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# Development of a Texture Sensor Emulating the Tissue Structure and Perceptual Mechanism of Human Fingers

Yuka Mukaibo*, Hirokazu Shirado**, Masashi Konyo***, Takashi Maeno****

*Department of Mechanical Engineering*
*Keio University*
*3-14-1 Hiyoshi, Kohoku-ku Yokohama, Japan*

**mukabo@mmm-keio.net, **shirado_hirokazu@mtb.biglobe.ne.jp, ***konyo@educ.cc.keio.ac.jp, ****maeno@mech.keio.ac.jp*

***Abstract* – This paper discusses a novel approach in developing a texture sensor emulating the major features of a human finger. The aim of this study is to realize precise and quantitative texture sensing. Three physical properties, roughness, softness, and friction are known to constitute texture perception of humans. The sensor is designed to measure the three specific types of information by adopting the mechanism of human texture perception. First, four features of the human finger that were focused on in designing the novel sensor are introduced. Each feature is considered to play an important role in texture perception; the existence of nails and bone, the multiple layered structure of soft tissue, the distribution of mechanoreceptors, and the deployment of epidermal ridges. Next, detailed design of the texture sensor based on the design concept is explained, followed by evaluating experiments and analysis of the results. Finally, we conducted texture perceptive experiments of actual material using the developed sensor, thus achieving the information expected. Results show the potential of our approach.**

***Index Terms* –*Texture Perception, Tactile Sensor***

## I. Introduction

Senses are known to be the critical features of human beings for survival. Of our five senses, the sense of touch is said to be the only sense that if lost, may even lead to the loss of emotion and the will to live. Therefore, in the fields of robotics, medicine, and virtual reality, it is considered extremely important to learn more of and apply the texture perception mechanism of human beings to artifacts. For example, in a master-slave robotic operation system, if the slave device could detect the roughness of an object it touches and the master device could accurately feedback the sense of touch to the operator, this would enable the system to conduct a wider variety of tasks.

An approach to create such systems is the many attempts to develop tactile sensors for various robotic applications [1] [12]. Such sensors can be categorized into two types. One type is created to control grasping force of robot hands, so as not to let an object slip out of the hand when handling it. The other type is used to sense and evaluate the surface and stiffness of an object. We call the first type a grasping sensor and the other a texture sensor. In the field of robotics, it has been a challenging quest to lift and maintain grasp of an object with unknown weight and friction coefficient. Many researches have attempted to confront this problem by focusing on a phenomenon known as 'partial slip' of the contact surface between the robot fingers and an object. Partial slip is slipping that occurs at only a part of the contact surface [2] [3]. Existing methods have not been able to obtain accurate distribution of the contact area and researches have pointed out that measuring the area of the finger in contact with the object is one way humans determine how soft the surface of an object is. Authors attempted to confront such problems creating a grasping sensor by mimicking the structural features of humans to detect precise contact distribution [4].

On the other hand, being able to detect how slippery or rough a surface is, is an interesting feature of the sense of touch. Being able to quantitatively evaluate this information is necessary for the development of robots that can autonomously detect the surface of objects, or in master-slave systems for tele-operation and virtual reality. Such technologies have also started to attract attention in the fields of medicine, fabrics and cosmetics when creating artificial surfaces to substitute actual material. Tanaka conducted texture evaluation of fabric and human skin using the output of a sensor using PVDF (Polyvinylidene fluoride) film sensors [5]. Pai et al. created a wireless texture sensor for simultaneous texture measurements [10]. However, preceding methods have only been able to derive partial information of the surface such as spatial frequency and friction coefficients. Furthermore, the surface of the sensor that touches the object is rigid, meaning that information derived can possibly be different from what a human being would feel when touching the same surface, and important information could be lost. Hristu et al. created a deformable membrane tactile sensor adapting the deformable feature of human fingertips [11], yet since the information is based solely on graphics this method also lacks in abundance of necessary information.

