A Tactile Distribution Sensor Which Enables Stable Measurement Under High and Dynamic Stretch

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Abstract

Recently, we have been studying various tactile distribution sensors based on Electrical Impedance Tomography (EIT) which is a non-invasive technique to measure the resistance distribution of a conductive material only from a boundary, and needs no wiring inside the sensing area. In this paper, we present a newly developed conductive structure which is pressure sensitive but stretch insensitive and is based on the concept of contact resistance between (1)a network of stretchable wave-like conductive yarns with high resistance and (2)a conductive stretchable sheet with low resistance. Based on this newly developed structure, we have realized a novel tactile distribution sensor which enables stable measurement under dynamic and large stretch from various directions. Stable measurement of pressure distribution under dynamic and complex deformation cases such as pinching and pushing on a balloon surface are demonstrated. The sensor has been originally designed for implementation over interactive robots with soft and highly deformable bodies, but can also be used as novel user interface devices, or ordinary pressure distribution sensors. Some of the most remarkable specifications of the developed tactile sensor are high stretchability up to 140% and toughness under adverse load conditions. The sensor also has a realistic potential of becoming as thin and stretchable as stocking fabric. A goal of this research is to combine this thin sensor with stretch distribution sensors so that richer and more sophisticated tactile interactions can be realized.

Index Terms: I.2.9 [Artificial Intelligence]: Robotics—Sensors; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 Introduction

An ideal tactile sensor should be thin, high-resolution, soft and stretchable. Most conventional tactile sensors have been fabricated over thin film-type substrates, and use matrix-based wiring technique which can handle n^2 elements only using $2n$ wires. Film-type tactile sensors can be thin, have high resolutions and can be bent to adapt over mildly curved cylindrical surfaces.

However, they cannot adapt over spherical or more complex-uneven surfaces such as the face or the hand. This is because such conventional sensors are only bendable and not stretchable. Also, there are lots of cases where the tactile sensor needs to have direct contact with human body. However, film-type tactile sensors are not suitable for such applications because of their lack of softness.

If tactile sensors can become soft like cloth and stretchable like human skin, they will undoubtedly become much more utilized in various fields. such as (1)robotics: Dexterous manipulation, safety management for man-machine interaction, (2)ergonomics and sports science: Monitoring and analysis of contact between human and objects such as chair, bed or hand tools, (3)elderly care and welfare: Movement assistance, soft-contact input devices for the disabled or elderly and (4)interfaces: Input devices for virtual reality or computer applications.

The authors are studying intelligent motion control during active interaction between robot, human and the environment. Our interests include, whole-body motion control such as lifting large objects and dynamic rise-up motion, and providing care for the elderly and disabled.

For this purpose, we developed tactile sensors which can cover whole body of humanoid robots and humans [10], and are using them in real world applications and under very tough conditions. Through the development phase and by conducting many experiments, various problems such as the following have come into view:

1. Difficulties of implementation on highly stretching area such as the area around joints or the waist.
2. Difficulties of implementation over complexly curved surfaces such as the face or the hands.
3. Sensitivity towards rich tactile interactions which involve skin deformation such as pinching or rubbing.

Developing stretchable tactile sensors is the most important issue for solving the above problems. A main factor preventing stretchability in tactile sensors is the massive wiring inside the sensing area of the sensors. Two of the conventional approaches to the wiring problem have been (1)developing stretchable wiring and substrates and (2)developing small wireless tactile elements.

Examples of the first approach include using wires made of silicone based conductive glue with Ag fillers [11] or polymer-carbon-nanotube composites [8] as well as spiral-formed conformable substrates [9]. In this approach, fine and precise wiring is difficult. Moreover, supposing frequent stretching, durability of the connection between wire and element could be a major concern.

Using small wireless devices approach[7] might be a most straightforward solution, however there are problems such as large power dissipation, and high development cost of special small devices. Also, Two-dimensional signal transmission technique[6] is a remarkable approach, which has features such as contactless coupling with tactile elements and low energy dissipation, though there are some difficulties such as standing waves and measuring tactile data between the elements.

Recently, we have been studying a different approach towards stretchable tactile sensors[3][4][2]. The new sensor is based on EIT (Electrical Impedance Tomography), an inverse problem analysis technique used in non-invasive inspections and medical imaging. EIT can estimate the resistance distribution of a conductive body by using measurements only from its boundary. In a special case when a pressure sensitive conductive rubber (PSCR) sheet is used as the conductive body, the resistance distribution estimated by EIT

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IEEE Symposium on 3D User Interfaces 2009
14-15 March, Lafayette, Louisiana, USA
978-1-4244-3965-2/09/$25.00 ©2009 IEEE

will represent the pressure distribution in the PSCR sheet. Since the measurements are performed only on the boundary and no wiring is used inside the sensing area, the EIT-based sensor can be flexible and stretchable just like normal rubber sheets. Also, by using different conductive material such as conductive rubbers, conductive foams, or conductive fabrics, there is a great potential of realizing highly stretchable and soft tactile sensors.

