Master's Thesis
석사 학위논문

The study of sensor structure to distinguish a surface morphology for psychological tactile sensor

Hyunchul Park(박 현 철 朴 賢 喆)

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Advisor: Professor Jae Eun Jang
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By

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

12. 27. 2017

Approved by

Professor Jae Eun Jang (Advisor) (signature)

Professor Seong-Woon Yu (Co-Advisor) (signature)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

The study of sensor structure to distinguish a surface morphology for psychological tactile sensor

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Accepted in partial fulfillment of the requirements for the degree of Master of Science.

11. 28. 2017

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ABSTRACT

Artificial tactile sensors have been recently studied by various research groups mimicking the human sensing mechanism. Tactile sense takes an important part in the human's daily life such as griping and, perceiving objects based on information, their shape, size, temperature and texture. To get the tactile information, the human skin is packed with various tactile receptors corresponding to each of these stimuli. Through these receptors and nervous system, humans can feel various tactile sensations at the same time without limitation. Additionally, the human perceive diverse psychological sense such as roughness, hardness, warm, cool or even the pain by touching some external objects. However, researches about these psychological feeling have not been done so far because the degree to which each person feels about the same material is different. Therefore, there are a lot of issues as to which physical elements are most important for generating psychological sensations. If robots or artificial systems can generate this psychological feeling, more creative or human-like work will be possible. To give these psychological feelings to robot or artificial system, detecting surface characteristics of object should be a starting point among various tactile parameters. Many researchers are approaching the study of surface characteristics in various aspects such as friction, vibration, strain, softness/hardness, even the viscosity. Among them, the study of surface morphology is a very important parameter. There are some information related to surface morphology such as texture shape, height and width of the object, surface flexion and so on. Various sensing device such as optical device, piezo-photonic sensor and commercialized products like as surface profiler and AFM can be used to get the information of surface morphology. However, these things require additional equipment like light source and detector, also it is difficult to attach to the artificial skin, and robot arms. Therefore, in this paper, new artificial tactile sensor design based on a PVDF-TrFE were suggested and studied for detecting surface morphology. This piezoelectric material has many good advantages such as a flexibility, an ability to sense dynamic stimuli, an easy-fabrication and a self-power generation. Although, sensor structure should be deformed well according to depth profile of surface to obtain depth information of surface morphology, general pressure sensors based on 2-dimensional design fabricated by micro-fabrication process have been shown a poor deformation behavior to millimeter level curvature. To solve this problem, 3-dimensional probing tactile sensor design was suggested. A spring was mounted on the cell of sensor mimicking the deformation of human skin. Sharp tip was designed and fabricated to get spatial resolution, which positioned on the top of the spring. This structure allows for more accurate scanning. Also, flat structure is fabricated for transmitting the force well. So, the spring is compressed according to surface morphology. These spring deformations contain information about the surface and can be transmitted and interpreted through the sensor layer. The tactile sensor with spring structure can detect the deformation of spring through simple and easy calculation and signal processing. In the Integrate & Add graph, we can find out the peak of the signals mean that the spring is compressed to the maximum. The tactile sensor was pressed at four different depth (1, 2, 3 and 4 mm) under the condition of 10 mm/s. The depth which is the same with sensor is compressed can be obtained accurately in consideration of common error. Also, it is able to restore the width data of object surface by using sliding experiment. This experiment was carried out at three different speeds of 5, 10, and 20 mm/s for reliability. The restored information is highly accurate compared to the real structure. Also, using a bidirectional scanning method with a spring mounted sensor, we can obtain the perfect width information of the surface morphology with just a single cell without using an array structure. The information from the additional opposite scanning is used to compensated for the deficient part of the morphology. And, as the height of some morphology of object surface increases, the degree of deformation of PVDF film also increase, so the area of integrate & add also shows a tendency to increase. The ability of this sensor and spring mounted structure will be helpful for next generation artificial skin which is sense physical and psychological sensations.

Keywords: Piezoelectric, Array sensor, Psychological, PVDF-TrFE, surface morphology, Tactile sensor;

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Ⅰ. INTRODUCTION

1.1 Overview

Humans have five essential senses such as sight, hearing, smell, taste and touch. Using these valuable ability, Humans interact with the external stimuli and get the vital information which is important to enjoy their life. Researches on sight and hearing have been continued from the past, and camera and audio are now commercially available. However, the sense of touch is relatively less developed and can be more improved. Especially, tactile sense takes an important part of the human's daily life such as grasping, perceiving some objects, and feeling psychological sense like hardness, roughness, cold, warm and even the pain. Humans have various tactile receptors in their skin to feel these psychological sensations. Various types of tactile receptors interact to the external environment and generate electrical signals, called the action potential[1]. The signals acquired from the many kinds of tactile receptors are transmitted to the human nervous system, so human beings perceive the various tactile sensations and lastly do the corresponding activity[2]. These feeling help humans work correctly and also apply to others industrial field. Recently, many research groups are studying about the tactile sensing in the robotic field and other interfaces mimicking the human tactile receptors. For example, resistive[3][4][5], capacitive[6][7][8], piezoelectric[9][10][11], optical[12][13], and pyroelectric[14][15] sensors have been researched to perceive force and temperature, So that sensors play the role like mechanoreceptors or thermoreceptors of the skin.

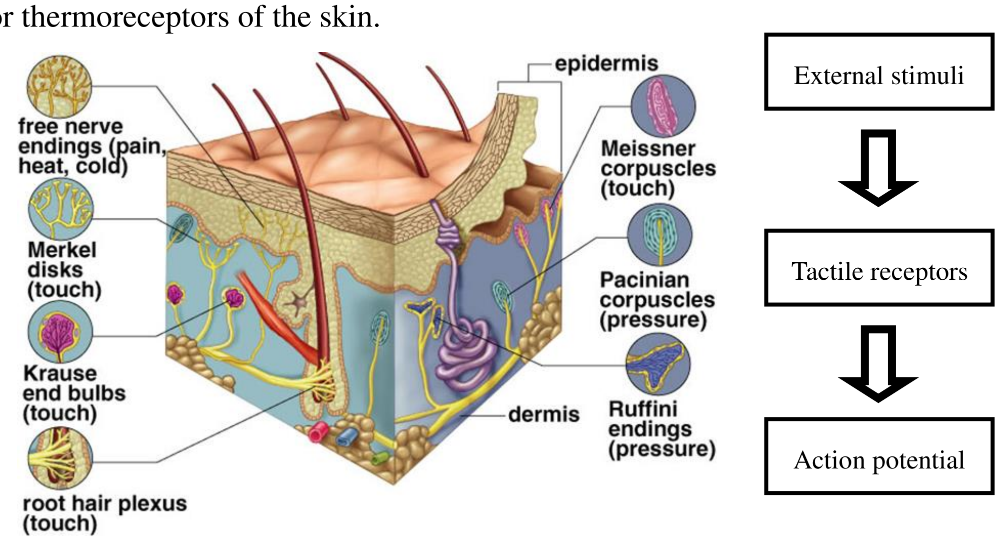
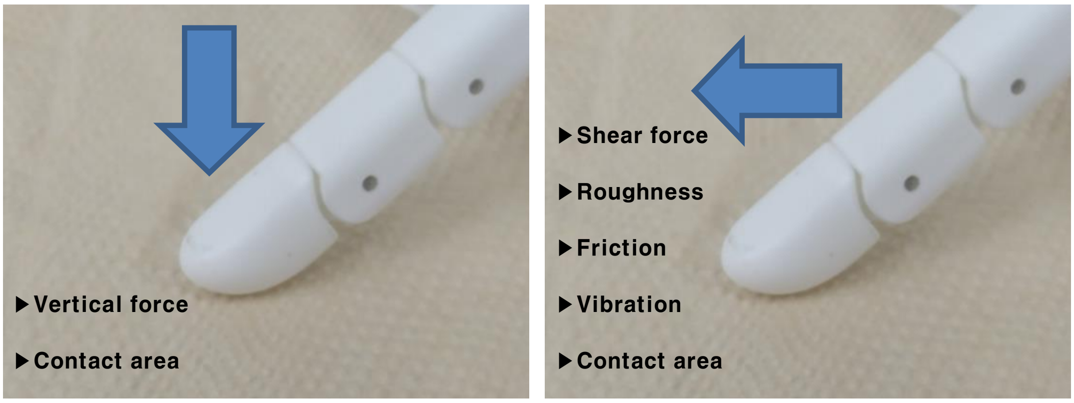


Fig 1.1.1 Schematic of different sensory receptors and Sensing process. Tactile receptors generate electrical spikes which is called the action potential when external

In addition, there are also studies on touch sensors for sensitivity, multi touch, flexibility, and strong to the external stimuli. But still these artificial sensors do not perfectly replace the real human skin because there are a lot of things to consider. Humans can fell the psychological feelings such as pain, roughness, hardness, and softness, but it is difficult to mimic the psychological sense because of diverse and undefined parameters[16]. Also, humans feel different psychological feeling about the same materials. There are some studies about sensing the surface texture such as piezophotonic[17][18] and optical sensors[19][20], However the sensors have to use a light source and additional equipment, and also it is difficult to attach to artificial skin of robots. To perceive the roughness and hardness feeling, it is important to obtain the information of the surface texture. In general, humans can detect surface texture by sliding their finger on a surface of object. At the same time, normal or shear force, friction, hardness, vibration, contact area and morphology must be considered simultaneously. Among them, surface morphology of the object is very significant elements to define the surface texture. Therefore, we design tactile sensor which can detect surface morphology by touching and sliding objects on the sensor.

1.2 Motivation

This study will concentrate on the tactile sensor for detecting surface morphology of the object. Commonly, two processes are needed to obtain the information about the surface texture: contact and sliding[21].



(a) Contact (b) Sliding

Fig 1.2.1 Optical Images of contact and sliding method. The human can obtain the information of the surface texture by using contact and sliding methods. (a) The information of vertical force and contact area is obtained by contact motion (b) The information of shaear force, roughness, friction, vibration, and contac area is obtaind by sliding motion.

In the case of humans, the information of height and contact area of the surface can be sensed by touching or sliding the surface of the object with their fingers. For example, when humans touch some absolutely flat structure like stiff paper, they feel the same normal force across the contact area. On the other hand, when humans contact some uneven structures such as the objects having diverse height of surface morphology, they experience higher pressure at the top point than lower region. Therefore, humans are able to recognize one of the parameters related to roughness sense. But, it is difficult to determine surface morphology just considering the height of the surface. The designed tactile sensor has to obtain other information such as shape and pitch of the surface for more accurate detection of surface morphology. Sliding is the powerful solution to resolve these troubles[22]. Normally, humans can perceive surface texture more correctly by sliding surface of the object than just touch action. Through the sliding process, many parameters like shape, pitch, vibration, friction and shear force are sensed by the human tactile system. In conclusion, the process of sliding at the same time as pressing must be performed in parallel to enable more effective analysis. In the study of artificial skin on the robotics, an artificial sensor consists of diverse sensors such as pressure, temperature, hardness and etc[23]. However, this sensor can't acquire the information of surface morphology. The thesis will show the tactile sensor which can perceive surface morphology by contact and sliding.

1.3 Thesis Overview

The thesis ensures appropriate sensor for detecting surface morphology and introduces backgrounds, experimental details, results and discussion and conclusion. The human tactile system including diverse tactile receptors and previous works/commercialized products about the detecting of surface characteristics are introduced in Chapter 2. And the principal of piezoelectricity, piezoelectric material, distinctive structure, fabrication and experimental setup are proposed in Chapter 3. Next, in Chapter 4, data on the morphology of the object surface are presented using contact and sliding methods. Finally, in chapter 5, the thesis conclusion is introduced and we talk about how this sensor will be applied and developed in the future.