In this study, we propose to design a texture sensor adopting the same approach as the authors creating the previously mentioned grasping sensor did [4], by emulating the structure of human fingers. Our novel sensor is different, however, since our aim is to handle texture, which is a combination of diverse types of information, not only the partial slip distribution. We thus realize quantitative texture perception and evaluation of the surfaces of various materials.

## II. Background

Preceding studies have suggested there are many specific features of a human finger that realize perception of such a wide variety of texture. From an anatomical layered tissue composing the finger, and the

TABLE I
ELASTIC COEFFICIENT OF EACH TISSUE LAYER

| Layer | Elastic Coefficient |
|---|---|
| Epidermis | $1.4\times10^5$ |
| Dermis | $8.0\times10^4$ |
| Subcutanea | $3.4\times10^4$ |

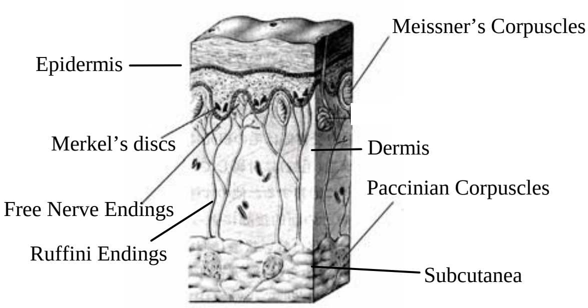


Fig. 1 Structure of Human Tissue

perspective, the structure of the finger, the structure of the mechanoreceptors within the tissue all play an important role in texture perception.

### A. *Finger Structure*

First, focusing on the structure of a human finger, a human fingertip is made up of tissue, bone, and nail. Tissue surrounds the bone, allowing the finger to take an oval-like form. The curve of the oval shape allows consistent precise grasping and manipulation. The rigid nail helps secure the tissue so that the finger can touch the object without having to deform too much to accomplish a task. Nails are also known to play an important role in texture perception, in which it helps to enlarge the stimuli on mechanoreceptors by sandwiching the tissue between the surface and nail.

### B. *Tissue Structure*

Looking more closely at the tissue structure, studies have noticed that human tissue is made up of multiple layers, each with different mechanical properties. The elastic coefficients of the layers are shown in Table 1.The outmost layer is the epidermis, beneath it the dermis layer, and the layer closest to the bone is the subcutanea. The epidermis is the hardest layer, with the smallest elasticity and is approx. 1mm thick. Epidermal ridges cover the surface of the epidermis. The effect of these ridges will be mentioned late. The dermis is a softer layer with more elasticity, usually 1 to 3mm thick. Innumerous protrusions compose the boundary between the epidermis and dermis securing the two layers. The subcutanea which fills the space between the dermis and bone is mainly composed of fat and functions as a cushion when shock load is applied to the finger.

The multilayered structure enhances effective texture perception. Due to the difference in elastic coefficients, there is greater deformation of the inner layers than the outmost epidermis when the finger presses into or moves

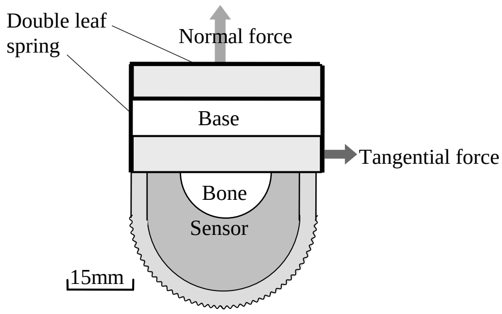


Fig. 2 General image of sensor

along a surface. This is why human fingers can derive consistent texture information regardless of the pressure applied to the finger. This phenomenon is also believed effective in force control of multiple fingers upon grasping tasks.