We have confirmed the basic characteristics of the tactile sensor and also some of its unique features and applications. Fig1 shows a number of interesting results. Our developed conductive knit realized tactile sensing under conditions with over 150% stretching which is higher than conductive rubber. At the same time, the conductive knit shows less hysteresis than conductive rubber material and is therefore more suitable for dynamic applications. However, resistance distribution of the conductive knit or conductive rubber is influenced by not only pressure but also stretch. Therefore, to distinguish these two stimulations, we needed the stretch conditions to remain constant or be acquired from additional information such as joint angles, so that the effect of stretch can be canceled out.

In order to solve this pressure-stretch indistinguishability problem, we present in this paper, our newly designed and developed conductive fabric structure which is sensitive to pressure but insensitive to all other stretch stimulations. Also, this sensor has other intriguing characteristics such as very high stretchability up to 140%, and stable sensing of pressure stimulations under high stretch and deformation. One of our main goals is to realize a more sophisticated tactile sensor which can detect multiple types of tactile stimulations, by layering and combining this thin pressure distribution sensor with others such as stretch distribution sensors.

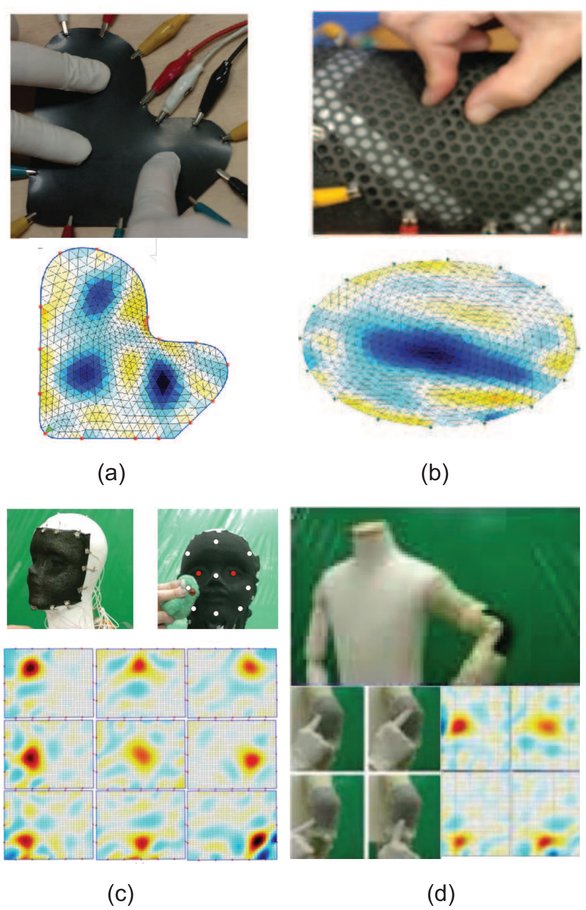

Figure 1: Unique characteristics and applications of our EIT-based tactile sensor: (a) validating usability of irregular-shaped conductive bodies. (b) detecting pinching and rubbing, using our stretch sensor made of a porous conductive rubber sheet. (c) pressure distribution sensing over complex curved surface of a dummy face, using conductive knit. (d) sensing of a contact point on the highly stretchable area such as elbow and shoulder, using conductive knit.

2 Sensor Concept

The tactile sensor is based on Electrical Impedance Tomography (EIT) which is an inverse problem analysis technique. Much like the CT scan (Computed Tomography Scan) computes the X-ray transmissivity distribution of an object by radiating X-rays from different directions, the EIT estimates the electrical resistance distribution inside the conductive body by injecting electric current from different directions on the object boundary.

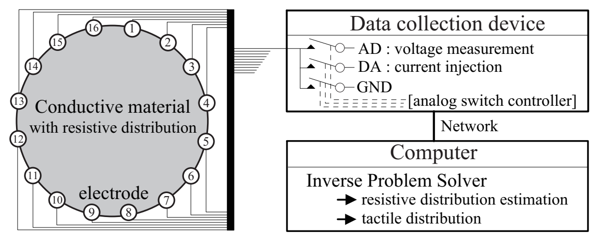

Figure 2: Basic components of the EIT-based tactile system.

2.1 Tactile Sensors Based on EIT

It is easily imaginable that a tactile sensor can be made by applying EIT to conductive materials such as conductive rubbers. Fig.2 shows the basic components of a tactile sensor system based on EIT.

Since the tactile sensors based on EIT need no wiring inside the sensing area, not only thin and flexible but also highly stretchable tactile sensor can be realized. This fact leads following potentialities of the sensor:

1. The sensor can be implemented over the highly stretching surface around movable joints in robots or humans.
2. Since most of the conductive rubbers are also stretch-sensitive, a stretch distribution sensor for detecting richer tactile stimuli can be realized.
3. Implementing the sensor over complexly curved 3D surfaces such as the face becomes extremely easy.
4. Since the sensor does not depend on the size of the conductive body, Measuring small areas such as fingers are also possible.
5. As the sensor sheet could be extremely thin, there is a potential to realize a multi-layered system capable of simultaneously detecting multiple tactile stimuli.