Ⅱ. Backgrounds

2.1 Human Tactile system

It is helpful to study and examine real human tactile system before producing tactile sensor. Based on our understanding of human tactile systems, we can create more creative and distinctive tactile sensor devices. Many types of sensors are being developed by motivating the human tactile system, and there are many things to reference. In Chapter2, the human tactile system and previous research even the commercialized products about the surface characteristics sensing are introduced.

2.1.1 Diverse Tactile Receptors

Various types of receptors that respond to a variety of external stimuli are located in the skin. The sensory receptors in human skin generate electric signal, called action potentials and, convey these signals to the brain through the nervous system. The tactile receptors are distributed in human skin epidermis with various degrees of distribution. Tactile receptors are divided into four major groups: pain receptors, cold receptors, warm receptors and mechanoreceptors[1]. Among them, mechanoreceptors must be studied intensively in order to obtain and analyze the information on the surface of objects. There are four types of mechanoreceptors regarding to physical stimuli[24]. First of all, mechanoreceptors are classed as two broad categories, that are slow perception receptor (SA-Ⅰ: Merkel cell, SA-Ⅱ: Ruffini) and fast perception receptor (FA-Ⅰ: Meissner corpuscle, FA-Ⅱ: Pacinian corpuscle). Slow perception receptors perceive static forces, on the other hand, fast perception receptors respond to dynamic forces and vibrations.

Physiological subtype	Associated fiber (conduction velocity[1])	Skin type	End organ/ending type	Location	Optimal Stimulus[4]	Response properties
SAI-LTMR	Aβ (16-96m/s)	Glabrous Hairy	Merkel cell Merkel cell (touch dome)	Basal Layer of epidermis Around Guard hair follicles	Indentation	
SAII-LTMR	Aβ (20-100m/s)	Glabrous Hairy	Ruffini[2] unclear	Dermis[3] unclear	Stretch	
RAI-LTMR	Aβ (26-91m/s)	Glabrous Hairy	Meissner corpuscle Longitudinal lanceolate ending	Dermal papillae Guard/Awl-Auchene hair follicles	Skin movement Hair follicle deflection	
RAII-LTMR	Aβ (30-90m/s)	Glabrous	Pacinian corpuscle	Deep dermis	Vibration	
Aδ-LTMR	Aδ (5-30m/s)	Hairy	Longitudinal lanceolate ending	Awl-Auchene/ Zigzag hair follicles	Hair follicle deflection	
C-LTMR	C (0.2-2m/s)	Hairy	Longitudinal lanceolate ending	Awl-Auchene/ Zigzag hair follicles	Hair follicle deflection	
HTMR	Aβ/Aδ/C (0.5-100m/s)	Glabrous Hairy	Free nerve ending	Epidermis/Dermis	Noxious mechanical	

Fig 2.1.1.1 A comparison of Cutaneous Mechanoreceptor Subtypes Markl cells, Ruffini receptors, Meissner corpuscles, and Pacinian corpuscles are typical mechanoreceptors. Each mechanoreceptors have distinctive properties and react to specific stimuli due to its unique performances.

Markel cells are positioned near the surface of the skin and react to static forces with high resolution. The conduction velocity is about 16~96 m/s. Their optimal role is detecting indentations such as shapes and surface textures.

Ruffini receptors are located deeper in the skin. The conduction velocity is about 20~100 m/s. Their major role is detecting stretch sensation. They are suitable for the feeling of shear force.

Meissner corpuscles are located near the surface of the skin and sensing low-frequency stimuli related to object control and texture. The conduction velocity is about 21~91 m/s. They are responsible for sensing the moving position of objects.

Pacinian corpuscles are located deeper in the skin. The conduction velocity is about 30~90 m/s. They respond to high-frequency vibrations (up to 400 Hz) over large extent. Pacinian corpuscles are also sensitive to vibration and roughness.

2.2 Previous equipment for Sensing Surface characteristics

A surface morphology is an important parameter among diverse information of surface characteristics such as roughness, friction, adhesion, softness/hardness and etc. In particular, if the data on the surface morphology of the object can be completely imported, it will be a great help in interpreting the other parameters. There are several information regarding to surface morphology such as texture shape, height or width of the object surface, and so on. To measure these surface characteristics, there are some commercialized equipment such as AFM(Atomic Force Microscope), Surface profiler, and so on.

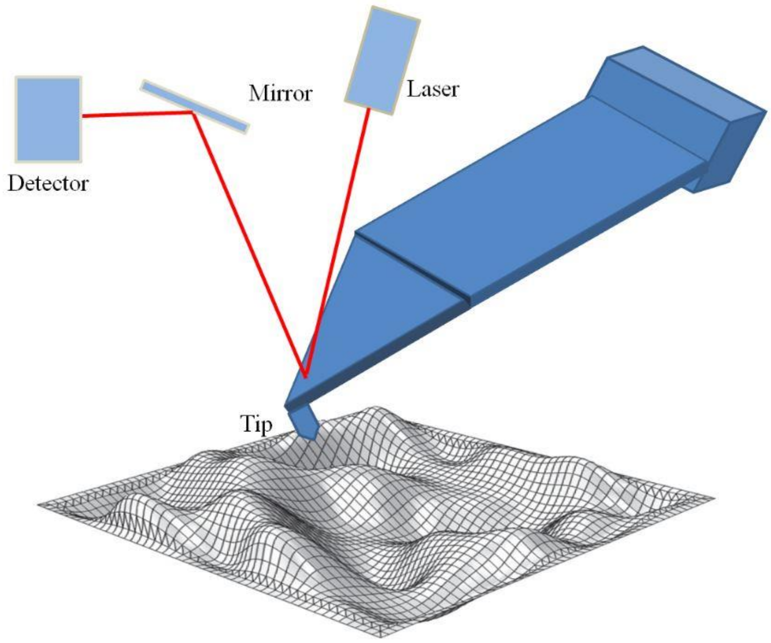


Fig 2.2.1 Schematic image of AFM AFM can obtain the information of the object surface with scanning method.

AFM is equipment using scanning method with attraction and repulsion force between the atoms. The surface is scanned with a very small tip, with constant attraction or repulsion force between the tip and surface of the object. At the same time, Laser beam detects a change of tip's height which depends on pattern or shape of surface and laser detector senses the changing values, that is, AFM can get the information of ridge's height. The tip is moved on x-axis and y-axis, from these information AFM get 2D image of the surface. And finally, 3D image of surface is also obtained from several information of surface like pattern, shape and even height of ridge by adding laser detection. However, there are several disadvantages to this powerful structure, which is that it is difficult to attach to the skin of robot arms and additional equipment are needs for detecting surface texture. Slow scanning speed is also a weak point.

2.3 Previous studies for Sensing Surface characteristics

Humans are very easily recognize the characteristics of an object surface by sliding their fingers on the object surface, however there are many problems how a robot is able to get these surface information because many parameters have to be considered to analyze surface texture[25]. Studies related to surface parameters such as friction, roughness, softness/hardness have been progressed in robotic and artificial skin field. It is very important issue to prevent any object from slipping and hold something accurately. But so far, research on this surface texture has been less improved than simply sensing pressure or temperature. Only a few optic[17] and piezophotonic[19] sensors have been proposed in hardware field, and robotic fingers applied feedback system or complicated algorithm have been suggested in software field to perceive surface characteristics[26][27][28]. So, research is needed to obtain surface morphology with more easy and simple way.

2.3.1 Friction

Friction is one of the most important parameter among the surface properties for smart robot grasping. It is known that humans can easily pick up some objects irrespective of the friction coefficient between the fingers and the object. However, this incredible sensing mechanism is now well defined. So, one method to replace this task in robotic field is needed such as getting the information of friction coefficient before grasping work. Nakamura et al. suggested that a tactile sensor detecting friction coefficient in the instant of touching[29]. They asserted that the friction coefficient between a sensor and an object is detected by perceiving vertical and horizontal force simultaneously. And they demonstrated a sensor struture using ARTC tactile element and displayed the good result of detecting of friction coefficient. By using this sensor they could get ‘minimum force for grasping’ with increasing both grip force and lift force according the sensor signal. Also, there is a commercialized product detecting the static friction coefficient. made by Heidon conference is a portable measuring instrument that can easily be used by anyone to measure the static friction coefficient between the device and objects. The sample object can be diverse material, such as metal, glass, textiles, plastic, wood, and paper. Tremblay et al.[30] developed a manipulator which is detecting incipient signals of slip with dynamic tactile sensors, and at the same time measuring normal and tangential forces at the finger, a controller can calculate the coefficient of friction at the contact.

Fig 2.3.1.1 Optical image of 94i-Ⅱ The Hiedon 94i-Ⅱmeasur the static friction coefficient.

2.3.2 Roughness

Roughness is also another important factor used to evaluate surface characteristics. There is no exactly definition about the roughness. In general, Roughness feeling is made by shear motion of the finger on the surface.[31][32][33] There are several studies to perceive surface roughness with various methods. A commonly used process is scanning method with small tip. The tip contacts and scans the surface of the object, and gathers information about the surface roughness. Also, it has been proposed that roughness is related to vibration sensing [34]. When the finger is moving on the surface of the object, the PC units installed over the finger provide the information about the vibration stimuli between finger and object. However, this contact method has the disadvantage of damaging the sensor tip or the object to be observed. Another process is non-contact method such as using optic sensor. Nan-nan et al. demonstrated the multi-wavelength fiber sensor for detecting surface roughness and surface scattering.[35] The sensor analyze different surface roughness by using diverse light source: 650 nm, 1310 nm and 1550 nm. The accuracy for estimating surface roughness by multi-wavelength fiber sensor is about twice as that by single-wavelength fiber sensor.

2.3.3 Softness/hardness

In addition to roughness, both compliance and viscoelasticity influence on surface characteristics[36][37]. Softness means the viscoelastic properties of an object[38][39][40]. It has been guessed that the softness feeling may be associated with action in the SAI fibers because their rate of activity is determined by the quantity of sustained deformation[41]. Softness/hardness perception can be obtained with vertical motion[42][43][44][45]. Omata et al.[46] conducted the development of a new type of tactile sensor which is consist of a strain gauge, conductive elastomer and piezoelectric polymer film. The experimental results appear that this sensor is able to perceive the hardness and/or softness of an object as the human hand does. Also, the sensor showed the visualization of the characteristics of an object clearly.

2.3.4 Optical sensor

Optical sensor is also well known tactile sensors having good sensitivity. Also this device is immune to electromagnetic noise and can be used in harmful environments where it is needed to protect sensitive electronic devices[47]. The tactile sensors based on optical method detect the information of surface from analyzing the light intensity. But this kind of sensor has to prepare summative tool such as light source, light guide and photodetector etc. Persson et al.[48] proposed a device applicable to surface-roughness measurement. The principle of measurement is light scattering. The light scattered by the surface of the object is induced by a fiber to a detector. Based on this paper, the optical device is suitable for surface-roughness measurement even inside a tube or cylinder. Also, the device is proper non-contact measurement, so it is possible to measure repeatedly without damaging both the sensor and the object.

2.3.5 Capacitive sensor

The distinction of surface texture is an important characteristic of artificial tactile sensor in robotic field, manufacturing industries and minimal invasive surgery. The development of tactile sensor is carried out mimicking the performance of the mechanoreceptors of the human finger. Muhammad et al.[59] introduced a silicon MEMS based capacitive sensor which has array structure. It has the ability to resolve forces and provide directional information. Also, this sensor could differentiate surface texture by using scanning method and assessment of the frequency spectrum of the sensor signals. And Sung-Hoon Kim et al.[60] developed polymer-based MEMS tactile sensor array which can classify surface texture. This sensor shows that a MEMS tactile sensor which is built using a polyimide substrate similar to human skin. Surface texture can be categorized by combining these sensors with good statistical approaches.

