technique allows for detecting the pressure distribution in a large area by a distributed touch sensor. The sensor is fabricated by filling a circular shaped phantom with liquid conductor and covering with an elastic shell on the top. The proposed sensor can detect the pressure applied to the elastic top using electrical impedance tomography imaging method. The sensor can therefore operate as a touch sensor mimicking a piezo-impedance operation in a simple fashion. The new sensor can differentiate between various force levels and their locations and thus produces a distribution of pressure. Such a simple sensor can function as a large area skin, enabling smarter human-machine interactions in emerging augmented reality and robotic applications.

1. Introduction

Electrical impedance tomography (EIT) is an imaging technology that uses voltage and current data measured at the boundaries of a domain to determine the electrical conductivity or resistivity distributions inside an object. The EIT system measures the boundary voltage by injecting a constant sinusoidal current into the object, and uses an image reconstruction algorithm to reconstruct a cross-sectional image of the conductivity distribution from the boundary potential data [1, 2]. EIT achieves a visual measurement by reconstructing the resistivity or conductivity distribution of the medium in the sensitive domain in the form of an image. EIT-based soft sensors that are sensitive to pressure and deformation can be used in robotics to realize important human-computer interaction (HRI) by identifying and interpreting tactile information. With the advantages of low cost, non-invasiveness, and non-radiation [1], EIT has considerable application prospects in the medical and industrial fields, and has been widely concerned by the researchers [3]. New interest raised in robotics and pressure sensing in recent years. In robotics, the sensing of tactile stimuli is of great significance. By identifying and interpreting tactile information, HRI can be achieved [4]. Tactile sensing can be achieved by EIT sensors that are sensitive to pressure and deformation. EIT has instant feature in data collection and fast response to touch stimuli, providing a basis for real-time touch sensing [5]. If the soft sensor is thin, flexible and stretchable, the artificial skin for robot can be created through its large-scale application [6].

The focus of this work is to create soft pressure-sensitive sensors. Up to now, most researches had focused on the development of conductive flexible materials. In the early stages, conductive rubber made by mixing rubber with conductive carbon particles was first applied to EIT-based pressure sensitive skin manufacturing [7]. However, due to the nature of rubber, the skin is elastic but not stretchable. Then, a single-layer conductive fabric is created by spraying a conductive coating on the surface of ordinary fabric, and a pressure-sensitive skin is made based on this material [8]. Due to the high stretchability, it can cover the 3D parts of the human model, such as the face or elbow, and measure the pressure distribution in these areas. Based on the single-layer fabric, conductive fabrics made of multilayer composite materials have been developed. Using this material, a wearable haptic glove with a haptic unit and embedded data acquisition electronic device was constructed, which can...
measure the pressure on the entire palm surface and all fingers [9]. In recent years, elastic composite materials have been used in the development of flexible sensors [10, 11]. This type of elastic material is shaped by thermal processing, allowing more shape changes and having a wider range of applications. Another way to realize soft sensors is to apply non-conductive soft materials with embedded micro-channel networks [12]. The channels are usually filled with conductive liquids, such as electrolyte solutions [13] and room temperature ionic liquids (RTIL) with a discrete network structure area sensing [12]. The conductive liquid based sensor offer new opportunity in soft sensing. Compared with the conductive fabric sensors, the main advantage of such soft sensors is that the resistance change is more predictable and repeatable [12]. A new type of EIT based sensor is investigated with simulated and real data that unlike [12] a continuous ionic liquid is directly acting as pressure sensor.

2. Sensor design and manufacturing

From the perspective of information theory, the EIT system is mainly composed of the following three parts: (i) information extraction unit. It consists of electrode arrays arranged at equal intervals on the boundary of the measured field, which has an important impact on the performance of the sensitive domain; (ii) information transmission unit: It can quickly, accurately and stably collect the data reflecting the distribution of the medium conductivity in the measured domain, and complete the corresponding demodulation and filtering; (iii) information recovery unit. It can use the image reconstruction algorithm to reconstruct the medium conductivity distribution in the sensitive domain in the form of 2D or 3D images. As shown in figure 1, generally, the EIT system consists of the following actual parts: sensors, hardware and computer, which are responsible for information extraction, transmission and recovery, respectively [14–16]. A 16-channel EIT system used in this experiment was developed in the lab. The instrument diagram has the working frequency of 50 kHz, using the adjacent driving and measuring mechanism that makes 208 measurements per frame. User-configurable current injection range is 6 to 18 mA [15].

The sensor phantom was constructed using three-dimensional printing (3DP). The conceptual diagram of the sensor is shown in figure 2. The shape of the sensor is a thin cylinder. The upper and bottom surfaces are made of silicone, which is elastic and non-conductive, and the interior is filled with water as liquid conductor. The electrode array composed of 16 screw and pins is casted evenly on a rigid frame and is positioned on the boundary of the sensor phantom.