2.2 EIT Systems

Typical EIT systems have 16 or 32 electrodes for injecting electrical current and measuring potential distributions on the boundary. These systems commonly use the adjacent method for data acquisition and Newton's iterational method to estimate the resistance distribution. In a system with 16 electrodes which uses the adjacent method, current is injected through pairs of neighboring electrodes, namely (1,2),(2,3),...(15,16),(16,1). For each of these current injection patterns, a unique potential distribution pattern emerges and the voltage difference between every other 2 neighboring electrode pairs are measured and collected into a set of 13 measurements.

Considering all the 16 current injection patterns, vector V_m containing a total of $208(16 \times 13)$ measurements is obtained and fed to the Newton's method in order to estimate the resistance distribution.

Assuming γ_i as the actual resistance distribution, and c as the injected current patterns, Newton's method minimizes the error in the boundary voltages between V_m and simulated data ($V_i = F(\gamma_i, c)$) obtained from forward modeling. The equation for forward modeling $\nabla.(\sigma\nabla\Phi) = 0$ is derived from the Maxwell's equation where σ is electric conductance and Φ is the electric potential.

Normally, an FEM (Finite Element Method) model of the conductive body is used for the forward modeling of the problem. A Jacobian matrix J_i represents the effect on the boundary voltages for a slight change in the resistivity of the FEM elements. J_i is calculated based on the resistance distribution γ_i, and is used to estimate a more accurate resistance distribution ($\gamma_{i+1} = \gamma_i + \delta\gamma_i$) which will reduce the error between V_i and V_m. By setting an initial resistance distribution and repeating this iterational process, the estimated resistance distribution map converges towards the true resistance distribution. The equation below shows the ith step of the Newton's method.

$$\begin{aligned} &min : \|V_m - V_i\|^2 + h^2\|R\gamma_i\|^2 \\ &\gamma_{i+1} = \gamma_i + \delta\gamma_i \\ &\delta\gamma_i = (J_i^T J_i + h^2 R^T R)^{-1} J_i^T (V_m - V_i) \\ &J_i = \partial F / \partial \gamma_i \end{aligned}$$

Because of the ill-posed nature of the problem, a regularization term($h^2\|R\gamma_i\|^2$) is also introduced to stabilize the answer. The regularization term contains a scalar weight h and a regularization matrix R. We have used the Laplace image prior for R, but the unity matrix could also be used. Parameter h defines the smoothness of the estimated resistance distribution. For further information on specific EIT methods and available software platforms, please refer to literatures such as [5][1].

3 Pressure-Sensitive Stretch-Insensitive Sensor

The most straightforward stretchable conductive materials for EIT-based tactile sensors are different types of conductive rubbers. However, conductive rubbers have a number of problems such as (1)their relatively small stretchability, (2)their high hysteresis[2] and (3)their sensitivity towards both pressure and stretch.

These problems led to the development of an original conductive knit fabric which was more stretchable (up to 50%) and showed much lower hysteresis. However, the 3rd problem regarding the conductive rubber was also true in the case of conductive knit fabric. Therefore, in order to only extract pressure distributions, we used the sensor in constant stretch conditions or alternatively provided additional information about the stretch distribution.

For example in Fig.1(c), the sensor is fixed over a dummy face. Although a large stretch has been applied to the sensor to fix it on the dummy face, the amount of this stretch is constant and therefore, the changes in resistance distribution of the sensor will only be a function of pressure. Also, in case of Fig.1(d), when the tactile sensor is placed over a joint, stretch distribution mainly depends on the joint angle. This means stretch distribution can be estimated and compensated by using information from the joint angle sensors.

However, there are cases were we have to use the sensor under complex stretch conditions and we have no additional information to cancel out the stretch effect. In order to solve this problem, rather than simply using conductive knitted fabrics, it is preferred to use a conductive body which is sensitive to pressure but insensitive to stretch.

3.1 Design

In order to realize a Pressure-Sensitive Stretch-Insensitive (PsSi) tactile sensor, we have implemented a special design shown in Fig.3, which consists of two different types of stretch-insensitive conductive sheets. Moreover, a mechanism for pressure sensitivity based on nonlinear contact resistance between the two layers.

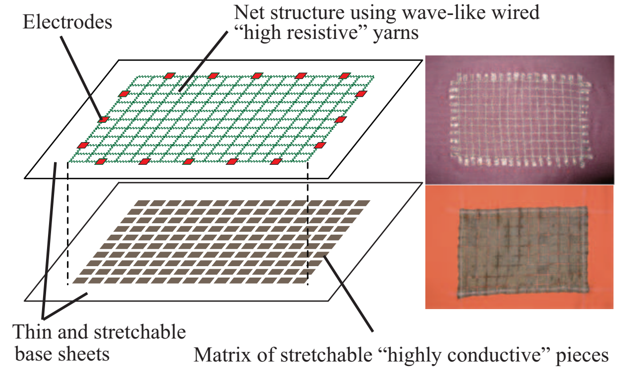

Figure 3: The basic structure of the PsSi tactile sheet: design concept (left) and photos of the fabricated layer before integration(right).