2.3.6 Piezoresistive sensor

As the robot field has expanded significantly over the last few decades, there has been a great interest in the research and development of tactile sensor for robotic hand or artificial skin. Piezoresistive mechanisms are one of the widely used methods for this purpose, showing simple and low cost, low power consumption, and the use of easy and clear read-out devices. Various methods such as piezoresistors, strain gauges, percolative and quantum tunneling devices have been researched with each of their advantages and disadvantages[61]. De Boissieu et al.[62] proposed MEMS-based tactile sensor with three-axial structure. In this paper, one of these sensors are packaged with a solid structure for the bone and a soft rubber for the skin. This sensor has the ability to sense the periodic pattern of fabrics or differentiate papers from fabrics calculating a friction coefficient.

Ⅲ. Experimental details

3.1 Piezo sensor

In this paper, a tactile sensor used piezoelectric material and sensor structure designed with springs is invented for detecting surface morphology. Because flexible substrate and some polymer piezoelectric soft material were used to the tactile sensor similar to human skin. Also, these materials are separated by their capability to react actively changing stimuli as a result of converting mechanical to electrical energy and vice versa. This implies the piezoelectric materials can be used for both sensor and actuator performances[49].

There many kinds of sensors using piezoelectric materials. Jeong et al.[10] demonstrated a piezoelectric sensor with nanowire cell structures for sensing pressure. When an external contact force effects on the surface of the sensor, the force can be separated into normal force and lateral force. Chung et al.[50] conducted a tactile sensor that can detect both two forces through the column-like microstructure. Oddo et al.[51] introduced a Bio-inspired MEMS-based tactile sensor array that were integrated with polymeric packaging providing in total 16 sensitive elements in an area of about 20 mm^2. It was very similar to the SA1 innervation density in humans. This sensor demonstrated the suitability of the developed tactile sensor for revealing medium-coarse spatial characteristics of the surface, both with static and dynamic stimuli. The structure of sensor is also important element to effect the sensitivity of sensor. Many research groups have studied about this subject to improve the performance of sensors. Pu et al.[52] suggested hierarchical nanostructure with combination of 2-d nanosheets and 1-D nanorods for functioning as electronic skin. Hierarchical nanostructures are suitable and used in nature to achieve tasks effectively. The hierarchical sheet-rod structures have a high surface area, so the areal capacitance is over an order magnitude higher than just flat structure. In addition, the piezo sensor has another nice advantage. Recently, wireless devices are widely used in real-time biomedical monitoring and detection system. However, those devices have to use a power source. The sensor using piezo materials reduces the need for additional power source and also complexity of electrodes[53].

3.1.1 Principal of piezoelectricity

Piezoelectric sensors convert an applied pressure or external force into an electrical signal[54]. In general, Piezoelectricity has linear interaction between mechanical and electrical systems in non-centric crystals or asymmetric structure materials[55]. The direct piezoelectric effect is determined as the change of electric polarization corresponding to external stress. When the external mechanical force gives rise to dielectric displacement in the material, it is said to be piezoelectric. This displacement appears the internal electric polarization. It should be known that piezoelectric performance strongly depends on the symmetry of the crystal structure. A crystal having enough low symmetry structure produces electric polarization under the influence of external mechanical stress. On the contrary, the converse piezoelectric effect is the opposite principle of direct piezoelectric effect. The crystal structure of piezoelectric material becomes strained if an external electric field is applied.

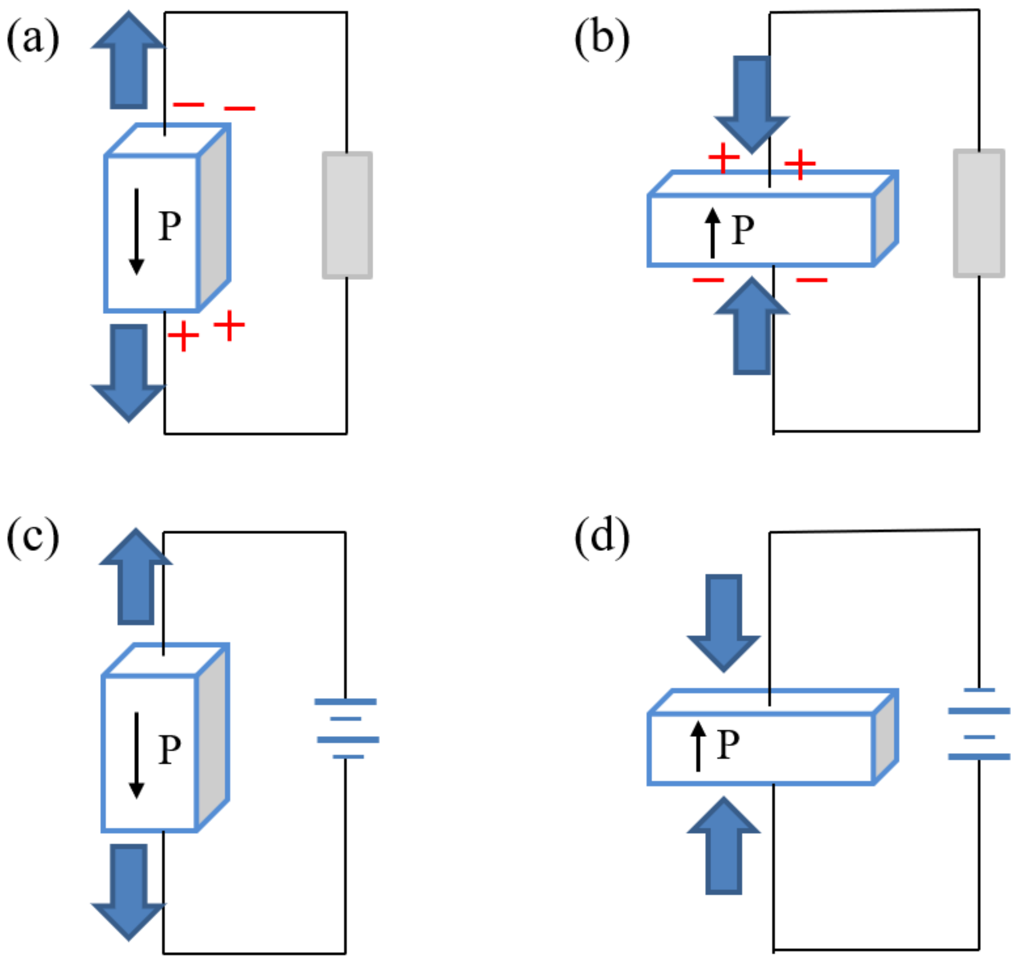


Fig 3.1.1.1 Principles of the direct and converse piezoelectric effects. Direct piezoelectric effects: (a) The polarization charges are induced the surface of the material, when the strain is applied to the material, (b) The polarization is the opposite of (a), when the compressional force is applied to the material, Converse piezoelectric effects: When the positive (c) or negative (d) electric field is applied to the material, the material is deformed.

In Fig. 3.1.1.1, the schematic of piezoelectric effect is introduced. If a compressional force F is applied, the polarization P parallel to the thickness is proportional to the stress T=F/A. Therefore, the polarization charges on electrodes consisting of major faces A is proportional to the force causing the strain. If we apply tension, the direction of pressure is reversed and the direction of the electric polarization reverses as well. When an electric field E is applied along the thickness of the plate the quartz plate is deformed.

3.1.2 Piezoelectric materials

There are various types of piezoelectric materials such as crystals, ceramics, and polymer, so that it is be able to carry out diverse fabrication processes and acquire a variety of piezoelectric characteristics depending on the materials.

Quartz, Rochelle salt, and lithium niobate($LiNbO_3$) are the typical piezoelectric crystal. They are commonly grown synthetically. To use practically, those materials have to be oriented and cut along specific crystallographic directions so as to get the best piezoelectric performance. Quartz is the most popular single crystal piezoelectric material and it is used for transducers because of its high mechanical quality factor. Quartz is also used extensively in accelerometer[56]. Lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$) are both used as high temperature acoustic sensors because they both retain high sensitivity up to 400 ℃ [57].

Barium titanate (BaTiO3) and Zirconatetitanate(PZT) are most well-known piezoelectric ceramics. In particular, the PZT ceramics have been widely used in applications because of very reasonable price. Also, the PZT has good piezoelectric characteristics that can be controlled by doping different substitution atoms. PZT ceramics are usually used for high power transducers or sensor.

Polymer piezoelectric material is also popular in these days. First ferroelectric polymer : polyvinilidene fluoride (PVDF) was discovered in 1969. Due to its strength to the harmful chemical materials, this polymer used in structural coatings to prevent damage. Another excellent functional characteristic is a very low value of the acoustic impedance, so it allows for the better acoustic matching to water environment. Piezoelectric polymers have a lower piezoelectric coefficient in comparison with the ceramics. But, high values of voltage constant are possible because of the low permittivity. In addition to many advantages, they have advantages such as flexibility, lightweight and low cost. The PVDF has little different mechanism of amorphous and other piezoelectric materials. But, the PVDF has particular alignment of molecules, so it is possible to induce internal polarization when external force is applied. Polymerized monomer $(-CH_2-CF_2-)_n$ exists in several phases different in the structure of the molecular chain. The most important phase is β-PVDF phase. In β-PVDF phase, the electric dipoles at C-F bonds are aligned in parallel direction. Dipole moments could be possibly further aligned by the annealing process. Recently, extensive research has been focused on their copolymers with trifluoroethylene (TrFE). PVDF-TrFE (Polyvinylidene difluoride trifluoroethylene) has much noticeable piezoelectric characteristic than a normal PVDF. The PVDF-TrFE copolymer is also applied to the tactile sensor in this paper because of its high sensitivity, easy fabrication, flexibility, and ability of dynamic sensing.

3.1.3 Spring structure

The human can perceive the morphology of object surface through a deformation of skin. For example, If the more pressure is applied to the skin, the more skin deformation will appear. So, human can separate between the flat and uneven surface of objects. Therefore, we concluded that mimicking the human skin will help the sensor distinguish surface morphology of the object. Shin [58] developed tactile sensors which can detect surface texture including the velocity and pitch values. However, it was hard to deal with a z-axis information. So, other structural changes or sensing mechanism are needed. To solve this problem, we applied spring having good elasticity to the sensor. The spring repeats compression and tension between the sensor and the surface of the object and can help to provide information about the height more reliably.

3.2 Fabrication of sensor and spring structure

3.2.1 Fabrication of sensor

The piezo sensor consists of bottom layer for a common electrode and top layer for a sensor structure. Fig 3.2.2.1 shows a fabrication course of the sensor layer. First, a polyimide film was cleaned by acetone, Isopropyl alcohol (IPA), and Deionized (DI) water to remove organic particles by using ultrasonic cleaner. The polyimide film substrate was attached on a glass using kapton tape to prevent separation between the substrate and glass during spin coating process. Then, positive photoresist (AZ GXR-601) was spin-coated on the Polyimide film substrate with 3000 rpm. After coating the photoresist, the coated substrate was baked on a hot plate in 100 ℃ for 2 minutes. After baking, the photoresist was exposed by ultraviolet ray(UV) through the 3 x 3 square array pattern in photo-mask.