Figure 3 illustrates the cross-sectional view of the sensing area before and after a touch stimulus is applied. When pressure is applied to the elastic film, the film sinks downward. This movement changes the resistivity distribution in the way that the elastic film intrudes into the liquid phase creating a non-conductive region in the domain. The level of conductive water rises in surrounding area of the pressure point accordingly. Such changes firstly modelled by creating a cone-shaped inclusion and the increased water level in the surrounding area in the 3D forward model; and subsequently they can be reconstructed by 2D EIT image reconstruction algorithms. Alternatively, if the sensor is filled with the water then the 3D effects might behave differently.

3. Simulation results

The fundamental equation for the EIT forward model mathematical model is as follows:

\[ \nabla \cdot \left( \sigma \nabla \Phi \right) = 0 \]  

(1)
The EIT forward problem is to determine the voltage distribution in the sensitive domain with a given current when the medium resistivity or conductivity distribution inside the sensitive domain is known. The finite element method (FEM) with complete electrode model can solve the forward problem numerically by discretizing the domain into small elements to transform the continuous problem into a discrete problem. The Tikhonov regularization solves for $\Delta \sigma$ with the following equation:

$$\Delta \sigma = (J^T J + \gamma^2 R)^{-1} J^T \Delta u$$  \hspace{1cm} (2)

Where $R$ is the regularization matrix based on the discrete Laplacian, and $\gamma$ is the regularization parameter, which is empirically selected, and $J$ is the Jacobian which is essentially a ‘sensitivity distributions’ within the domain. For simulation study cone shape pressure point modelled in 3D FEM as shown in figure 4.

Figure 5 are the reconstructed images applying Tikhonov regularization algorithm. Overall, the reconstructed images managed to show the pressure effected areas in the model. Since the conductivity of the inclusions is lower than that of the background water, the pressure acted area is with lower conductivity with respect to the background. The areas of positive conductivity values are in the boundary are the result of rising water level.

4. Experiment and results

This section introduces the pressure test experiment of the fabricated pressure sensor to validate its proposed functionality. From the pressure test experiment results, reasonable ameliorated orientation could be proposed. The water level should be higher than the electrode plane. After the elastic film is pressed, the drained water should not cause the water level to rise too much and overflow the phantom. The phantom with water medium is covered with the elastic film and connected to the EIT system (figure 6). Then the pressure test starts. The first step is single-point test. A single point of compression has been performed on the elastic film by a finger (as shown in figures 7(a), (b)). Measurements without pressure acted on is used as background data, and then perform pressing operations from the upper and lower half of the sensor, respectively. The EIT system collects the datasets over a period of time, which are used to reconstruct images. If the images can successfully show the corresponding pressing area, the sensor is then proved function as proposed. The quantification of the imaging
scale with pressure applied relies on a better understanding of the mechanical deformation of the silicon cover. We choose an ionic liquid in this study but gel type conductor could be used for which the self-healing properties and hysteresis could be important factors for such a quantification.

The second step is the multi-point test where the method remains the same as test one. Two fingers are used to execute double pressure points on the elastic film at the same time, and the corresponding datasets are collected. The action points are shown in figure 7(c). Reconstructed images are shown in figure 8.

The main source of error in the experiment is that the electrodes cannot be truly evenly distributed during installation, resulting in the electrodes not in the exact same plane; the geometric dimensions of each electrode are not completely identical, resulting in different sensor performance. A total of 433 sets of data were collected in the experiment. Background data was an average over the chosen number of background datasets. The first 50 datasets were set as background, and 360 valid images were obtained finally.

Figure 9 shows the plot of pressure profile over time (2D and time). The experiments include 352 frames of data, going upward in time as shown from one area of pressure (similar to figure 8(a)) to another on point of pressure in the other side (similar to figure 8(b)) and finally to two areas of pressure (similar to figure 8(c)). This is a cross sectional profile of (x,t) in (x,y,t) representation of dynamical images [17].
Figure 6. Phantom connected to the EIT electrodes.

Figure 7. Pressure test: (a) first single-point test, (b) second single-point test, (c) multi-point test.

Figure 8. Reconstructed images of pressure test, applied Tikhonov regularization algorithm: (a) first single-point test, (b) second single-point test, (c) multi-point test.
5. Conclusion

Human skin is a self-healing touch sensing system that detects various mechanical contact forces. To mimic these capabilities, this paper proposes an artificially created skin like sensor using a liquid container and EIT imaging. The liquid ionic material allows a self-healing process, and by tuning the mechanical properties of the silicon cover and other design factors, one can create a piezo-impedance like sensor. These are developed using an EIT system and an image reconstruction algorithm allowing for a large area pressure sensing with small number of sensor in its boundary. The new sensor is sensitive to an object’s contact force and can show the distribution of the touch location. Moreover, the sensor combining a silicon based cover and liquid materials has the self-heal autonomously and regain sensing function immediately with high frame rate of the EIT device. Experimental results shows similar performance as the simulated data both in terms of identifying the pressure positioning and the effect of higher level of water in surrounding area of the pressure areas. Specific type of robotic sensor can be designed based on proof of principle shown here.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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