Firstly, conductive yarns with relatively high resistivity are used to form a net structure (top sheet in Fig.3). Stretchable wavelike yarns are used which allow the fabricated net to be highly stretchable. Furthermore, since the total length of the wavelike yarns will remain constant during stretch, there will be no change in the resistance of the net structure as a result of stretch. The net structure is placed over a non-conductive thin and stretchable fabric base and the electrodes are fixed on its boundaries. This net structure is only a highly stretchable conductive sheet with a constant resistance distribution which by itself cannot detect neither stretch nor pressure.

In order to add pressure sensitivity to the structure, we have implemented the concept of contact resistance between different conductive materials. A high contact resistance between two materials means that they should be pressed hard against each other in order for full conductivity between them. On the other hand, when two materials have a very small contact resistance, there will be high conductivity as soon as they touch and there is no need to apply pressure.

By using another highly conductive stretchable layer which has an appropriate contact resistance against the conductive yarns of the net structure, we can have the two layers connect to each other only when a certain amount of pressure is applied regardless of stretch conditions. Also, in order to detect multiple points simultaneously, the highly conductive stretchable layer should be made of small unconnected pieces of highly conductive and stretchable material rather than one continuous conductive layer. (bottom sheet in Fig.3).

The highly conductive stretchable layer is then placed under the previously mentioned stretch-insensitive net and is connected to it on the boundaries. When little or no pressure is applied, the two layers are not fully connected to each other because of the existing contact resistance between them. When pressure is applied, it will reduce the contact resistance between the two layers in the pressed area, causing a change in the resistance distribution of the stretch-insensitive net.

One of the characteristics of the EIT technique is that one has to stimulate at least a minimum area over the sensor sheet in order for the stimuli to be fully detected. This area is called the Minimum Detectable Area or MDA and is about 0.25%   1% of the total area of the sensor sheet (5% 10% in length) depending on the distance from the electrodes. Therefore, making excessively dense nets, where the area of each grid cell is too much smaller than the MDA, would not be beneficial in any way.

It should be noted that when stretch is applied to the sensor, each grid cell will grow in size. This means that for a highly conductive piece on the bottom layer to fully touch the conductive yarns in the top layer, a relatively larger area must be pressed.

On the other hand, one important benefit of this design is that we can sense the pressure patterns, without having any knowledge of the stretch conditions. Also, since the length of the yarns are constant at all times, the model of conductive sheet for EIT stays unchanged and the inverse problem can be safely solved using one single model. This in turn, significantly improves the dynamic response and stability of the measurements compared to the case of using conductive rubbers or foams which generally demonstrate a high hysteresis effect.

3.2 Fabrication

In order to fabricate this PsSi conductive structure, we introduced copper sulfide bounded nylon yarn as conductive yarns for the upper sheet, and Ag-coated knitted fabric as small conductive pieces for the lower sheet. Nonlinearity and specifications of contact resistance between copper sulfide and Ag are suitable for measuring human interactions.

We have used the stretch sewing function of the sewing machine to sew the conductive yarns over a highly stretchable knit fabric. Each grid cell is almost 9mm x 9mm in size. Next, we have used a highly-conductive stretchable knit and cut it in small square pieces of 10mm x 10mm. We then placed the pieces over a stretchable knit base and used liquid rubber to fix and insulate each piece. This sheet is then placed under the stretch-insensitive net structure and the area around the boundaries are sewed together to form a composite 2-layer tactile sensor module.

The final size of the rectangular sensor sheet is 90mm x 160mm and it can be stretched to up to 140% of its original size. We have placed 3 electrodes along the width and 5 electrodes along the length of the sheet as is shown in red dots in Fig.3.

Because of the size of each grid cell in the net structure (9mm), the total resolution of the sensor will also be around 9mm. Therefore, stimulated areas which are smaller than 10mm (0.7% of sensor's total area) are extremely hard to detect and larger stimulated areas 10mm 20mm can be detected in some areas but not all over the sensor sheet.

4 Experiments

As for the data acquisition device, we have developed a real-time device which uses the adjacent sampling method and can acquire high resolution samples at a maximum rate of around 40 fps. In the experiments of this paper, a 16 electrode configuration is used with the adjacent sampling method, and the sampling rate is around 24 fps. For further information on the data acquisition electronics and the EIT solver program please refer to our previous work[2][4].

Please note that, for the forward model of EIT, we have not used a model corresponding to the actual net structure but rather a finer pitch FEM model which is used for continuous conductive sheets. Also, we have used a non-iterative first order estimation technique for the EIT solver which is common in real-time EIT.