### C. *Mechanoreceptors*

Texture perception of humans is said to be conducted through determination of a combination of certain types of information such as "roughness", "thickness/softness", and "friction" [8]. Four types of mechanoreceptors, Meissner's Corpuscles, Pacinian Corpuscles, Merkel's discs, and Ruffini Endings, are situated within a human finger and are each assigned to detect different types of information (Fig. 1). For example, the Meissner's corpuscles, closely packed on the epidermis-dermis boundary, are said to be effective in detecting the roughness of a surface. Meissner's corpuscles respond to the change in velocity and are most activated when stimulation with frequencies below 100 Hz is applied. Therefore, when touching motion is conducted, the roughness of the surface the finger is touching generates vibration on the surface of the finger tissue, and this ignites the Meissner's corpuscles. Pacinian Corpuscles, on the other hand, are highly sensitive pressure receptors that are located deep in the dermis. These also respond to vibration rather than to prolonged pressure, but of higher frequencies than the Meissner's corpuscles. Vibration with frequencies higher than 100Hz is believed to relate to friction or how slippery the surface is. The tactile display device using ICPF (Ionic Conducting Polymer gel Film) actuators developed by Konyo et al. have proved that accurate texture perception is indeed possible by displaying a combination of the three types of information. [7]

### D. *Epidermal Ridges*

Epidermal ridges are approximately 0.1mm in height, 0.3 to 0.5mm in width, and cover the surface of a human finger. They are also an extremely important element in texture perception. The shape of an epidermal ridge is a combination of a trapezoid and semicircle. This shape is the most effective for even distribution of normal force at the surface. Maeno et al. have discovered through simulation that the existence of epidermal ridges affects the activity of Meissner's corpuscles which are located directly beneath these ridges [6]. Further evaluation on the effect epidermal ridges have to improve tactile sensitivity has also been

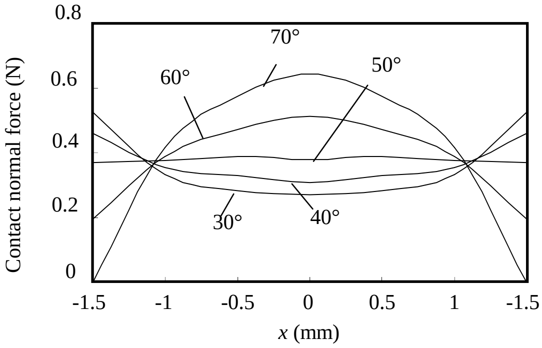


Fig. 3 Normal force distribution

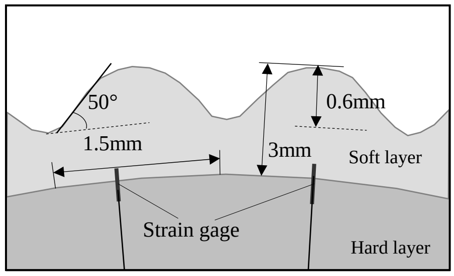


Fig. 4 Sensor Tissue

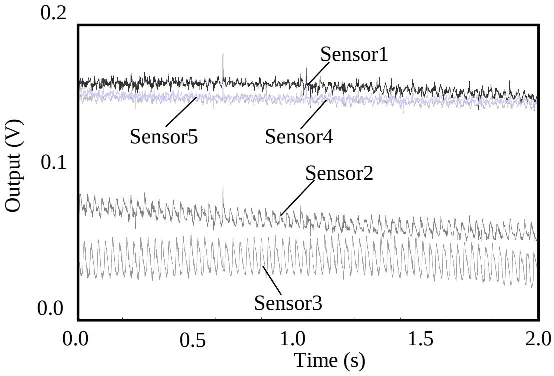


Fig. 5 Output of the five strain gages

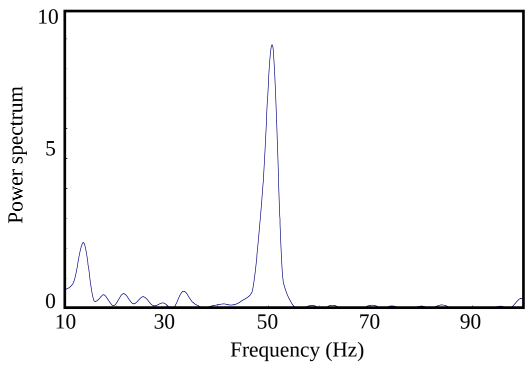


Fig. 6 Spectral analysis of sensor output (wavelength 0.4mm)

