Abstract: Tangible interface can be understood as a newly defined concept, which can provide an effective and seamless interaction between the human as a subjective existence and the cyberspace as an objective existence. Tactile sensation is essential for many exploration and manipulation tasks in the tangible space. In this paper, we suggest the design of an integrated tactile sensor-display system that provides both of sensing and feedback with kinesthetic force, pressure distribution, vibration and slip/stretch. A new tactile sensor with PDVF strips and display system with bimorph actuators has been developed and integrated by developed signal processing algorithm. In the scenario of haptic navigation in the tangible space, tactile feedback system is successfully experimented.

Keywords: tactile sensor, tactile display, tactile feedback, tangible space, PVDF sensor

1. INTRODUCTION

Recently, cyberspace technologies enable computer users to do the Internet shopping or communication at home and also to obtain entertainment and educational information. However, it is possible to experience just visual environments in the cyberspace which does not exchange sufficient information such as tactile feeling, taste, and smell. That is, the cyberspace has been limited in reflecting our physical environments because of the lack of tangibility such as tactile, tasty, and smelling sensibility. Thereby a new project called TSI (tangible space initiative) has been launched by the KIST (Korea institute of science and technology) to overcome the limitations of the cyberspace and to explore a new digital life society [1]. The tangible space has a different concept from the visual cyberspace in that it introduces tangible agent (TA).

The tangible agent transfers real world information to computer environment. The real world information includes video, texture, sound, and smell which cannot be experienced due to time and space limits. Also it goes directly to some place and does tasks on behalf of human. For the TA, there are technologies such as mobile robot manipulation, real-time stereoscopic video, and tactile sensing technologies. The TI (tangible interface) gives human various feelings and information. These two technologies are organically coupled with the cyberspace and build the tangible space. For example, in the tangible space, it is possible for computer users at home to see, smell, touch, and select apples in a remote market or to feel the texture of fabric in a clothing shop and buy it.

In this paper, we focus on the tactile feedback in the tangible space. For the first step of realizing the tactile feedback, we make an effort to develop the hardware which can sense the texture from various materials and display the tactile signal on human’s finger.

There have been several research results to obtain and display the texture. Kawabata developed the commercialized Kawabata texture evaluation system for standardization of fabric [2]. Shimoda et. al proposed a texture sensor using pneumatic pressure and a phase shift of microphone [3]. Howe et al. suggested dynamic texture sensing using PVDF (polyvinylidene fluoride) strips [4]-[5], and one-variable restoration algorithm for texture sensing is developed. However, they showed the results of experiments demonstrating the validity of the restoration algorithm for only one raised metal edge. A number of researchers have also proposed their own tactile display systems to generate physical quantities. To provide tactile sensation to the skin, they tried various display methods such as mechanical, electrical and thermal stimulation. Most mechanical methods were comprised of an array of pins with a linear actuator such as a solenoid, piezoelectric actuator, or pneumatic actuator. Ikei et al. designed a vibrotactile device fixed at 250 Hz; this device had fifty pins driven by adjusting the natural frequency to expand the displacement of a piezoelectric actuator[6]. Hayward and Cruz-Hernandez focused on the tactile sensation of lateral skin stretch[7] and suggested a tactile display device for stimulating a small displacement of distributed lateral skin stretching up to several kilohertz but not for the normal stimulation of pressure distribution. The device was comprised of 64 piezoelectric actuators connected to a membrane. Konyo et al. used an electroactive polymer for the mechanical stimulation actuators. He proposed a tactile device to express the fine touch of a cloth surface using vibration rates of up to 100 Hz in frequency[8]. The stiffness of the soft high polymer gel, however, was so low that it could not display the intensive stimulation of the virtual texture. Some research has been done on electrical tactile display devices because of their advantages over mechanical tactile display devices. Poletto and Doren developed a high-voltage electrocutaneous stimulator with small electrodes[9]. Kajimoto et al. modeled a nerve axon model based on the properties of human skin and proposed an electrocutaneous display using anodic and cathodic current stimulation[10]; however, these tactile display devices sometimes involve user discomfort and even pain.

