Development of a highly stretchable tactile sensor with easy wearability

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Abstract
We have developed a highly stretchable tactile distribution sensor which requires no wiring in the sensing area by applying Electrical Impedance Tomography (EIT), a non-invasive tomography technique, on a stretchable conductive structure. We have shown that our proposed stretchable conductive structure can significantly improve the quality of pressure distribution measurements over dynamically deforming surfaces, and is suitable for implementation over smooth surfaced humanoids as well as measurement of human skills. As a part of this work, we have developed a new conductive net structure with a higher grid resolution which requires a smaller stretching force and shows a greater stretchability compared to our previous results. We have successfully implemented the new tactile distribution sensor over a human elbow joint and picked three natural interaction scenarios to demonstrate the sensor’s performance compared to existing sensors.

Introduction
The authors have been studying the development of highly stretchable tactile distribution sensors based on Inverse Problem Analysis methods such as EIT, which is originally used in medical imaging as a cheaper alternative to CT-Scan. The basic structure of a tactile sensor based on EIT is shown in Fig.1-a. A number of electrodes placed on the boundary of a conductive sheet, are used to inject electrical current into the conductive sheet from different pairs of neighboring electrodes and at the same time measure the electrical potentials. The sampled data sets are then used to estimate the resistance distribution of the conductive sheet, based on the concept of Inverse Problem Analysis. Since no electrode or wiring exists inside the sensing area, highly stretchable and deformable materials which are also pressure-sensitive can be used as the conductive sheet. This approach results in an EIT-based stretchable tactile distribution sensor which can be implemented over complex 3D curves as well as dynamically stretching areas. It should be noted that the conductive sheet used in the EIT-based tactile sensor can be of arbitrary shape, and is not only limited to circular or rectangular shapes.

Previously, we demonstrated utilizing sensor’s stretchability in order for easy implementation over a non-deformable complexly curved 3D model of human face, and showed how pressure distribution can be estimated successfully. However, in cases where stretch and pressure stimulations are simultaneously applied to the conductive sheet (i.e. when sensor is implemented over area around robot joints) it is not trivial to distinguish between the two types of stimuli. This is due to the fact that most conductive materials including conductive rubbers and conductive knits show similar levels of sensitivity towards both pressure and stretch. As a typical solution to the pressure-stretch indistinguishability problem, we have demonstrated the possibility of using a reference sensory data from other sources such as joint angle values, to cancel out the effect of dynamic stretch and deformation. This approach requires preparing a one-to-one mapping between the reference sensory information (i.e. joint angle) and the no-load resistance distribution of the sensor (i.e. when no external pressure is applied). The reference sensory

information is then used to determine the no-load resistance distribution and dynamically calibrate the sensor. For example, in the case of applying the sensor to area around joints, this approach requires calibrating the sensor for each joint angle value in order to successfully detect the distribution of external forces applied to the sensor at that specific angle. However, in cases where no reference data is available or the surface deformation patterns are too complex, preparing a one-to-one map between the reference data and the no-load resistance cannot be considered practical.

Therefore, we have also focused on producing Pressure-sensitive Stretch-insensitive (PsSi) materials and structures suitable for tactile sensing. Here, the conductive material itself is engineered in order to reduce its sensitivity towards stretch and deformation while increasing its sensitivity to external pressure. We have confirmed that the overall performance and dynamic range of the sensor are superior in the absence of stretch sensitivity. In this work, we introduce our newly developed PsSi conductive structure and its performance over a human joint angle.

**Pressure-Sensitive Stretch-Insensitive Sensor**

In order to reduce the effect of dynamic stretch on resistance distribution results, we have developed a special pressure sensitive stretch insensitive (PsSi) conductive structure (Fig.1-b) which is made by stacking two layers of stretchable conductive material over each other. The first layer is a net structure made of stretch-insensitive conductive yarns with relatively high resistivity (top sheet in Fig.1-b), which by itself can detect neither stretch nor pressure stimulations.

In order to add pressure sensitivity, we have utilized the concept of contact resistance between two conductive materials. Electrical conductivity between conductive materials normally takes place as soon as they touch. However, by selecting the appropriate pair of materials (CuS and Ag in this case) we can have electrical conductivity between the two materials change proportionally to the applied pressure resulting in a relatively wide dynamic range which can be used for pressure measurement.

Based on the above effect, the net structure is combined with another highly conductive stretchable layer. The highly conductive layer (Ag) has an appropriate contact resistance against the conductive net structure (CuS) which means even though the two layers may be touching; the electrical conductivity between them is proportional to the applied pressure and independent of stretch conditions. Furthermore, in order to detect multiple points simultaneously, the highly conductive stretchable layer should be made from small unconnected pieces of highly conductive material rather than being one continuous conductive layer. We have previously demonstrated that this type of PsSi sensors can successfully detect the change in pressure distribution over dynamically deformable and stretchable surfaces which are under complex stretch and deformation patterns, such as the surface of a balloon (Fig.2).