conducted [9]. When moving the finger along a surface, vibration of the epidermal ridges is directly transmitted to the corpuscles where as without the ridges, the finger would just slide along the surface unable to distinguish between a rough surface and a smooth one.

## III. Design

Knowing the specific features of human fingers, we designed a texture sensor emulating the characteristics as listed below.

*1) Elastic material*: Silicone rubber is used emulating the human tissue. This was necessary to create a soft contact surface which has been proved to be is effective in detecting the texture of soft material

*2) Two layered structure*: Emulating the structure of human tissue, two types of silicone rubber with different elasticity (elastic coefficients are the same as those of the epidermis and dermis layers of humans)

*3) Distribution of bone and nail elements*: In order to effectively derive sensory information, parts that function as the bone and nail are situated at the base of the sensor

*4) Macro-scale curvature*: The surface of the sensor that touches the subject material is curved in order to detect the difference in contact area.

*5) Distribution of multiple sensor elements*: To emulate mechanoreceptors of the human finger, a total of five strain gages were placed inside the silicone rubber, on the boundary of the two different layers, just like Meissner's Corpuscles. This is to obtain spatial distribution of sensory outputs.

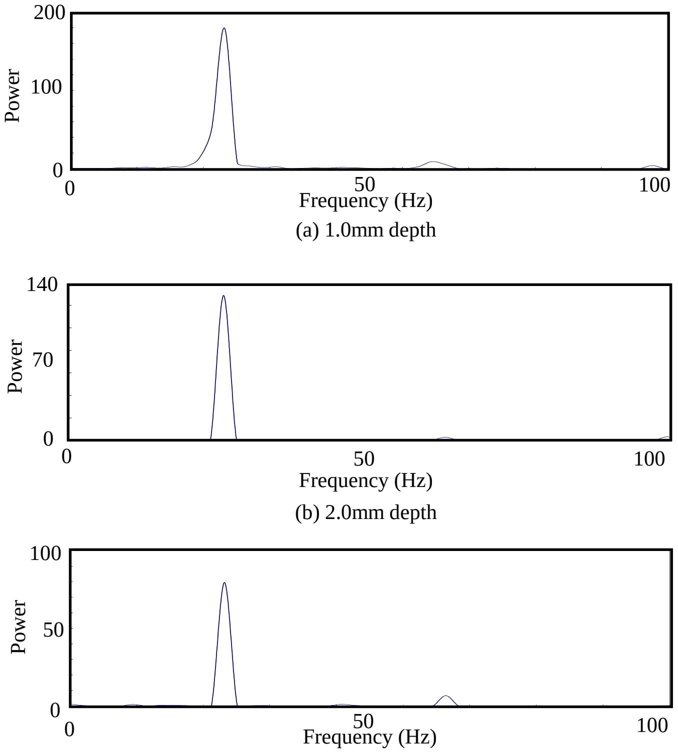
*6) Epidermal Ridges*: Epidermal ridges were placed along the surface of the sensor to achieve the same effects as human fingers do, as explained in the previous section.

*7) Force sensing at the base*: Two double leaf springs are positioned at the base of the sensor to measure the total normal force and tangential force that is applied to the sensor.