In this research, a new tactile sensing system is designed to get texture with high resolution and wide dynamic range. At first, a PVDF sensor is made of piezoelectric polymer strips molded in silicon rubber and attached in a rigid cylindrical body. The sensor is fixed to a scanning mechanism for dynamic sensing which implies that the sensor moves on the surface of objects. Second, a new signal processing algorithm for restoration of texture is developed based on experimental data. As a starting point of our research, we develop a dynamic tactile sensing algorithm to extract the shape of edges and the vibratory components of normal and shear force in which direct current components are subtracted because PVDF film can give only dynamic properties. Dynamic relation from measured PVDF sensor signals to force and shape is directly modeled in one-step by using a time-domain multi-input multi-output autoregressive moving average model which
does not need forward modeling from texture to measured PVDF sensor signals. The structure and the order of the model are decided by a loss function calculated from restored signals and original FT (force torque) sensor signals and original shapes. Finally, the multi-dimensional texture is obtained by using the developed on-line signal processing algorithm. We also propose a new type of an integrated tactile display system. The piezo-bimorph actuators and a peltier heat pump make it possible to provide human’s finger with tactile and thermal feedback. The system can generate the wide-bandwidth signal from static pressure to high frequency vibration mode. It can also make the signal with high resolution beyond the sensing capability of human’s fingertip.

Even with both of tactile sensory and display system, just transferring the signal from the sensor to the display system doesn’t make the realistic tactile feedback since the sensor differs with human finger and the display cannot generate continuous shape of a real texture. We propose a primitive solution of the tactile sensing to display problem. We separate approaches for the macro-level and roughness-level tactile signal transfer.

Finally, developed systems and transferring algorithm are implemented for the demonstration of the tangible space named ‘haptic navigation’. The tactile sensing and display system play a role of one of a few haptic devices.

The paper is composed of four sessions. In section 2 and 3, we introduce the developed tactile sensory and display system. Section 4 gives the idea of the tactile sensory to display algorithm and shows how the tactile system is involved in the demonstration scenario. Conclusion and some future work are remarked in Session 4.

2. TACTILE SENSOR WITH PDVF STRIPS

3.1 Why PDVF?

Sensors using PVDF polymer has advantages such as wide dynamic range, durability, and no use of external voltage source [11]. The skin of a human finger has four types of sensors to feel stimuli exerted on the skin. The frequency characteristics of PVDF sensors is similar to that of Meissner corpuscles in human finger skin. The sensors can detect the force signal from 10–60 (Hz) since the PVDF sensor is known to be appropriate for sensing 10–50 (Hz) signal range [4], [12]. The dynamic PVDF sensing proposed in [4]-[5] can give sensitive signals in spite of small changes on surface and is useful when sensing fine surface features. While computer vision sensors give the global information of surface, the dynamic PVDF sensor is a good candidate of sensors which can give local and detailed information such as coefficient of friction, normal force, shear force, and roughness. The sensing performance is independent of changes of material brightness unlike computer vision sensors. For example, the PVDF sensor can be used as an off-line texture registration device for fabric, furniture, or apples like commercial barcode scanners in shopping malls. And it can be attached to the finger of a robot hand to touch and sense the surface of products in real time if the robot agent goes to some place where the products are located.

3.2 A Sensor with Two PVDF Film Strips

As is shown in Fig. 1, a PVDF sensor strip is made to obtain estimated vibratory normal and shear force and shapes of metal edges according to movements of the sensor module on the surface of objects. Polyvinylidene fluoride pallets (supplied by Shine-Tsu Chemical Co. Ltd.) are used as a raw material, and they are prepared as laminated film strips by using a hot-press process. In the process, the PVDF pallets are pressed under high pressure condition for 1-2 minutes between two pieces of polymide film at a high temperature. Quenching out the press before the films are removed from the polymide film pieces follows those samples. To perform the poling treatment of the films, aluminium electrodes are attached to both sides of the PVDF film and the electric field is applied by using a high-voltage power supply. It is carried out without changing the process temperatures. We fabricate several films while varying the poling voltage and optimal processing conditions are determined according to the experimental data. The film has a piezoelectric property after polling. Also, silver electrodes are made by silk-screen technique with silver on both sides of the film according to a desired electrode pattern. Finally, silicon rubber is coated on both sides of the film to prevent the damage externally. Two strips of piezofilm in 30 µm thickness, 0.5mm width, and 35mm length are molded into the silicon cover. The picture of the developed PVDF sensor module is shown in Fig. 2(b). Two strips are located perpendicular to each other, and as closely located as possible. A piece of foam rubber is inserted between a rigid cylinder and the silicon rubber for a good contact condition.