A basic experiment has been designed in order to demonstrate the sensitivity of the sensor. We have used a force gauge sensor to gradually apply pressure to a circular area(20mm diameter) on the side of the sensor and then unloaded the pressure after a peak value was reached. Fig.4 shows how the sensor value changes in a nonlinear way as a result of the applied pressure and the change in contact resistance between the two layers. The mean estimated value of elements in the stimulated region is taken as the sensor value.

4.1 One-Way Stretch

Fig.5(a)-(e) shows the results of 5 experiments in three different lengthwise stretch conditions: zero stretch (top row), 20% stretch (middle row) and 40% stretch (bottom row).

The white color shows regions which had no change in resistance (no-load regions) while red color range show regions where the resistance has decreased (pressure has been applied). There are also blue regions which show that the resistance has increased to a higher value. Since in this tactile design, there is no possibility of a rise in the resistance value, the blue regions are only due to EIT estimation errors. These blue regions can be easily filtered out in order to have cleaner results but were intentionally not filtered so that some of the characteristics of EIT estimation can be demonstrated.

In (a) we have applied 10N and (b) 20N to the center of the sensor in a circular area with Φ20mm. When a 40% stretch is applied, the size of each grid cell will grow to 12.6mm x 9mm which means that the size of the stimulated area will become relatively smaller compared to the size of each grid cell. Therefore, as the applied stretch over the sensor increases, the stimulation area will become smaller and the detected signal will become weaker as seen in the results. Also, the results in (a) where we have a 10N load in zero stretch, are almost the same size and intensity as the results from (b) where we have a 20N load and a 40% stretch. This is due to the fact that a heavier load will be detected as if it has a slightly larger stimulation area meaning that the current sensor cannot distinguish slight differences in pressure and stretch. This characteristic is heavily dependent on the estimation algorithm used in EIT and could be improved by using a more accurate algorithm instead of the current real-time algorithm.

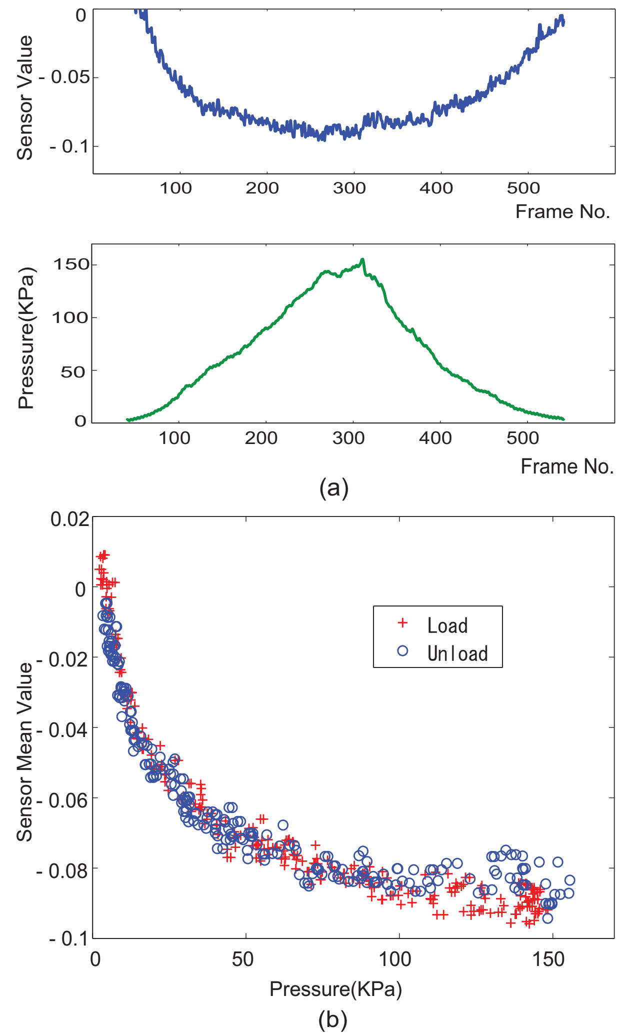

Figure 4: Pressure vs. Sensor value: Pressure is applied to a circular area with a 20mm diameter on the side of the sensor. Sensor value(a) and pressure value(b) in each acquired frame. Nonlinear relationship between applied pressure and tactile sensor value.