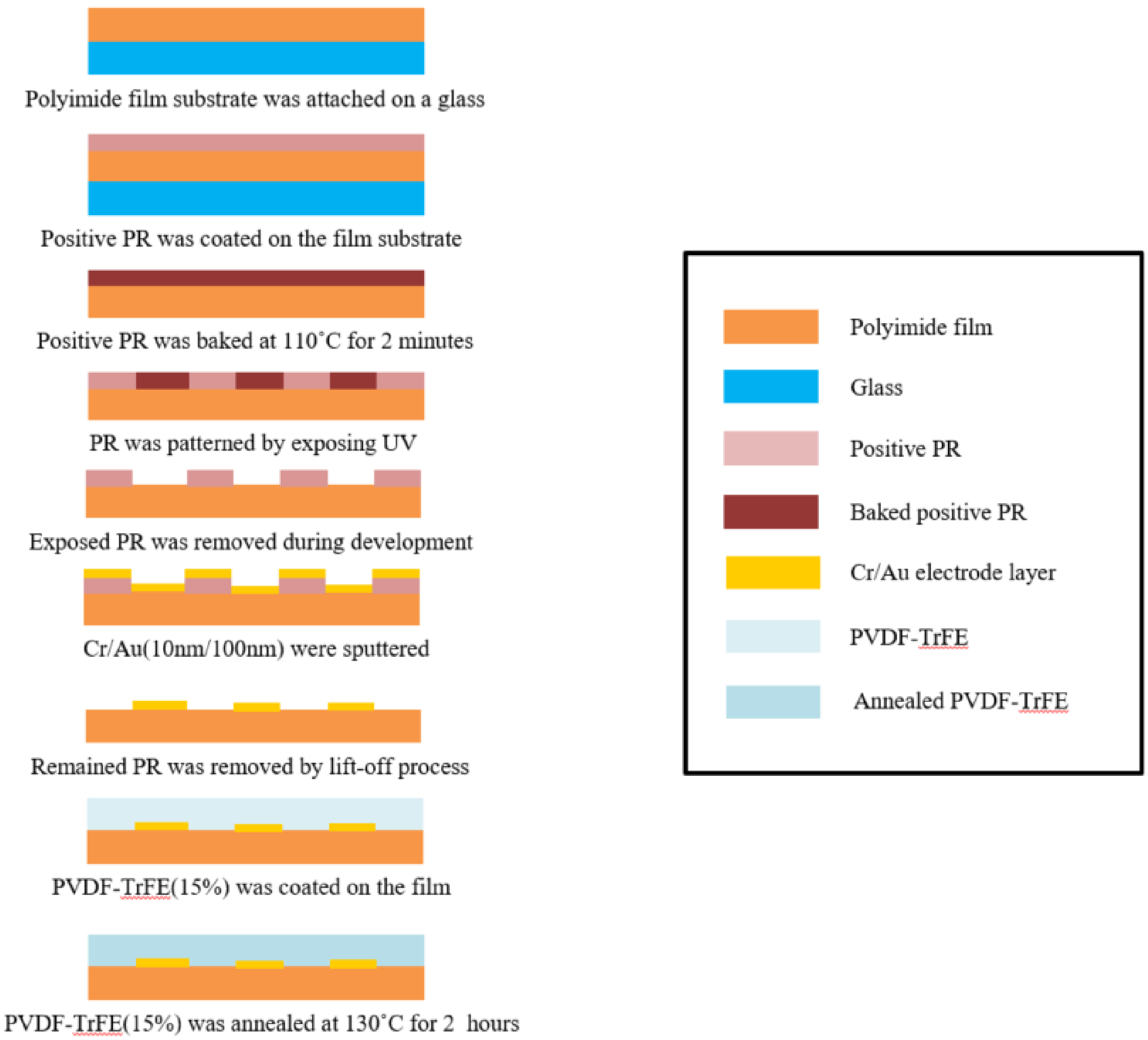


Fig 3.2.2.1 Schematic of the fabrication process of the top layer

After that, the samples coated PR were immersed in AZ-300 developer for 1 minute to remove the unnecessary photoresist parts. After developing, the samples were cleaned by DI water and blown by N_2 gas. After photolithography process, 30 nm thick Chrome (Cr) and 100 nm thick gold (Au) layer were deposited by using a radio frequency (RF) magnetron sputtering system at an input power of 100 to make metal electrode layer. The Cr layer was stacked to enhance the adhesion between the polyimide substrate and Au layer. Next, the 3 x 3 top electrode layer was obtained through the lift-off process immersing in acetone and IPA by using ultrasonic cleaner. The size of each cell is ~ with ~ mm pitch. The PVDF-TrFE 15% solution was produced by mixing PVDF powder with 2-butanone solution. The mixed solution was stirred completely by using magnetic stirring system. Next, completely mixed PVDF-TrFE solution was coated with 3000rpm on the top electrode. Finally, the samples coated with PVDF-TrFE were annealed at 130 ℃ for 2 hours. The fabrication process of the bottom layer is much easier than the top electrode because the bottom layer was used for a common electrode. 30 nm thick Cr layer and 100 nm thick gold layer were sputtered on all over a polyimide substrate.

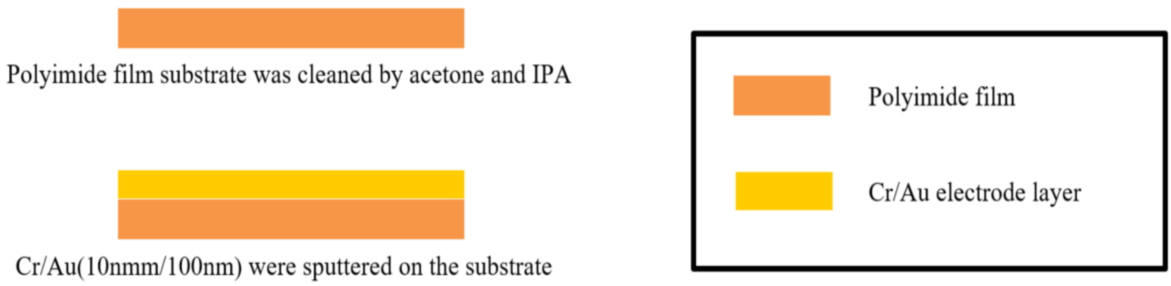


Fig 3.2.2.2 Schematic of the fabrication process of the bottom layer

To make the bottom and top work as sensors, the bottom layer was placed under the top layer. And the top layer was overturned to make PVDF-TrFE layer face the bottom electrode. After that, both layers were fixed with taping operation.

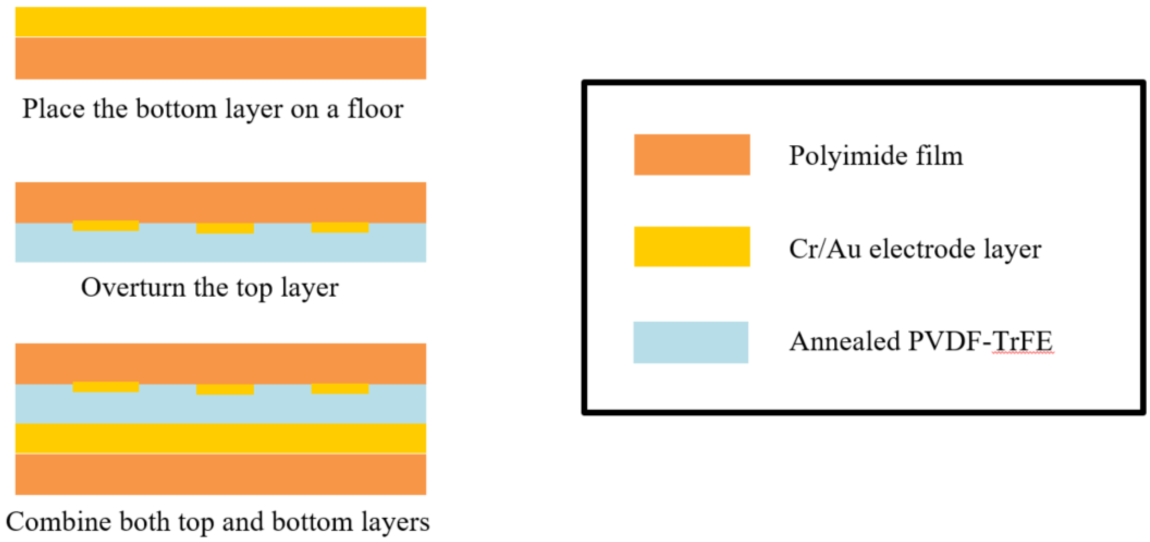


Fig 3.2.2.3 Schematic of the fabrication process of the combination of Top and Bottom layer

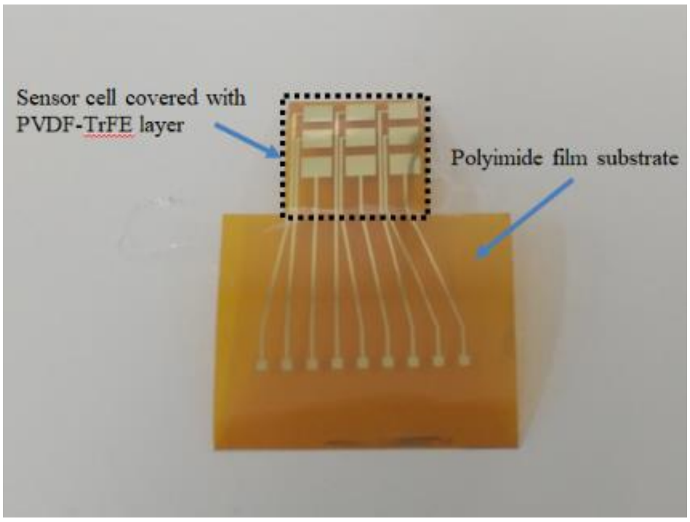


Fig 3.2.2.4 Optical image of the top layer coated with PVDF-TrFE layer

3.2.2 Fabrication of spring structure

A new structure design was proposed to mount the spring on the sensor correctly in this paper. PVDF-TrFE is typical piezoelectric materials, so the piezo-signal is proportional to applied pressure. Therefore, a structure is required for the force applied by the surface of the object to be transmitted to the sensor through the spring well. Without the spring-supporting structure, the forces transmitted from the object surface will not be delivered correctly. In the chapter 1 and 2, contact and sliding methods were recommended for detecting surface morphology. In general, a sharp tip has more advantage than a wide or round tip for accurately scanning the surface of an object. This is because if we use a wide tip, the tip can't scan the entire surface of the object due to its shape. Also, because of the linear structure of the springs, the spring can't transmit the force well. To solve this problem, a flat structure was installed on the bottom of the spring.

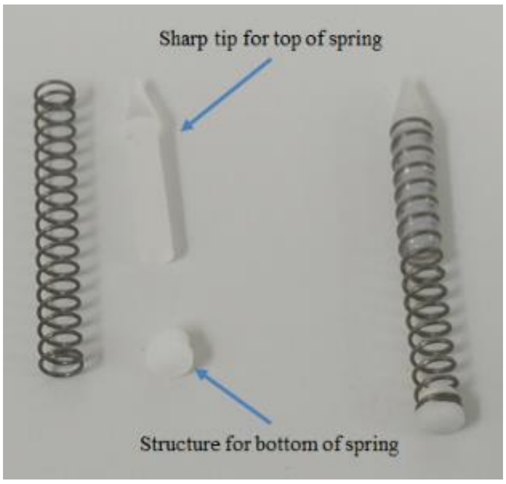


Fig 3.2.3.1 Optical image of the spring and Structure for mounting

In addition to these structures, it is also an important issue that the positions of the sensor cell and the spring are well match. If the position of the spring and the cell are aligned well, the force transmitted from the surface of the object will be transmitted to the sensor well through the spring. To overcome this issue, a perforated box structure which is designed with reflecting size of the sensor cell.

Fig 3.2.3.2 shows a bottom structure for attaching the PVDF-TrFE tactile sensor which is consist of Top sensing layer and bottom common electrode layer and a top structure for aligning the spring on the cell.