Fig.1 PVDF sensor strip

Fig.2 (a) Cross sectional view of a sensor module (b) PVDF sensor module

3.3 Scanning Mechanism

A new texture sensing system is designed to get texture of several types of objects with high resolution and a wide dynamic range by using the PVDF sensor. To obtain the texture, a new scanning system is developed as shown in Fig. 3. Rotation of a DC motor is converted to linear motion by a ball screw which gives 10 (mm) movement per one revolution. A simple balancing mechanism is attached to the PVDF sensor module in order to maintain a consistent normal force condition while linear motion is being performed. The raised metal edge bed can be changed according to the edge shapes.
3.3 Restoration Algorithm

The restoration problem is to transform from stress rate signals of the PVDF strips at the location A into two estimated surface line forces and other texture components at the location B as shown in Fig. 1 [4]. Note that the proposed algorithm is not based on theoretical modeling but on experimental data which reflect correlated noise. Thus it needs neither parameters of PVDF strips nor electric circuit, and can outperform the algorithm based on the theoretical modeling in [4]. Dynamic relation from measured signals to force is directly modeled in one-step with a nonlinear MIMO (multi-input multi-output) ARMAX (autoregressive moving average) model, which does not need forward modeling from texture to measured sensor signals, and a time domain least squares estimation technique. The detailed signal processing algorithm is referred in [13].

3.4 Amp Circuit for the PVDF Sensor Module

Piezoelectric transducers are most frequently used with amplifiers so that the output voltage signal is proportional to the measured stress rate because a PVDF sensor produces small signal from the PVDF strip. A current-voltage converting amplifier with an OP-amp feedback resistance is used to amplify original signals from PVDF films. A 60Hz-notch filter is implemented to get rid of AC noise from power supply. In addition to this amplifier circuit, a low pass filter with 100 (Hz) cut off frequency is used by software algorithm in order to diminish high frequency noise. Since a PVDF sensor is known to be useful for sensing 10~50Hz signal [12], the 100 (Hz) cut off frequency is reasonable.

3.5 Tactile Sensing to Edge Profiles and Reconstruction of the Texture

As described in [4], approximate impulse responses can be used to obtain a forward model from texture to measured PVDF signals. In this study, however, we do not use impulse responses for the forward modeling. That is, several edge profiles are used to directly obtain a backward model from measured signals to texture using time-domain nonlinear least-square estimation. As a starting point to texture sensing, shapes of metal edges and vibratory components of the normal and shear force after DC components are subtracted are restored from measured PVDF signals, because the output of the PVDF sensor in steady-state rapidly disappears and because obtaining initial conditions for integration of the output is difficult. The vibratory signals can be displayed as vibratory forces by haptic devices in normal and shear directions. We evaluated the orders of the linear and nonlinear model using measured signals of an FT sensor and the PVDF sensor for six types of edge profiles. Two profiles of the six are shown in Fig. 4 where rectangular and triangular edges are machined with 1mm height. The 3rd and 4th metal edge beds are made in 6mm wide interval for each shape. The 5th and 6th metal edge beds are machined with a narrow 2mm interval. On these edges, the developed PVDF sensor is moved with velocity 10 (mm/s).