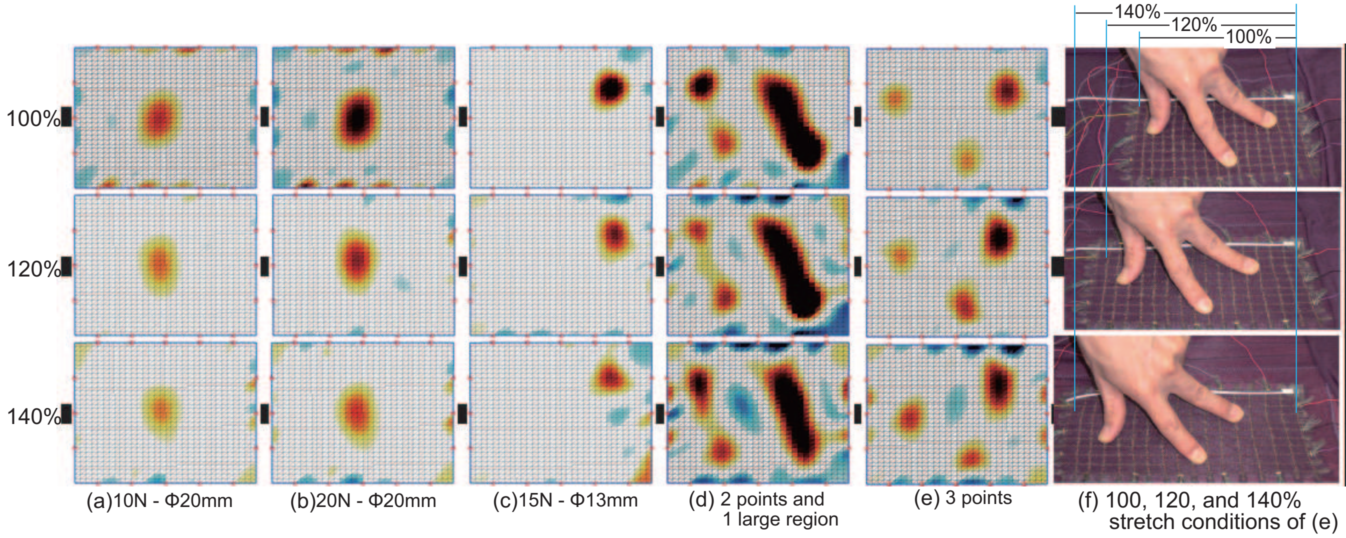

Figure 5: The results of 5 experiments in different lengthwise stretch conditions: zero stretch (top), 20% stretch(middle) and 40%(bottom). The amount of stretch can be seen in the photos of the right column.

In EIT, the resolution in the center of the conductive material is lower than the areas closer to the boundaries and therefore even smaller stimulations can be detected when they are closer to electrodes. For example, (c) shows the results of applying a 15N load close to the boundary of the tactile sensor in a circular area with 13mm diameter. It is possible to compensate for the inhomogeneous sensitivity of the sensor but it is not done here in order to observe the most basic properties of the EIT-based sensor.

Also, (d) demonstrates the results from two smaller circular stimulations on the right and one relatively large regional stimulation on the left, while (e) shows 3 fingers being detected. Please note that the loads in (d) and (e), are applied by human hand and therefore the pressure is not the same in the case of zero, 20% and 40% stretch.

4.2 Two-Way Stretch and 3-dimensional deformation

Next, we will demonstrate experiment results under a more realistic situation where the tactile sensor is placed over a 3-dimensional curved surface and stretch and deformation are applied in several directions.

At first, we pressed the sensor sheet against a foamed styrol sphere (Φ60mm), and then applied pressure to the sensor with two fingers. The pressure distribution results are shown in Fig.6(a). At the top part of the sphere, stretch is applied almost evenly and in all directions. Also, because of the relative hardness of the sphere's surface, applying pressure is easier and the results are more stable.

Fig.6(b) and (c) we have used a balloon with a 90mm diameter shown in the picture, and pressed the sensor over its top. Pressing the balloon by a finger will cause a great deformation over its surface. As can be seen in the results, even in the presence of such stretch and deformation, the finger tip is very clearly detected. Fig.6(c) shows the results when we two fingers of one hand to pinch the balloon and another finger of the other hand to stroke the surface. Despite extremely complex stretch and deformation which can only be seen on the surface of a balloon, the sensor still sticks to the surface of the balloon and can clearly detect 3 points of pressure stimulations on the surface. The fact that the sensor can stably detect pressure distributions over a balloon surface which is extremely stretchable and can deform into highly complex curves, came as a surprising delight to the authors.

Fig.6(d) shows the results of pressing the sensor sheet over a PET bottle. In contrast to cases (a),(b) and (c) where we had a more gently curved surface, the sensor is under much tougher conditions with a very sharp deformation and pressure concentration on and around the cap of the PET bottle. The sensor can cope with such