Fig.2 illustrates the structure of the designed sensor. Due to the limit in size of strain gages that were available, the sensor is designed to be three times the size of an average adult male finger, which is a semicircle-like form that is 45mm in diameter. Thus, the size of epidermal ridges was also tripled. As for the detailed dimensions, Sato et al. conducted simulations to derive what angle of the trapezoid would be most effective for realizing even distribution of force. As shown in the results in Fig. 3, the distribution was most balanced when the angle of the epidermal ridges were set to 50 deg. Therefore this result was applied to the sensor developed. (Fig. 4)

The five strain gages are each deployed directly beneath an epidermal ridge. This will allow us to obtain both vibration information and deformation of the epidermal ridge when in contact with an object surface. The area of a contact surface can be measured by placing multiple strain gages, and keeping track of the output of each strain gage.

As previously mentioned, giving the sensor a multiple layered structure is effective in order to prevent large-scale deformation of the outer layer. This means that the strain gages will remain vertical to the contact surface, regardless of the pressure applied or the shape of the object being touched. Therefore constant and reliable information can be obtained. However, in realizing this specific feature, force




(a) 1.0mm depth

(b) 2.0mm depth

(c) 2.5mm depth

Fig. 7 Spectral analysis of data at different pressure depths

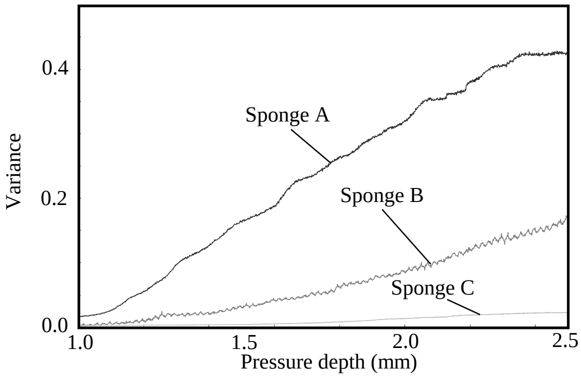



Fig. 8 Evaluation of softness

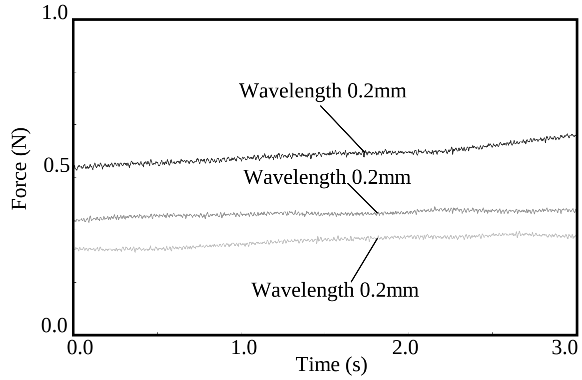



Fig. 9 Measured tangential force

applied to the sensor cannot be measured solely from the output of the five strain gages. It is extremely important in tactile perception to know how much normal and tangential force is applied in detecting the elasticity or friction coefficient of the surface being touched. Humans are also known to decipher softness and friction of the object combining the inner senses and the output of the mechanoreceptors. Thus two double leaf springs were situated at the base of the rubber part to obtain this information.

## IV. Fundamental Experiments

Using the developed texture sensor, we conducted a number of fundamental experiments to prove the effectiveness of the sensor proposed.

To correspond to texture perception of humans, the sensor must be able to obtain quantitative information on roughness, softness, and friction of the material it touches.

### *A. Roughness Experiments*

We first created acryl plates with ridges of various wavelengths. The sensor was pressed 1.5mm into the plate, and then moved along the ridges at a speed of 20mm/s. This speed is the average speed of a human finger when touching different surfaces. The bandwidth of the sensor corresponds to that of a human finger; therefore, we consider this speed relevant to conduct the experiments. An example of the output of the 5 strain gages are as shown in Fig. 5. Here, sensors 1 and 5 are the outmost gages, and sensor 3 is the gage in the center. We then conducted spectral analysis of these outputs in order to make a quantitative evaluation of the abilities of the sensor. Fig. 6 shows the results when sensing ridges with a wavelength of 0.4mm. A large power spectrum was obtained for a frequency of 50Hz. Frequency can be calculated by dividing velocity by wavelength as can be expressed in the equation:

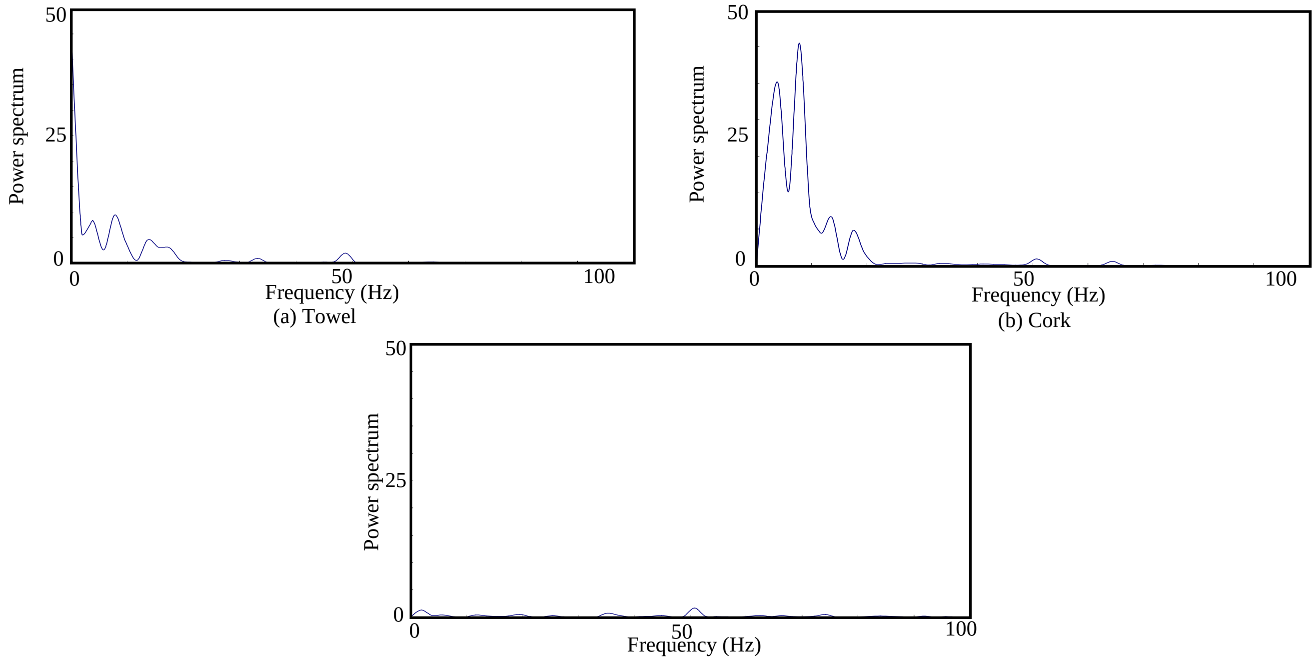
$$f = v/\lambda$$

where $f$ is frequency, $v$ is velocity, and $\lambda$wavelength. The experimental results satisfied this equation. The same could be said for wavelengths 0.2mm and 0.6mm, which means expected results were achieved, although the results were not so significant for the wavelength of 0.2mm. The size of the sensor being three times that of humans could possibly be the cause, however better results were achieved at lower speeds (10mm/s).

To next show the effectiveness of the two-layered structure, the sensor was moved along ridges of 0.6mm, but this time at various depths. The spectral analysis is shown in Fig. 7 and the results show that identical results were derived regardless of how much the sensor is pressed into the plate. From these results, we can say that the developed sensor is effective in obtaining roughness of a surface in terms of frequencies.