In our previous work, we have fabricated the conductive net by sewing conductive yarns over ordinary stretchable knit using the stretchable sewing function of the sewing machine. However, because of using a knit fabric as the base, the resulting conductive net required a stronger stretching force and its overall stretch was limited to around 140% of its original size. Furthermore, each grid cell in the conductive net had been 9mm x 9mm in size which resulted in rather rough and partly non-uniform measurements.

We have focused on improving those problems, and the new type of PsSi sensor presented in this work is fabricated by using a conductive net structure with a higher grid resolution and stretchability. The size of each grid cell in the conductive net structure is slightly less than 5mm x 5mm and the net can easily be stretched up to over 200% of its original size. It should be noted that the highly conductive layer (the second layer placed on the bottom) is less stretchable and therefore; the two-layer PsSi structure can only be stretched up to around 140% of its original size in both directions.

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When implementing the sensor over dynamically stretching and deforming surfaces, the deformation and stretch of the implementation surface will cause an internal force between the top and bottom layers to be applied to the sensor sheet. For example when bending the elbow joint, the convex surface at the center of the joint and the overall tension, cause an internal force being applied to the sensor in the absence of any external forces. The effect of this internal force on the resistance distribution of the sensor should be minimized in order to independently measure the external forces applied to the sensor. Placing the less stretchable layer of the sensor as the inner layer (closer to the implementation surface) and the highly stretchable layer as the outer layer, would mean that internal forces (due to stretch and deformation), will not be able to effectively press the two layers of the sensor against one another. On the other hand external forces applied to the sensor surface, will press the two layers of the sensor more strongly and cause a bigger change in resistance. This favorable characteristic helps reduce the effect of internal forces generated due to deformation or stretch in steeply convex implementation surfaces.

Sensor size is 10cm x 15cm and 16 electrodes are placed on the boundary of the sensor. The sampling is done by a 14mm x 15mm USB board which is fully bus-powered and can sample over 60 frames of data per second. For sampling the PsSi sheet, a 3.3V DC voltage is applied to neighboring electrodes (resistance is around 1KΩ) which results in an approximately 10mW power consumption for current injection. Data processing and visualization are also delivered in real-time on an ordinary laptop PC.

**Natural interaction**

The developed PsSi sensor is implemented over a sleeve-like knit fabric as the base, and worn over human joint elbow. The wiring of the electrodes is done only on the boundary of the sensor where the applied stretch is smaller. Fig.3 shows the results of experiments corresponding to three different natural interaction scenarios. (a1) to (a3) show the results of rolling the elbow on a desk surface. Experiments (b1) to (b3) show a case where the joint angle is first bent (b1), extended half-way and hits a second object (b2) and then fully extended over the object detaching from the table surface (b3). Experiments (c1) through (c3) show the results of pressing the same 2 points while changing the elbow joint angle.

It should be noted that a fully bent human elbow joint can be very hard and sharp and produces only a small contact area when pressed against the hard surface of a desk, which results in weak detection of contact point. To produce a stronger signal, we have used a 10mm think layer of urethane foam on the desk surface. In case of implementation over humanoid robots, this could be a less urgent issue due to rounder or softer elbow joints, but nevertheless, there is a need to improve the sensor’s sensitivity by improving noise conditions and resistance estimation algorithms. Also, since the resistance of the structure can only decrease due to applied pressure, the tactile distributions are filtered to exclude any estimated increase in the resistance of the sheet. As can be seen from the three experiments, the results show a clear improvement over our previous results with conductive knit fabrics.

**Conclusions**

Based on our previous and current work, we argue that the proposed Pressure-sensitive Stretch-insensitive conductive structure can significantly improve the quality of pressure distribution measurements on a highly stretchable and deformable surface. Also, since the developed sensor has been made of highly stretchable conductive net, it has remarkable advantages over rubber or film material, such as trivial implementation, superior ventilation to allow heat release in robots and comfortable touch during human-robot interaction.

In this work, we have developed a new PsSi conductive structure with easy wearability like ordinary clothes which significantly facilitates implementation and maintenance of tactile sensors. A new high resolution and more stretchable conductive net structure is used in the PsSi material which helps further reduce the effect of dynamic stretch and deformation. We believe that the developed sensor can be used for smooth-surfaced humanoid robots of next generation as well as measurement of human skills.
Fig. 1: EIT-based tactile sensor does not include wiring inside the sensory area (a). The PsSi structure made of two layers; a mildly conductive net on top and a highly conductive matrix at the bottom (b). Implementation of sensor over human elbow joint (c).

Fig. 2: PsSi tactile sheet is implemented over a soft and deformable balloon surface and pressed on multiple points which causing complex deformation on surface (a). PsSi sensor strongly pressed over a PET bottle to demonstrate stable measurement in presence of high stretch (b).

Fig. 3: Implementation of PsSi sensor to human elbow joint: (a) shows rolling of the elbow over a desk surface; (b) shows the bended elbow which extends and hits another object and then extends all the way detaching from table surface and (c) shows results of pressing the same 2 points while changing elbow joint angle [90° rotation].