Fig. 5 represents the signals detected by the PVDF sensor and a commercialized FT sensor and restored texture. Note that another data different from the data used in modeling stage is used in this final test of the model. Rapidly changing signals $m_1$ and $m_2$ can be seen in the first and second. Thus it is difficult to directly extract surface normal and shear forces $f_1(=f_z)$ and $f_2(=f_y)$ from $m_1$ and $m_2$. Thus, the signals $m_1$ and $m_2$ must be processed by a signal processing algorithm for restoration of the two forces and the shape of edges. We can see that the restored results $\hat{f}_1$, $\hat{f}_2$, and $\hat{f}_3$ (dotted-line) of $f_1$, $f_2$, and $f_3$ from PVDF signals $m_1$ and $m_2$ using proposed modeling method and filtering is similar to the original FT sensor signals and the shapes (solid-line). Note that the sensed force signals are used for backward modeling and comparing with the restored signals, not used in filtering step at all. We can see the restored signals correspond to the FT sensor signals and the shape of metal edges. For the narrow interval edges, the FT sensor signals are much different between the rectangular type and the triangle type. We can see that the restored results have approximately agreement in frequency and magnitude. From the restored results, we can see that human finger may clearly distinguish the two different type edges by the proposed sensing system, the algorithm, and some haptic devices. When the restored signal is displayed by the tactile display, whether human can distinguish the two types of edges or not is future work.

3. TACTILE DISPLAY WITH PIEZO-ACTUATORS

A new tactile display unit is designed to simulate the pressure distribution, vibration and lateral movement across the contact regions between the device and the fingertip. The device is comprised of a pin array and eight piezoelectric
bimorphs for normal vibrotactile stimulation. Compared with typical piezoelectric actuators, a piezoelectric bimorph has higher degree of stiffness, a displacement larger than 1 mm and a lower operating input voltage (±60V). In addition, its response time is in the millisecond range and it can provide a force of up to 1 N. Compared with Srinivasan’s study of the deflection mechanics of fingertip [14], the force of 1N is sufficient to press the skin with a deformation of 1mm. The capabilities of the tactile stimulator with piezoelectric bimorphs satisfy the condition, and, therefore, it is adequate for normal vibrotaction with required frequency range and stimulation intensity. As shown in Fig. 6, piezoelectric bimorphs are clamped with 1 mm spacing and the 6 x 1 pin array is attached at the end of one bimorph. As indicated in [15], the pin spacing is 1 ~ 1.5 mm and the diameter of each pin is 0.5 or 0.7 mm, enabling the display of a texture 8 mm wide. The head of each pin is rounded or cut and the crosssection is circular or square, thus, eight types of pin are designed. The clamping part is attached to a linear motion guide.

We also add an ability of thermal display to the tactile display unit. Even with the exact same roughness, a human can distinguish materials by thermal conductivity. We cover the pin array with a thermoelectric module called a peltier heat pump and a copper plate which can transfer heat fast as shown in Fig 4(b). The module can transfer heat with maximum +15.6 °C/s and -4.5 °C/s.

The results of our experiment revealed that bending actuator could travel up to 1mm in 200Hz frequency range, and it generated enough vibration to stimulate the skin at over 800Hz. Fig. 7 shows an example of the pressure distribution of the pin array to display small-scale shapes. We anticipate that the suggested system can server as a test bed for studies on tactile display algorithm.

As a tactile feedback component in the tangible space demonstration, the developed tactile display unit is located at the end of one bimorph in the tactile display unit. The developed tactile display unit is integrated with the haptic device so that a human can put his finger on the unit as shown in Fig. 8.

4. TACTILE FEEDBACK IN TANGIBLE SPACE

4.1 Scenario of the demonstration

As a demonstration of the TSI project in KIST[16], the scenario of haptic navigation is experimented. In the scenario, an operator is going to experience three different scenes which are composed of opening a door, feeling a stone tower, and ringing a bell as shown in Fig. 9. The operator moves in the virtual space visualized by four projectors and polarizing glasses, and he sees 3-D scenes of the scenario with the hand avatar which visualize the position and current state of the operator’s hand. In addition to the tactile feedback, a wearable haptic device and sound rendering gets an operator immersed in the tangible space by providing the force feedback corresponding to the information of collision sensed by the visual server and audio feedback.

At the first scene, the tactile display makes a wave carved on the surface of the door, waving along the vertical motion of human’s hand. The second scene allows the operator to touch and slide on the rough surface of a stone tower as shown in Fig. 10. At the final scene, the operator grabs the wire of a bell hammer and hits the bell. The operator can touch the bell and feel the cold surface. The tactile display device must provide the surface information of the object corresponding to the vertical coordinate of the finger obtained from the haptic device.