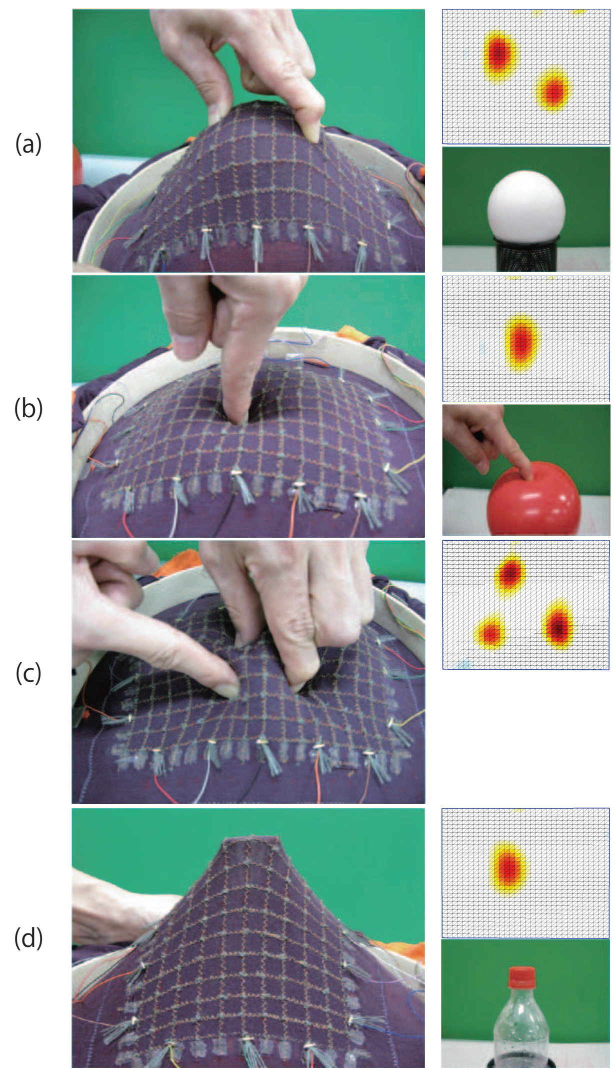

Figure 6: Developed tactile sensor under 2-way stretch: The sensor's response is demonstrated over a relatively hard foamed styrol sphere-Φ60mm(a), a highly deformable and stretchable balloon-Φ90mm (b,c) and a slim PET bottle cap-Φ20mm (d).

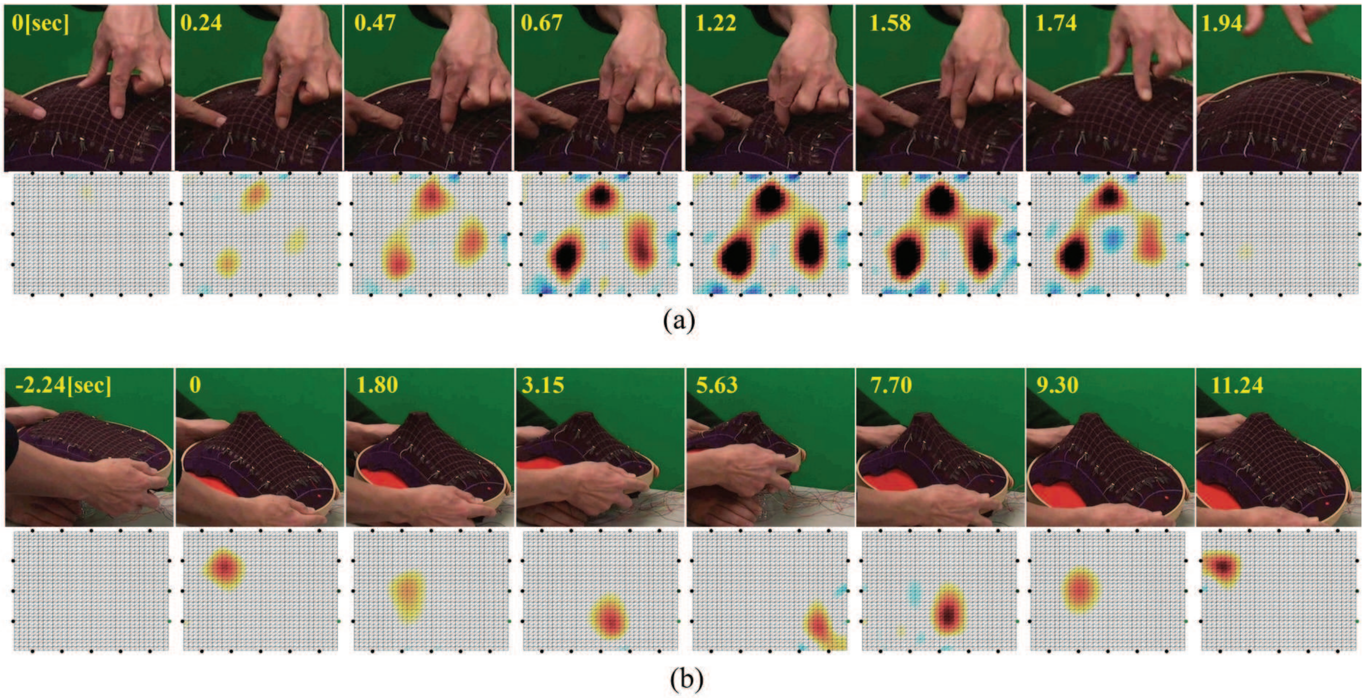

Figure 7: Dynamic pressure and deformation over the tactile sensor: (a) pinching the deformable surface of a balloon with 3 fingers and (b) sliding the sensor sheet over a PET bottle's cap.

conditions without a problem and still, as seen in the results, stably detect the applied pressure. It should be noted that in (a),(b) and (c), the pressure applied to fix the sensor over the surface is distributed on a wider area and the actual change in contact resistance is negligible. In case of (d) however, pressure is concentrated over the cap of the PET bottle and the bottle is pressed harder against the sensor causing over 40% stretch around the cap and therefore, pressure from the cap has been clearly detected.