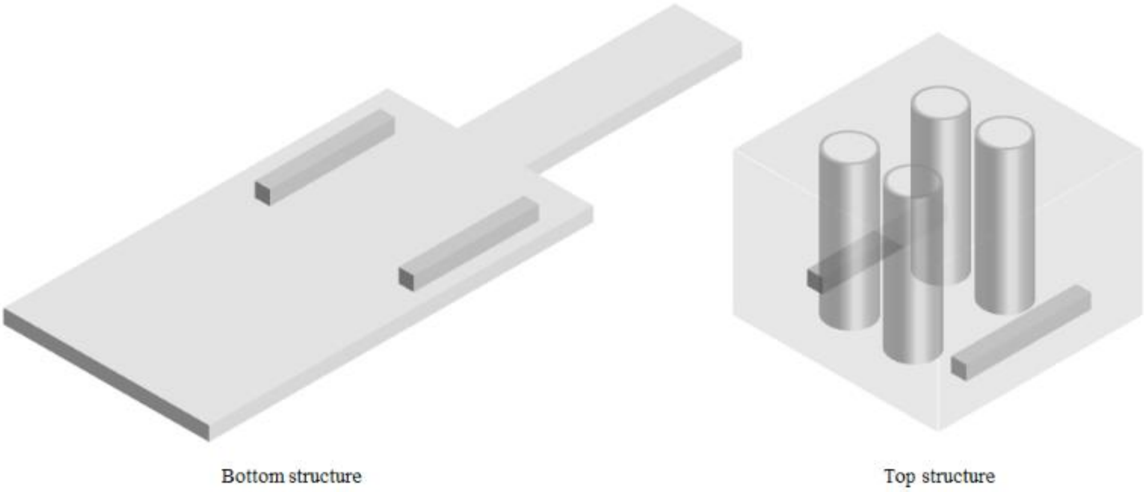


Fig 3.2.3.2 Schematic of bottom and top structure for mounting spring

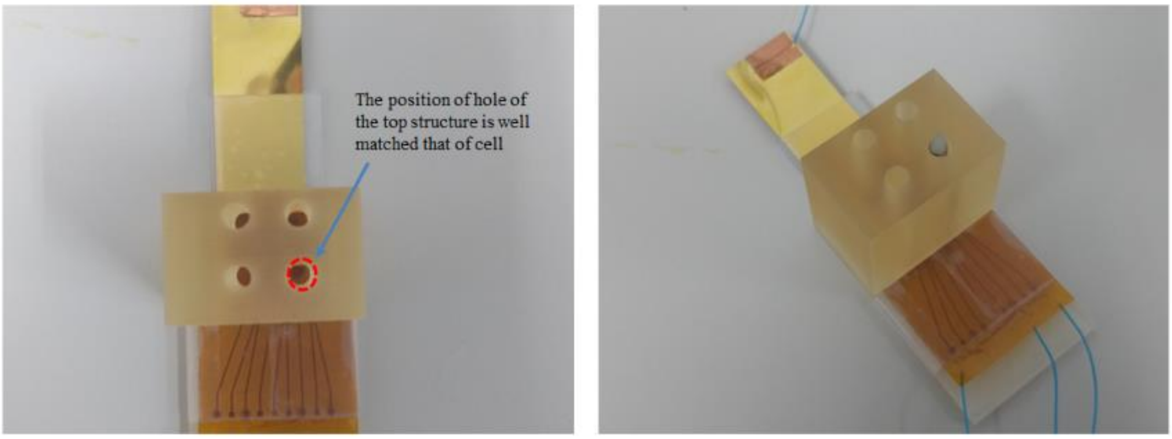


Fig 3.2.3.3 Optical image of combination of bottom and top structure

3.3 Design of test sample

In this paper, three different structures of samples which have different height and width were designed as 3D modeling for detecting morphology data. These three structures consist of triangle and trapezium figures. Fig 3.3.1 shows the scale of three test samples. The height of the figure increases by 1mm, and both left and right triangles of the trapezium are half of the triangle on the left. For the benefit of the analysis, the ratio of width to height was kept at 3:1. Test samples are designed with 3DS max and AutoCAD, and manufactured by using 3D printer.

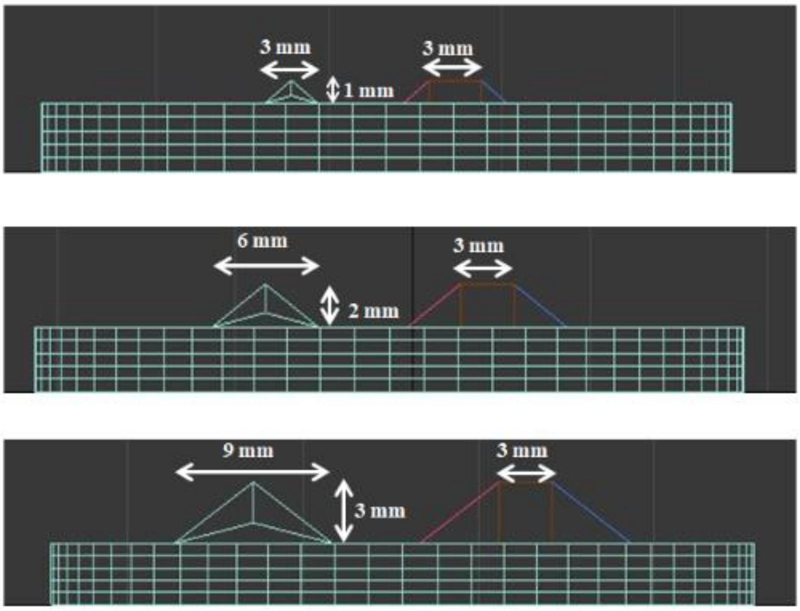


Fig 3.3.1 Schematic of the scale of three different test samples

Fig 3.3.2 Optical images of three different test samples

3.4 Experimental Setup

In this paper, touch experiment and sliding experiment were proceeded respectively to analyze the information of surface morphology. The piezo sensor was pressed by three different test samples through the spring. In the touch and sliding experiment, a xyz-axis stage (SM3-0806-3S, Science town) was used. The xyz-axis stage was controlled by using control program (PMC-1HS/PMC-2HS). The program controls such as sliding and contacting velocity, move distance, and repeated work. In sliding experiment, sliding velocity was set to 5 mm/s, 10 mm/s, and 20 mm/s for reliability. The electrical signals of the piezo sensor were measured through the mixed signal oscilloscope (MSO-X 2024A).

Fig 3.4.1 Optical image of xyz-axis stage

Ⅳ. Results and discussion

4.1 Push experiment

We checked that the sensor can measure a pressure basically. To measure the signal of the vertical pressure, the velocity and displacement were programmed on the z-axis stage to repeat the compression and tension of the spring. The piezo sensor was pressed with different four displacements such as 1, 2, 3, and 4 mm. The push speed was kept the same at 10 mm/s. Fig 4.1.1 shows the schematic image of the process of compress and release.

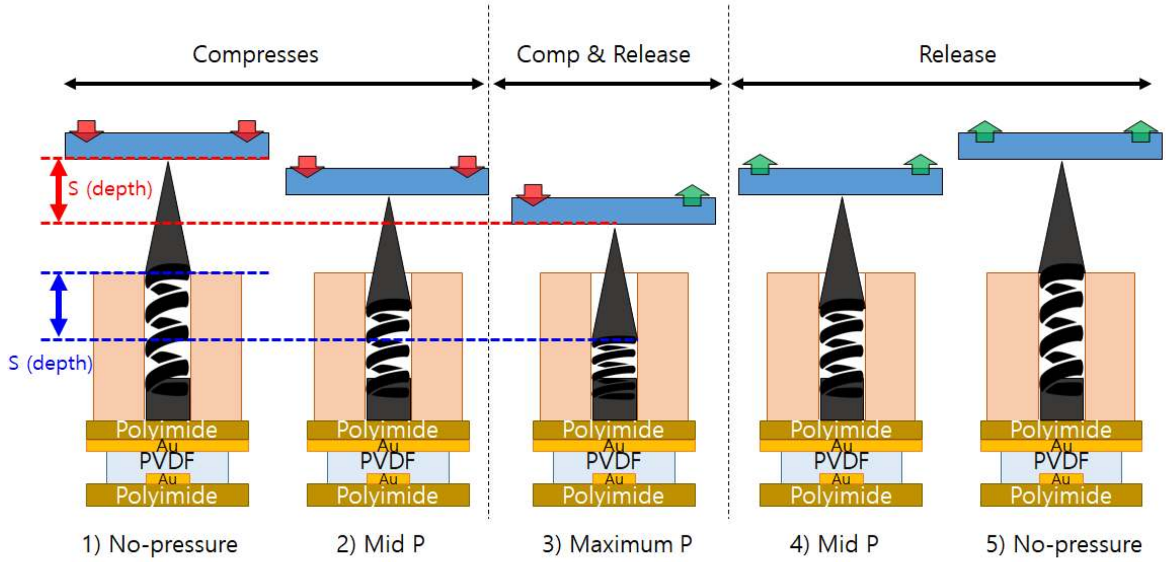


Fig 4.1.1 Schematic of compress and release process of the spring

An occurred voltage signals and Integrate & Add graph are introduced in Fig 4.1.2. The integrate & Add graph was obtained by increasing the integrate value in the voltage signal. Easier interpretation is possible in the Integrate & Add graph. In this graph, the peak of the signals means that the spring is compressed to the maximum. This is because the piezo voltage signal has a negative value because an object has started to fall off the sensor, which is that the integrate graph starts to decrease. Since we have already fixed the repetition velocity of push, we can find out how much the spring has been pushed through the calculation if we get the time from the peak to the next peak. In the case of S = 1 mm, Since the spring is pushed at a speed of 10 mm/s, the total time for pressing and releasing is 0.2 seconds. However, the period of the signal obtained from the experimental result was 0.3 second, and an error of 0.1 second occurred. In the case of S = 2 mm, Since the spring is pushed at a speed of 10 mm/s, to total time period is 0.4 seconds. However, the period of the signal obtained from the experimental result was 0.5 seconds, and an error of 0.1 second occurred repeatedly. Similarly, in case of S = 3 and 4 mm, an exact common error occurs between the calculated result and the experimentally acquired data.