### *B. Softness Experiments*

As previously stated, humans are said to be able to detect the softness of a surface judging from the relationship between sensory output and surface of the contact area. The sensor was pressed into blocks of sponge with different stiffness. From the output of the five strain gages, the variance of the output was calculated. Results are shown in Fig. 8. Here, the smaller the result, the little difference there is in the output of each sensor, which suggests the smaller




(c) Aluminum

Fig. 10 Spectral analysis of material surface

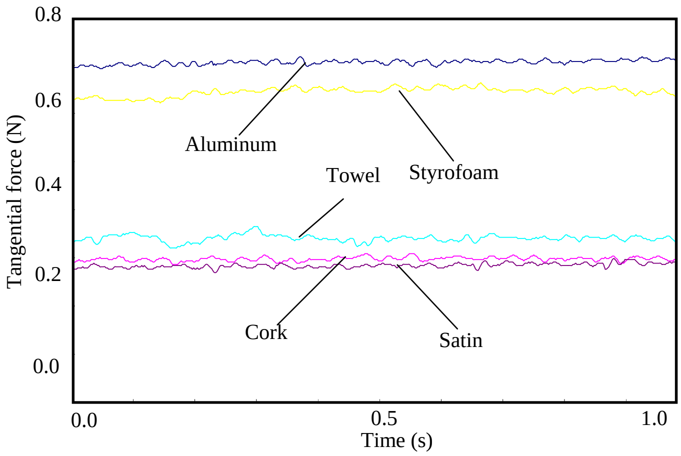



Fig. 11 Tangential Force when touching different material

the result, the softer the sponge. This can indeed be said of the experimental results

## C. *Friction Experiments*

Using the developed sensor, the measured tangential force can be considered a source in evaluating friction. However, the definition of friction itself is very complex, and material properties and the shape of the surface both affect what we would feel as friction. It is hard to evaluate the sensor using different materials since various components of the material property would take part in explaining friction, and setting constraint conditions is impossible. Therefore, here we looked at the tangential force output during the first experiment, changing the surface form. The larger the ridges, the more friction a human hand tends to feel. As illustrated in Fig. 9, tangential force that was generated during the experiments was greater at larger wavelengths and the output seems to relate to the dynamic friction coefficient of the subject material. There was also a difference in the gradient of tangential force when the sensor started to move. This can be thought of as correspondent to the static friction coefficient.

As shown in this section, the developed sensor could identify the difference in roughness, softness and friction. Therefore, we believe this sensor has the potential to detect accurate texture information quantitatively.

# V. Texture Perceptual Experiments

Having proven the effectiveness of the proposed texture sensor, we finally conducted texture perceptual experiments using different types of actual material.

Aluminum, cork, satin, denim, towel, styrofoam and an acryl board were used as subject material. The sensor was run along the surface at a speed of 2cm/s. Some of the results of spectral analysis are shown in Fig. 10. These results show that the sensor could indeed obtain information indicating the difference in roughness of the surface. Fig. 11 illustrates the tangential force generated while touching the material. You can see that rough material such as styrofoam and towel generated greater tangential force, where as satin and cork, with less roughness, exhibited little tangential force. However, aluminum generated the largest tangential force. This is because adherence occurred between the rubber surface of the sensor and the aluminum. By combining the results from Fig. 10 and Fig 11, we can accurately determine what kind of surface the sensor has touched. Please note that the information from the sensor shown here shows the roughness of a surface *while* it is touching the surface. Extremely precise measurement of the shape of a surface can be done using other laser measurement devices, however, when handling soft material, the material will deform, and even the same material may feel different depending on the pressing force.

## VI. CONCLUSIONS

In this paper, we have discussed the mechanism of texture perception of humans, and the features of the human finger. Based on this knowledge, a novel type of texture sensor has been developed, to realize quantitative evaluation of a texture surface. Experimental results have shown the developed sensor can derive accurate information such as roughness, softness, and friction of the object it is touching, and is capable of determining texture through data analysis.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