4.3 Dynamic Two-Way Stretch

Even conductive rubber sheets are stretchable, but in case of a change in pressure or stretch conditions, residual stress and other factors will cause a considerable hysteresis, delaying the full recovery of resistance for a few seconds or in some cases even a few minutes. In contrast with the conductive rubber, the developed PsSi conductive sheet not only can follow the complex and dynamic deformations on a surface, but also can detect dynamic and sudden changes in the applied pressure.

In Fig.7(a) we have used the sensor over a balloon surface similar to the cases of Fig.6(b) and (c). We have used three fingers to pinch the balloon surface and release it. The total length of the experiment is only 1 to 2 seconds. The sensor copes with dynamic and complex surface deformation together with fast changes in the applied pressure and still can detect the signal with no apparent hysteresis and in a very stable manner. It should be noted that there is an approximately 250 msec latency between actual stimulation (top rows) and estimated data (bottom rows), which is due to time needed for data acquisition and transfer, EIT solver computation, and graphics generation.

In Fig.7(b), we have used the same setup as in Fig.6(d) with the sensor being pressed against a PET bottle. This time, we have moved the sensor sheet in different directions. The high pressure concentration around the cap of the bottle does not cause any damage to the sensor. It is important to note that such physical toughness and stable measurements are extremely important factors in real world applications. The fact that our sensor can detect pressure distributions under tough and potentially harmful conditions, proves the effectiveness of EIT techniques for tactile sensing which do require no wiring or sensory elements inside the sensing area.

5 Conclusion

In the context of EIT-based tactile sensors which need no wiring in the sensing area, we have developed a new stretchable and soft conductive structure which can stably detect pressure distribution regardless of the complex, dynamic and severe stretch conditions.

We fabricated two stretch-insensitive sheets: (1)net structure using wave-like wirings with relatively high resistance (copper sulfide bounded conductive yarns), and (2)matrix of isolated highly conductive small pieces (Ag-coated knitted fabric); and stacked them to develop a 2-layer Pressure-Sensitive Stretch-Insensitive (PsSi) conductive structure.

While being soft and highly stretchable like ordinary knitted fabric, this sensor does not have large hysteresis problems as seen in conductive rubbers and foams. Most importantly this sensor resolves the problem of indistinguishability between pressure and stretch stimulations as often seen in both conductive rubbers and conductive knits.

In our experiments, we have shown how the sensor can fit over the extremely soft and deformable surface of a balloon and detect pressure distributions simultaneously. Also, we have demonstrated how the sensor can detect the pressure from the tip of a bottle even when under severe and uneven stretch. The above experiments have successfully shown the highly characteristic mechanical robustness and stable measurement ability of the novel sensor. Also, in comparison with rubber sheet or film base tactile sensor, the developed sensor has remarkable advantages such as ventilation ability to allow robot heat release, and comfortable touch for humans during human-robot interaction. Looking at the history of tactile sensors, we believe that these results will be a breakthrough in tactile sensing. We are expecting the wide utilization of this technology in fields such as robotics, ergonomics and input-device engineering.

Since the fabricated sensor sheets, currently have a rather coarse density, we are working to increase it. The resolution of the net structure which is currently about 9mm, is highly dependent on the available material, specifications of the sewing machine and manufacturing skills.

By improving these factors, it is very much possible to realize higher densities such as 6mm grid cells and introduce much thinner and more stretchable base sheets using fabrics such as stockings(150% 200% stretch). We are also working on another approach to reduce the size of the grid cells to less than 5mm by using fine pitch wave-like conductive yarns. It would also be possible to increase the resolution of the highly conductive sheet using conductive paints.

In addition, the wiring for the electrodes would be a next important issue. We have argued before that the issues of non-stretchable wires for electrodes should be dealt with in the overall design of the system [3]. However, we have now taken an approach to develop smaller distributed acquisition devices and also moderately stretchable wirings, to further increase the possibilities of the sensor.

It is possible to use a similar concept in order to make a Pressure-Insensitive Stretch-Sensitive (PiSs) sheet. By combining this PiSs sheet with the current PsSi sheet and sampling them independently, it will be possible to develop a multi-stimuli sensor which is capable of detecting stretch and pressure simultaneously.

Also, the EIT solver algorithm can be improved using numerous available research on EIT algorithms, and the accuracy can increase significantly by using a limited number of electrodes inside the sensing area which we are taking into consideration.

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