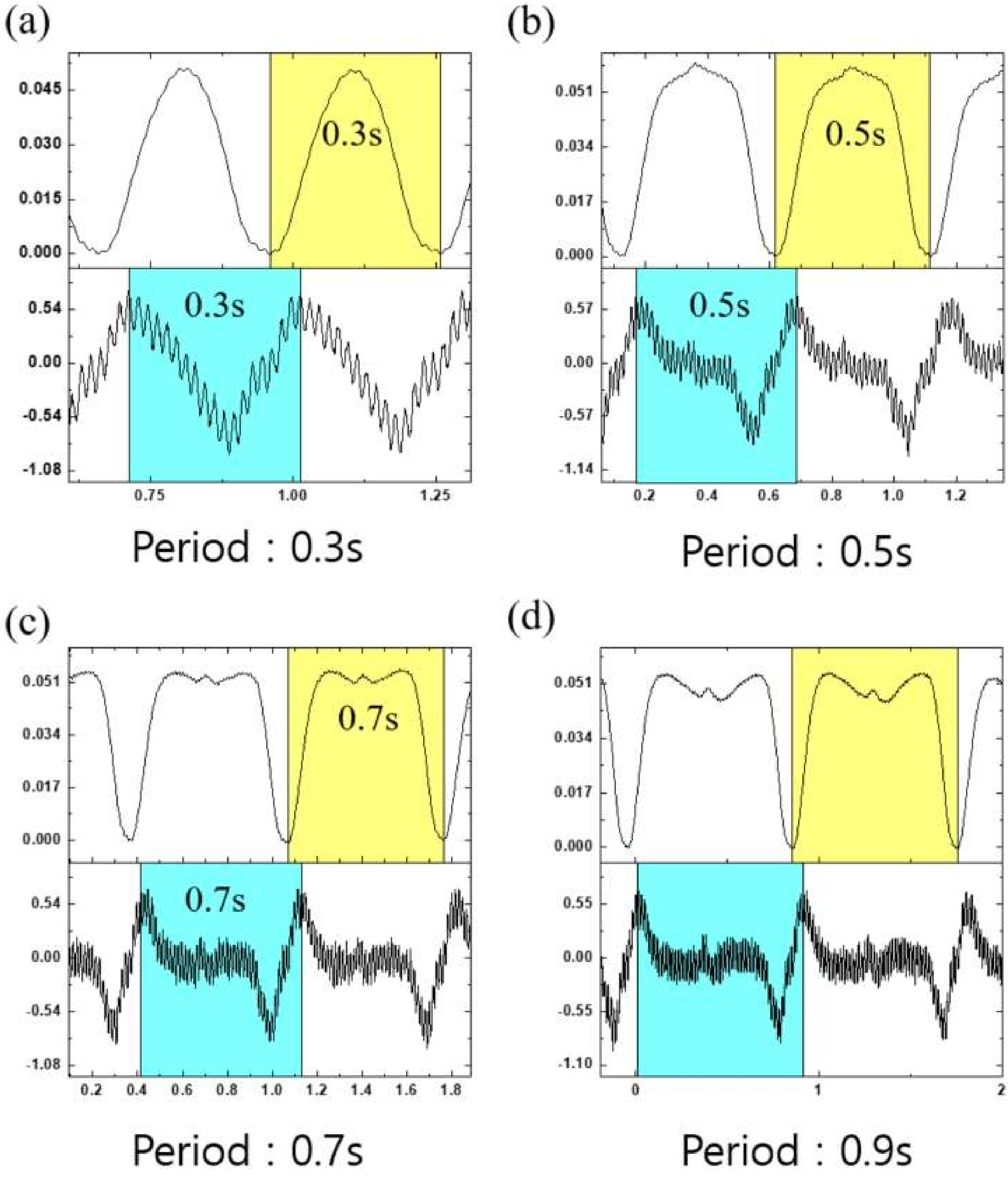


Fig 4.1.2 A pushing signals of the different pushing depth The voltage signal(lower graph) of the tactile sensor and Integrate & Add calculating graph(upper graph) (a) Depth S = 1 mm (b) Depth S = 2 mm (c) Depth S = 3mm, (d) Depth S = 4 mmm

If the linear stage is reciprocating, it will have a delay of 0.1 second when it moves down and then upwards again. That is, the error of 0.1 second occurred in all cases due to the hardware delay of the linear stage.

Therefore, to obtain the accurate pushing depth, the middle 0.1 second is taken as the delay interval in the Integrate & Add graph. Then both sides of the delay section mean from the time when the first press starts to the time when it is pressed to the maximum, and from the time when it is pressed to the maximum to return to the origin. In integrate & Add graph, it is possible to calculate the accurate depth by measuring the time from 0 to peak and multiplying by the moving speed.

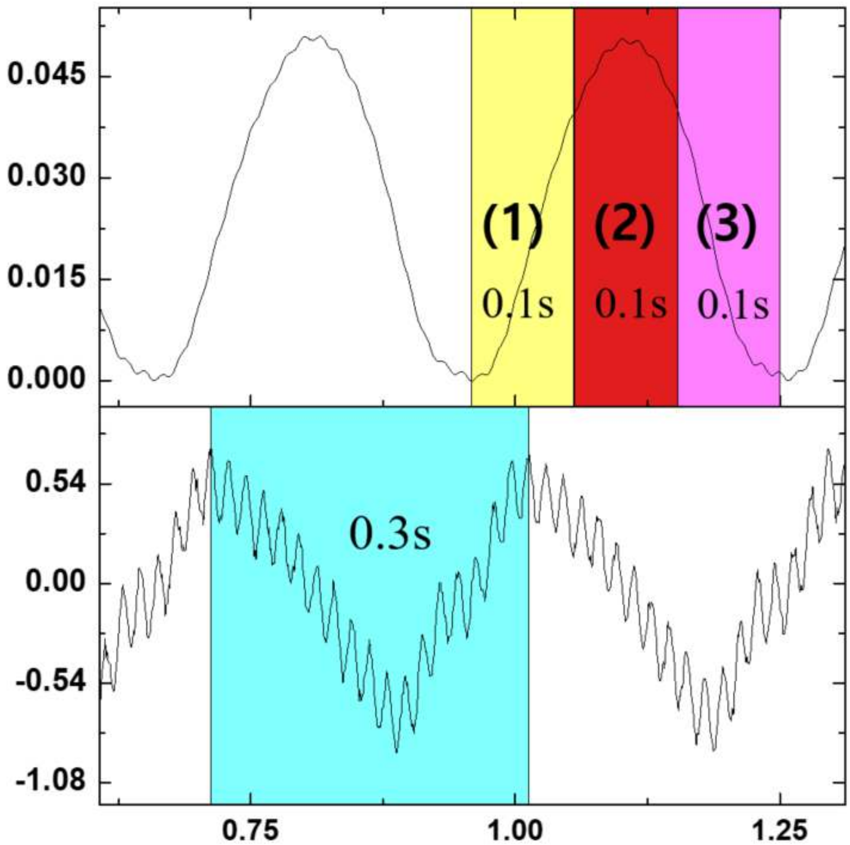


Fig 4.1.3 The delay interval of the linear stage The voltage signal(lower graph) of the tactile sensor and Integrate & Add calculating graph(upper graph). (1) The interval of Starting point to maximum pressed point (2) Delay interval time of the linear stage (3) The interval of maximum pressed point to starting point(origin point)

4.2 Sliding experiment

4.2.1 Signal analysis of different test samples

Sliding is another important method for detecting surface morphology. Three different test samples which have different height and width of structure were sliding on the sensor for the sliding experiment. This experiment was carried out at three different speeds of 5 mm/s, 10 mm/s, and 20 mm/s for reliability. Fig 4.2.1.1 shows schematic images of compress and release process and the analysis of the signal. First, Voltage signal and the value of Integrate & Add start to increase simultaneously, when the sharp tip begins to contact the test sample. Next, when the tip is between the starting point and the maximum compression point, the voltage value shows 0 DC level, but the value of Integrate & Add increases steadily. Finally, when the tip reaches its maximum compression point, after then, the voltage shows negative value and the value of Integrate & ADD begins to decrease gradually because the pressure applied to the PVDF-TrFE layer is lost steadily. In the section where the integral value decreases, the spring is maximally compressed and released. So, the spring vibration is repeated between the sensor and test samples. So, the signal of this value is noise because of the spring vibration. From the Integrate & Add graph, the interval between the starting point where the value increases and highest value means the time between tip and sample begins to contact and falls. So, using this interval value and fixed scanning velocity, we can get the information of width of the surface.

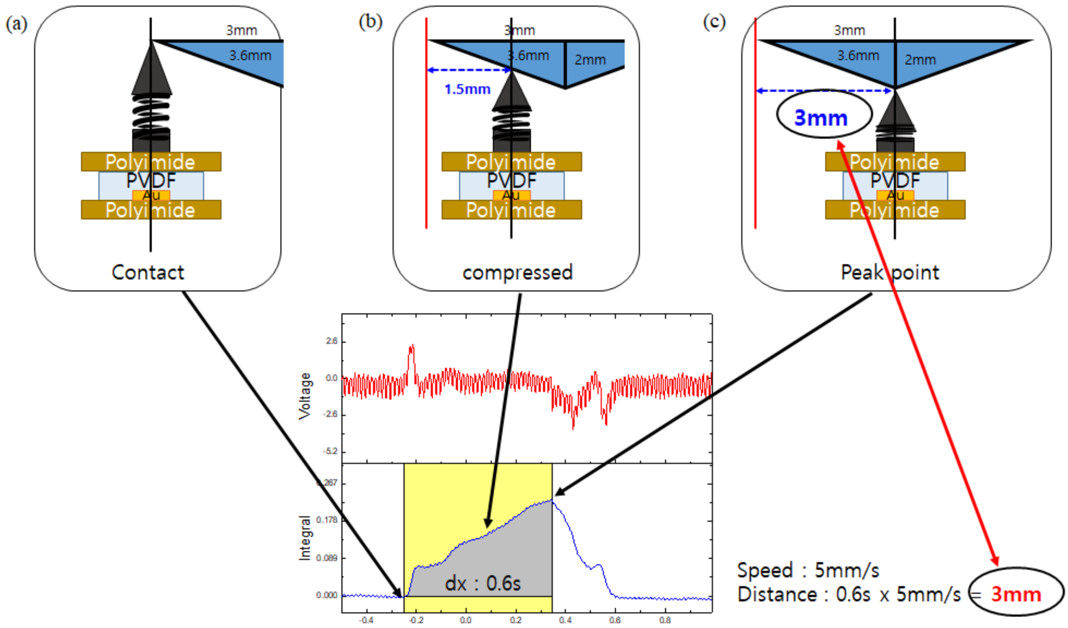


Fig 4.2.1.1 Schematic and signal analysis in 5 mm/s condition. (a) When the tip contact with the sample, voltage and the value of integral both increase (b) When the tip is positioning between the start point and maximum compression point, voltage show 0 DC level but the value of integral is still increase (c) When the tip reaches its maximum compression point, the voltage shows negative value and the value of integral is stated to decrease

Fig 4.2.2~4 shows the time interval from the contact point to the maximum compressed point. By multiplying this time interval by the scanning speed, information about the width of object surface can be obtained. The calculated values are also summarized in Table 4.2.1~3. We could check that the calculated value and the real width of each figure were well matched under each of the other three speed conditions.

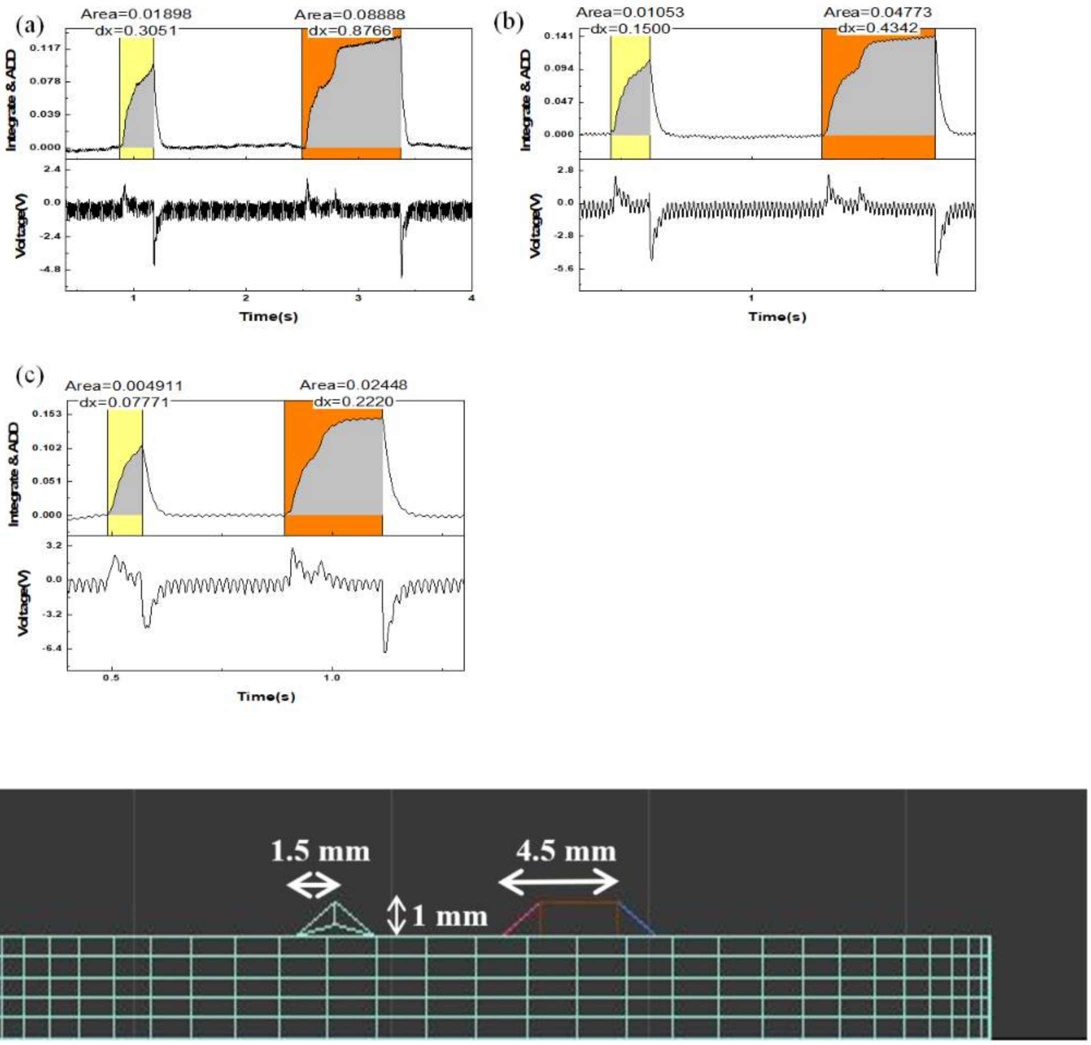


Fig 4.2.1.2 Sliding signal analysis in 1 mm height condition. (a) Sliding at 5 mm/s condition (b) Sliding at 10 mm/s condition (c) Sliding at 20 mm/s condition, and design image of test sample 1

