論文内容の要旨

論文題目：Development of a Highly Stretchable and Deformable Fabric-based Tactile Distribution Sensor
（伸縮・変形可能な布製触覚分布センサの開発）

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Abstract:

Deformable and stretchable tactile sensors are significantly important in order to measure contact conditions over soft and unconventional 3D surfaces or stretching surfaces. Also, deformable tactile sensors which are sensitive towards deformation and stretch can help provide robots with humanlike tactile interaction capabilities, higher motion dexterity and better safety standards. However, lack of deformability and stretchability has been a well-known shortcoming of conventional tactile sensors. This is due to the presence of non-stretchable components such as numerous sensory elements and complicated wirings inside the sensing area.

We have taken advantage of Electrical Impedance Tomography, which is an inverse problem analysis method for estimating the resistance distribution of conductive materials, in order to develop a highly stretchable and deformable tactile distribution sensor which has no wiring in most of the sensing area. The developed sensor is able to detect not only pressure, but also other types of tactile stimuli such as deformation, stretch or heat. We have investigated the basic characteristics of the sensor including its sensitivity, accuracy and the effect of material hysteresis. Also, in order to achieve higher deformability and stretchability, we have developed our original conductive knitted fabric which is more deformable than ordinary conductive rubber and has less hysteresis. An original Pressure-sensitive Stretch-insensitive (PsSi) conductive structure has been developed as part of this research which enables stable measurement of pressure distribution independent from stretch conditions.

We have shown the abilities of this sensor in detecting rather complicated tactile interactions which involve skin deformation such as rubbing or pinching. Furthermore, we have demonstrated that the deformable tactile sensor can be extremely useful for implementation over complex 3D surfaces such as the robot face. Finally, we have overcome a major challenge in field of tactile sensors by presenting a successful implementation of the stretchable tactile distribution sensor over movable joints. We have been able to detect external tactile stimuli over the joint surface at different joint angles and have estimated the joint angle value by using only the tactile distribution patterns from the tactile sensor. We have argued that the ability of the tactile distribution sensor to detect joint movements can be used to provide the robot with a somesthetic feedback which can lead to a sense of body image.

Finally, applications of the sensor particularly in wearable tactile systems and intelligent furniture are addressed. We have realized stable sensing of externally applied pressure over dynamically deforming and stretching surfaces such as the area around human elbow joint and the hip area, by minimizing the effect of stretch and pressure caused by body movements. This has not been possible using any of the conventional tactile distribution sensors.

This thesis is organized in 7 chapters as follows:

Chapter 1 (Introduction) presents the main problems with conventional tactile sensing technologies. The main characteristics of the human sense of touch and the centric role it plays in our everyday tasks are explained. We have argued that the dominant approach toward tactile distribution sensing in the past decades, has been the sensory array approach which houses numerous sensory element in a base material and samples them independently. We have argued about the limitations of this approach with regards to stretchability and deformability, which in turn are rooted in the complex wiring inside the sensor sheet. The main objective of this thesis, which is to introduce high stretchability and deformability to the tactile distribution sensors through elimination of wiring inside the sensor area, is presented and the contributions of this research are clarified.

Chapter 2 (Stretchable and Deformable Tactile Sensors) defines the concept of stretchability and deformability with regards to other commonly used terms such as soft and flexible and argues the necessity of stretchable and deformable tactile distribution sensors. It argues that, measuring the conditions and dynamics of contact on a target surface, requires a tactile sensor which is more conformable than the surface itself. Some previous works on stretchable tactile distribution sensors are presented and the novel approach of this research towards realizing stretchability and deformability through Inverse Problem Analysis is explained. Prospects of stretchable tactile distribution sensors in a number of different fields, such as medical and rehabilitation, robotics and wearable sensing devices are also discussed in this chapter.

Chapter 3 (Tactile Sensors Based on Inverse Problem Analysis) presents the main concept of Electrical Impedance Tomography(EIT), which is an Inverse Problem technique for estimating the internal resistance distribution of a conductive medium using measurements on the boundary. Mathematical framework of EIT, including the forward and inverse problems is presented and a typical EIT system is introduced. The implementation of EIT to tactile sensing and the characteristics of an EIT-based tactile sensor have been discussed. Measures for resolution and sensitivity of the sensor, such as Minimum Detectable Area, Minimum Detectable Resistance Contrast, Sensitivity and Selectivity distribution and distinguishability have been introduced and the effect of different modeling parameters on the resolution of the sensor is addressed through simulation. Furthermore, this chapter includes a brief section on the expansion of sensor coverage area and increasing the number of electrodes. The results of this section are independent of the material used as the conductive medium in the sensor.

Chapter 4 (Fabrication of EIT-based Tactile Sensors) presents the step-by-step guide to fabricating the proposed tactile distribution sensor, covering the data acquisition device, developed software and suitable conductive materials. Detailed characteristics of several conductive materials such as many types of conductive rubber, films and fabrics have been presented and their problems have been categorized into (1) high hysteresis and (2) indistinguishability of pressure and stretch. The first problem has been addressed by developing an original conductive fabric with very low hysteresis, and experiments demonstrating this superiority are performed. We have argued that although solving the second problem could have two major solutions, it would ultimately require a conductive medium which is only sensitive to one particular tactile stimulus (pressure or stretch). The design and development process of a fabric-based PsSi (Pressure-sensitive Stretch-insensitive) conductive structure has been presented and the response of the sensor towards pressure and stretch stimuli are demonstrated through experiments. Finally, the issue of electrode connection to the medium is addressed and our original stretchable fabric-based electrodes have been introduced. As a result, this chapter elaborates on the detailed process of design and development of a fully fabric-based tactile distribution sensor which is highly insensitive towards stretch and shows a very small hysteresis effect towards pressure.

Chapter 5 (Tactile Sensing Scenarios) categorizes the different surface types in which tactile sensing is required into (1) Flat rigid surfaces, (2) Complexly curved rigid surfaces, (3) Passively deforming surfaces and (4) Actively deforming surfaces. In each of the cases, we have presented a tailor-made sensing solution focusing specifically of the suitable conductive medium for the sensor. In case of actively deforming surfaces, the two solutions for pressure-stretch indistinugishability presented in chap.4 are implemented and the results of experiments are shown. This chapter also presents a solution for minimizing the effect of self-movements in an actively deforming surface on the sensor medium, which will enable us to detect only external pressure over the surface.

Chapter 6 (Applications and Results) demonstrated the applications of the fabric-based sensor in areas such as wearable sensors and intelligent furniture. We have implemented fabric-based PsSi sensors over highly deformable and stretchable areas such as human hip and elbow. Such areas are selected due to the high deformability and stretchability of the surfaces which has made it impossible for conventional tactile distribution sensors to cope with. Also, the implementation of the tactile sensor over the deformable surface of a chair is presented while demonstrating the possibilities of using the tactile distribution results as a control signal in intelligent furniture.

Chapter 7 (Conclusions and Prospects) presents a brief summary of the thesis and the full conclusions of this work. The contributions and originality of the work are addressed in detail, and the major characteristics of the developed tactile sensor are reiterated. This chapter discusses the general problem of low special resolution in EIT measurements and provides a number of solutions into improving the resolution in EIT-based tactile distribution sensors. Lessons learned from each application and the practicalities of the developed sensor are discussed. A brief section of this chapter discusses the commercialization prospects of the sensor including the production cost and potential roadblocks. Finally, some of the future directions and goals for this research are mentioned including the possibility for Stretch-sensitive Pressure-insensitive (SsPi) sensors, applications of the sensor in user interfaces and virtual reality environments and implementation of the sensor over deformable robots.