4.2 How to make a realistic tactile feedback?

Except for the third scene of the scenario where the develop tactile display system uses only the thermal display unit to cool the fingertip of the operator, the tactile display has to generate the shape of the door and roughness of the stone; the first one can represents macro shape and the other one does...
micro texture. At the first scene, we assume that sine waves are carved on the door for the convenience of the tactile display. For the second scene, we gather the real texture of a stone by scanning a rough brick. Sensed data from the stone is plotted in Fig. 11(a).

![Fig. 10. The second scenario of haptic navigation: scraping a stone tower](image)

As depicted in the introductive section, there are few research for the tactile sensing to display issue because this problem is related to the complex system of human sensation and even the design of the tactile sensor and display device. It is the fundamental problem that the tactile sensor and display are different from a human finger and a real object. In fact, our approach to the solution is also primitive and specialized for the demonstration of the haptic navigation. In our method, we do not deal with difference of the tactile sensor but that of tactile display and we propose intuitive algorithm of transferring the signal from the sensor to the display.

The tactile display device uses the pin array to represent the signal. Therefore, the signal has to be digitized with 1mm interval because of the pin spacing. For this reason, the same problem as analog to digital converter arises here. Although human finger’s sensation is known to be able to distinguish the sinewave signal above 3mm period[15], One can easily feel that the displayed shape with more than 3mm period is not like the sinewave when a position of his finger moves with faster velocity than suitable one. For example, people in our lab find out that round shape of the sinewave is not well sensed until the period of the sinewave goes over 12mm with his finger’s moving 30mm/sec, 16mm period with 50mm/sec, and 20mm period with 70mm/sec. It’s because the number of the pin array and the peg spacing are not enough. Therefore, we choose to display 20mm-period sinewave for the surface of the door since we think the normal velocity of the arm with scraping motion is about 50mm/sec. The sinewave of too long period also gives uncertain feeling than that of the proper period. We also give the display signal the 3-step depth with 50%, 75%, and 100% of the maximum amplitude along the depth of collision in the tangible space by experiments with our lab members.

Not like the case of the macro shape, we do not have the shape to be directly displayed. Instead, we use the signal from the tactile sensor as shown in Fig. 11(a). However, the feeling of the data made by the tactile display is not good quality because of lack of the resolution. The sensed data is obtained with 50mm/sec scanning velocity and 0.1mm resolution; the display device does not give continuous shape with this resolution. Above of all, the hardware resolution, that is, the pin spacing, is also limited. To solve this problem, we made a frequency signal based approach. Notice that the tactile display is able to generate a high vibration mode. The FFT data of the sensed signal is shown Fig. 11(b). There is a mode in about 3Hz, and three modes are located near 20Hz frequency. Therefore, we decide to use two major frequency information and make the display device generate the mixed vibration mode with 3.3mm and 0.5mm signal which match 3Hz and 20Hz modes with the 10mm/sec velocity. The amplitudes of modes are tuned to give most similar feeling like a real rough stone.

By the proposed strategy for macro and micro shape, the demonstration of the tangible space is performed.

5. CONCLUSION

In this research, we proposed the concept of the Tangible Space and developed tactile sensor and display system. We designed a dynamic texture sensing and display system. New type hardware of the sensor and display are constructed and successfully experimented in the scenario of tangible navigation. In the future, we will improve performance of each component; we expect to give more realistic tactile feeling to people in the Tangible Space.
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REFERENCES


Fig. 5 Along x-axis, results to single retangular/triangular edges, multiple wide-interval rectangular/triangular edges, multiple narrow-interval rectangular/triangular edges, sequentially. Along y-axis, PVDF signals $m_1$ and $m_2$, normal force signal $f_z(=f_1)$ (solid line) and the restored force signals $\hat{f}_z(=\hat{f}_1)$ (dotted line), shear force signal $f_x(=f_2)$ (solid line) and the restored force signals $\hat{f}_x(=\hat{f}_2)$ (dotted line), shapes of metal edges $f_3$ and the resored shapes $\hat{f}_3$. 