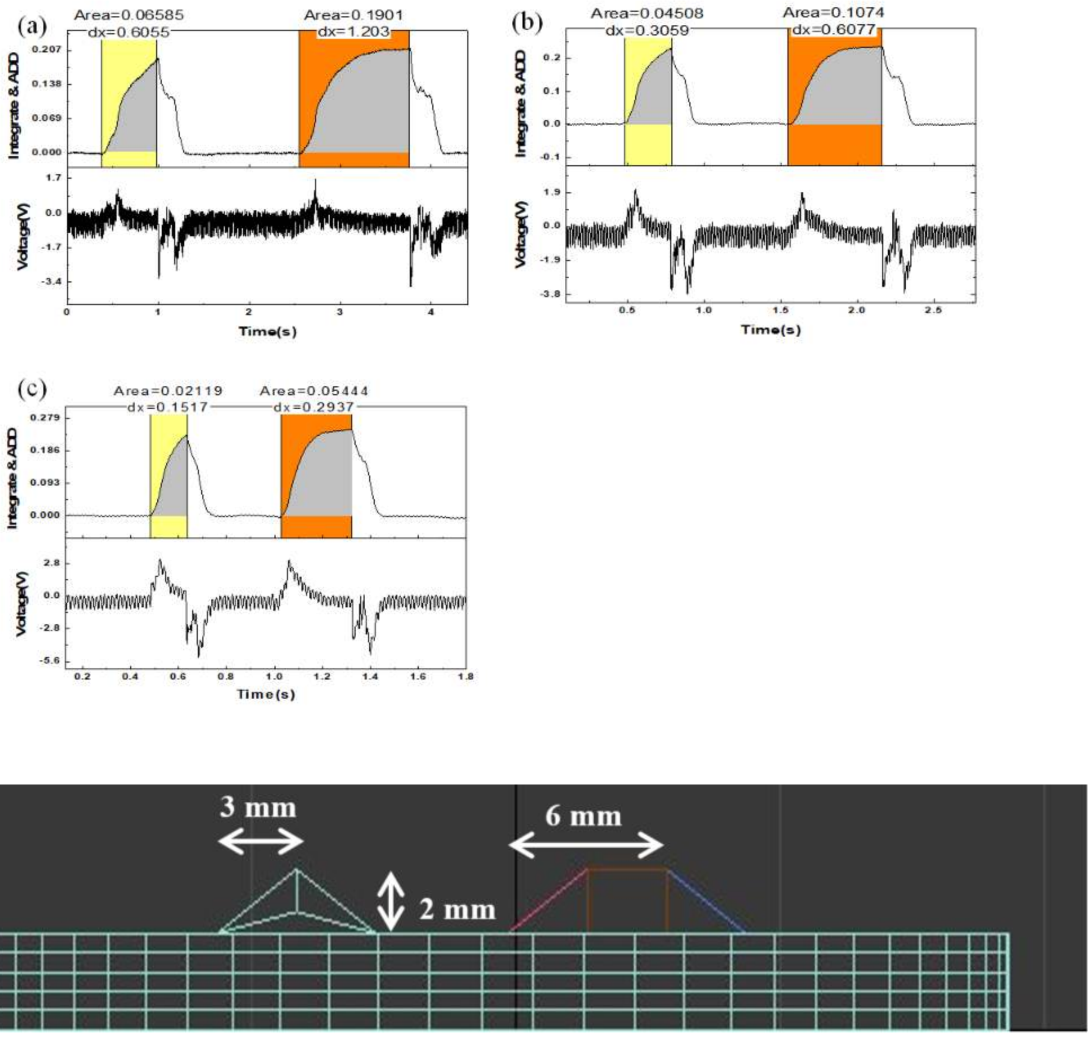


Fig 4.2.1.3 Sliding signal analysis in 2 mm height condition. (a) Sliding at 5 mm/s condition (b) Sliding at 10 mm/s condition (c) Sliding at 20 mm/s condition, and design image of test sample 2

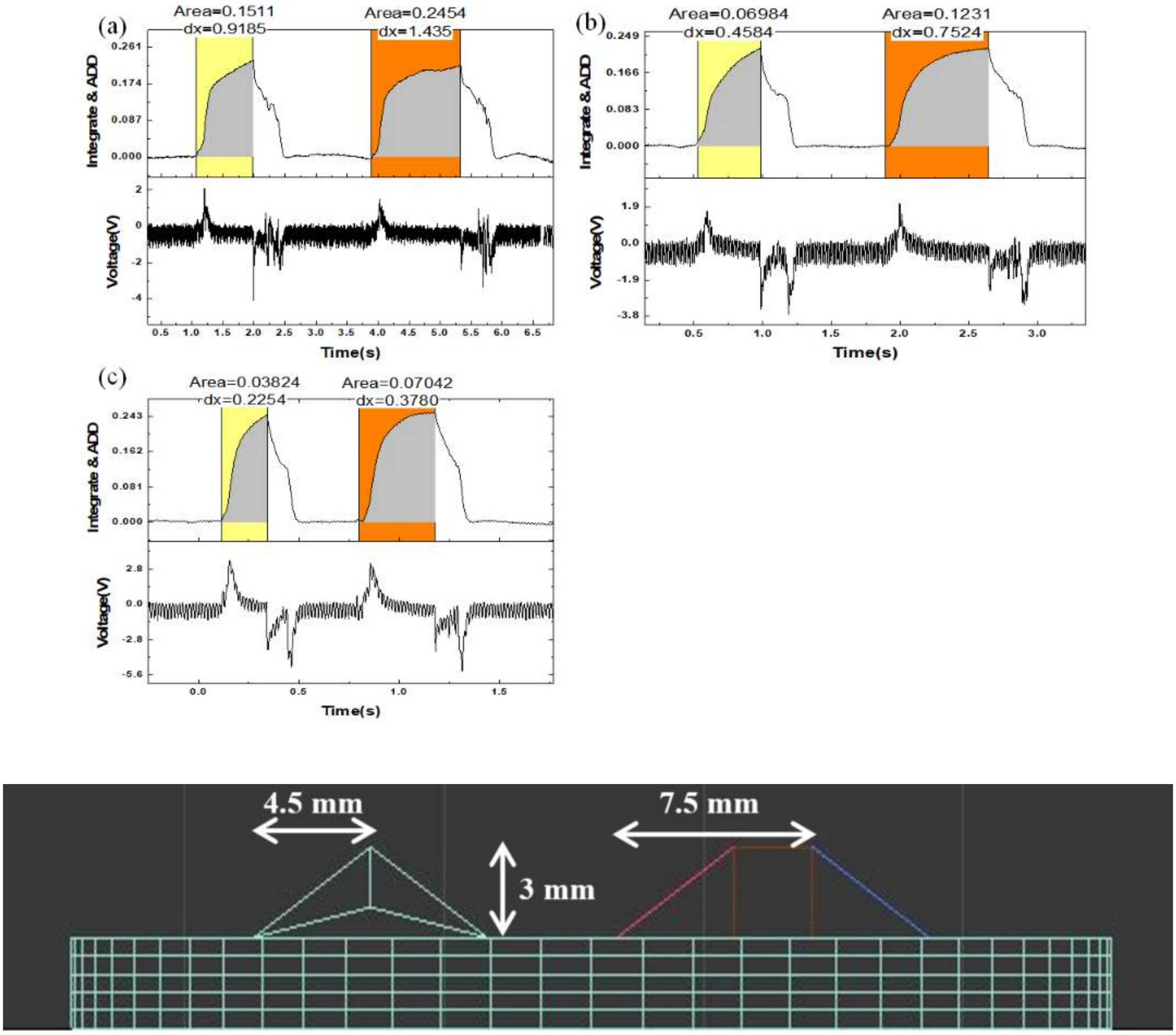


Fig 4.2.1.4 Sliding signal analysis in 3 mm height condition. (a) Sliding at 5 mm/s condition (b) Sliding at 10 mm/s condition (c) Sliding at 20 mm/s condition, and design image of test sample 3

	(a)	(b)	(c)	(d)	(e)	(f)
5 mm/s	0.3051	1.5255	1.5	0.8766	4.383	4.5
10 mm/s	0.1500	1.5	1.5	0.4342	4.342	4.5
20 mm/s	0.0777	1.5542	1.5	0.2220	4.44	4.5

Table 4.2.1.1 Sliding signal analysis in 1 mm height condition (a) Sliding time between the first contact and maximum compressed point at triangle (b) Calculated distance which is the half width of the triangle (c) Real half width of the triangle (d) Sliding time between the first contact and maximum compressed point at trapezium (e) Calculated distance which is the width of trapezium (f) Real width of the trapezium

	(a)	(b)	(c)	(d)	(e)	(f)
5 mm/s	0.6055	3.0275	3.0	1.203	6.015	6.0
10 mm/s	0.3059	3.059	3.0	0.6077	6.077	6.0
20 mm/s	0.1517	3.034	3.0	0.2937	5.874	6.0

Table 4.2.1.2 Sliding signal analysis in 2 mm height condition (a) Sliding time between the first contact and maximum compressed point at triangle (b) Calculated distance which is the half width of the triangle (c) Real half width of the triangle (d) Sliding time between the first contact and maximum compressed point at trapezium (e) Calculated distance which is the width of trapezium (f) Real width of the trapezium

	(a)	(b)	(c)	(d)	(e)	(f)
5 mm/s	0.9185	4.5925	4.5	1.435	7.175	7.5
10 mm/s	0.4584	4.5840	4.5	0.7524	7.524	7.5
20 mm/s	0.2254	4.508	4.5	0.3780	7.56	7.5

Table 4.2.1.3 Sliding signal analysis in 3 mm height condition (a) Sliding time between the first contact and maximum compressed point at triangle (b) Calculated distance which is the half width of the triangle (c) Real half width of the triangle (d) Sliding time between the first contact and maximum compressed point at trapezium (e) Calculated distance which is the width of trapezium (f) Real width of the trapezium

4.2.2 Bidirectional scanning method

We could obtain the information about the width of the object surface through the sliding experiment with spring mounted structure and simple mathematical calculation. However, as mentioned earlier, in the section where the value of integrate & add decreases, the spring is started to vibrate between the sensor and test samples. That is, the signal of this interval is a meaningless noise signal. Due to this drawback, accurate information about the width of object surface can not be calculated exactly. As shown in fig 4.2.2.1, additional process is needed to address the information of curious region. This problem can be solved by adding one more scanning in the opposite direction.

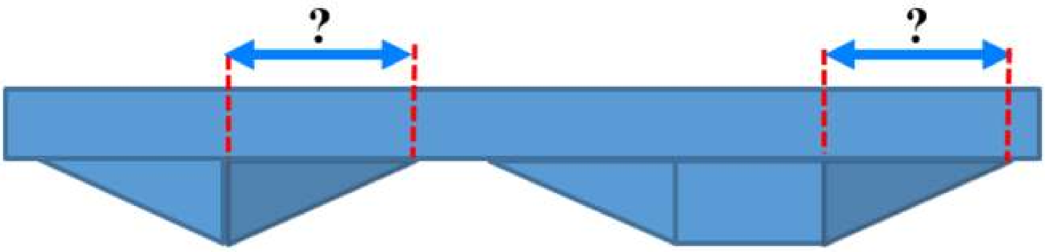


Fig 4.2.2.1 Schematic image of curious region

Fig 4.2.2.2 shows the voltage signal and Integrate & Add graph of bidirectional scanning experiment. The above three graphs are that the stage was moving from left to right and the lower three graphs are that the stage was moving right to left. From the both graph, we could get the complete width information for any shape by complementing the missing part of the graph. Using a spring mounted sensor, we can obtain information about the surface morphology with just a single cell without using an array structure.

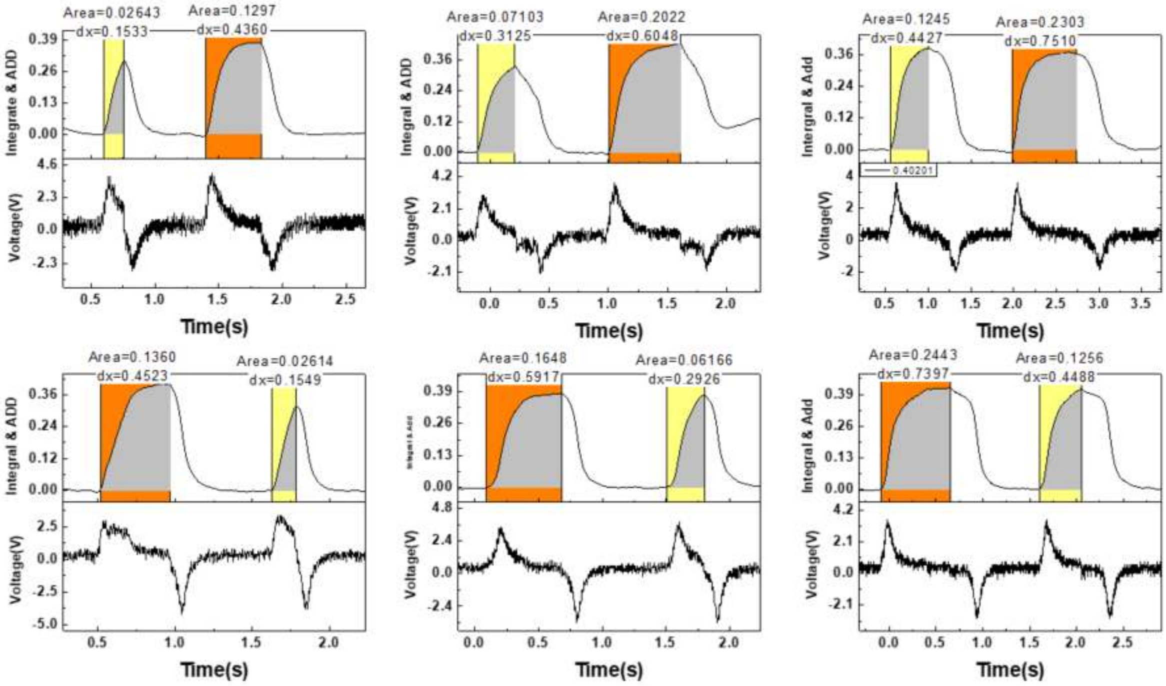


Fig 4.2.2.2 Bidirectional scanning method Above three graphs are that the stage is moving from left to right and lower three graphs are that the stage is moving from right to left. The scanning speed is 10 mm/s. Additional information from the graph below can be used to compensate for the scarcity of the graph.

4.2.3 Integral analysis of sliding experiment

Piezoelectric sensors convert an applied pressure into an electric signal. In this paper, we use PVDF-TrFE which is a typical piezoelectric material for sensing layer. PVDF film can generate electrical charges proportional to the stress, so it is suitable for dynamic force. As the height of some morphology of object surface increases, the degree of deformation of PVDF film also increase, so it can be predicted that electrical charge is generated a lot in the higher morphology case. Fig 4.2.3.1 shows the Integrate & Add graph of scanning experiment at different test samples. Since, the height and width ratio of the test samples are same, a similar waveform is shown in this graph. As the height increases, the area of integrate & add graph also shows a tendency to increase. This tendency can help to analyze the height information.

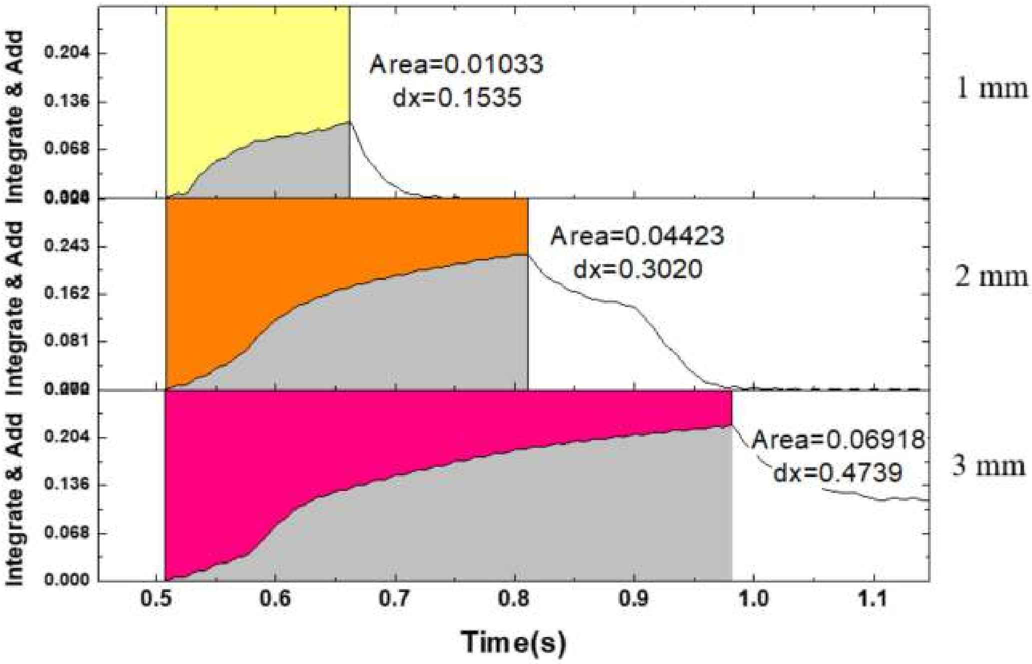


Fig 4.2.3.1 Area analysis of sliding experiment As the height increases, the area of integrate & add graph also shows a tendency to increase. The heights of three different structures are 1, 2 and 3 mm. The scanning speed of stage is 10 mm/s.

Ⅴ. Conclusion

We proposed a tactile sensor which can detect the information of surface morphology such as the width of the object surface and even the displacement of the spring. Surface width and variation of the spring are obtained with simple mathematical calculation.

PVDF-TrFE which is the typical piezoelectric polymer was used as the sensing layer to detect dynamic activity like sliding and repetitive work. The PVDF-TrFE has many good advantages such as flexibility, easy-fabrication and self-power properties.

The human can detect the morphology of object surface through a deformation of skin. So, we developed a spring mounted tactile sensor for mimicking the human skin. The spring which has good elasticity is easily deforms through the object surface when the test sample is sliding or pushing on the sharp tip of spring. Thus, the spring transmit various forces to the sensor depending on the surface morphology. A simple and easy calculation and signal processing was used for detecting the displacement of spring and the width of the surface morphology. These spring deformations contain information about the surface and can be transmitted and interpreted through the sensor layer. The tactile sensor with spring structure can detect the deformation of spring through simple and easy calculation and signal processing. In the Integrate & Add graph, we can find out the peak of the signals mean that the spring is compressed to the maximum. The tactile sensor was pressed at four different depth at 1, 2, 3 and 4 mm under the condition of 10 mm/s. The depth which is the same with sensor is compressed can be obtained accurately in consideration of common error. Also, it is able to restore the width data of object surface by using sliding experiment. This experiment was carried out at three different speeds of 5, 10, and 20 mm/s for reliability. The restored information is highly accurate compared to the real structure. Also, using a bidirectional scanning method with a spring mounted sensor, we can obtain the perfect information of the surface morphology with just a single cell without using an array structure. The information from the additional opposite scanning is used to compensated for the deficient part of the morphology. And, as the height of some morphology of object surface increases, the degree of deformation of PVDF film also increase, so the area of integrate & add also shows a tendency to increase. In addition, it will be possible to analyze inclination according to the morphology of the object in the Integrate graph.

The ability of this sensor and spring mounted structure will be helpful for next generation artificial skin which can sense physical and psychological sensations

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요 약 문

표면 정보 구분을 위한 정신감각적 촉각 센서 구조 연구

오래 전부터 인간의 오감은 매우 흥미로운 학문이었다. 특히 시각과 청각은 가장 많은 연구 성과를 이루어냈으며 그로부터 인간의 시각을 모방한 카메라나 청각을 모방한 마이크 혹은 오디오와 같은 제품들이 개발되어 상용화되고 있다. 최근에는 인간의 촉각을 모방하는 연구들이 각광받고 있다. 압력과 온도와 같은 대표적인 촉각감지 기술들이 다양한 물질들과 또 그것들의 결합으로 연구되고 있으며 많은 결과물들을 창출해 내고 있다. 또한 단순한 감지를 떠나서 실제 인간의 피부처럼 구부러지거나 늘어날 수 있는 인공피부에 대한 센서도 개발되고 있다. 하지만 아직까지는 촉각 센서들이 인간의 촉각을 완벽하게 구현해내지 못하고 있는데 이는 온도와 압력 같은 단순한 감각 외에도 거칠기, 부드러움 ,딱딱함, 점성 등 정신감각적인 요소들이 다양하게 존재하기 때문이다. 실제 사람의 피부에는 이러한 다양한 자극에 대응하는 촉각 수용기들이 밀집하여 있으며 이러한 수용기들과 신경시스템을 통해 사람은 제한 없이 다양한 촉각을 누릴 수 있다. 이러한 정신감각적 촉각에 대한 연구는 동일한 물질에 대해서도 각각의 사람이 느끼는 정도가 다르기 때문에 이를 해결하기 위해서는 많은 문제점들이 존재한다. 표면에 대한 정보를 얻어내는 연구는 아직까지 단순한 감각의 인지에 대한 것보다는 상대적으로 진척이 되지 않았다. 빛을 이용하거나 작은 팁을 이용하여 표면을 스캐닝하여 표면에 대한 정보를 얻어오는 상용화된 제품들이 있으나 이는 광원이나 디텍터와 같은 부수적인 장비들을 필요로 하고 실제로 로봇이나 인공피부 등의 분야에서 부착하여 사용하기에는 어려움이 따른다. 로봇 또는 장비 시스템이 이러한 정신감각을 분별해낼 수 있다면 보다 정밀하고 정확한 작업이 가능할 것이다.
이 논문에서는 압전물질과 스프링을 적용한 센서로 단순한 압력도 구할 수 있으며 단순한 계산을 이용하여 표면의 밀변과 스프링의 변위 정도 또한 알아낼 수 있다. 복잡한 구조를 사용하지 않고도 물질의 표면에 대한 정보를 얻어냄으로써 형태를 복원할 수 있으며 이러한 특징으로부터 촉각 센서가 단순한 정량적인 측정을 넘어서 정신 감각적인 분야에도 그 바탕이 될 수 있다.

핵심어: 피에조, 정신감각적, 표면형태, 스프링 구조