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How tactile sensors should be?

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1. Introduction

Tactile sensation consists of sensory information at a contact status between human and the other environment. The contact status draws some physical phenomena. The tactile sensor has to record the sensory information, so the sensor should record these physical phenomena. The physical phenomena of the contact point are listed as follows; deformation, stress, temperature, and time variation of these information.

When human touch some environment the human finger will be deformed according to the pressed force and the reactive stress from the environment. The deformation and the stress are linked together and occur according to the Young's modulus and the Poisson's ratio of materials of the finger and the environment. If the materials can be assumed to be the total elastic body, the deformation and the stress can be linked by the linear elastic theory.

Because there exists no total elastic body, the link between the deformation and the stress is a little complex. The complexity is enhanced when the contact state is changed according to time. For example, the human moves his finger toward the environment or touch a vibratory environment, the environment may return the damper or mass property with the change of movement speed or acceleration. The most characteristic example is a dilatants phenomenon. A dilatants material is one in which viscosity increases with the rate of shear.

As a simple environment model, there exists such an impedance model;

$$F(x) = k(x - x_o) + d\frac{dx}{dt} + m\frac{d^2t}{dt^2} \tag{1}$$

By using this model the authors have proposed an environment recording system (Saga, et al. 2005). However the model is only for one point contact movement, so it cannot express the distribution of the deformation.

That is the reason why many sensors assume the materials as total elastic or rigid body and measure the deformation or stress by using some physical principles.

In the temperature domain, a governing physical equation is a diffusion equation. The key points of the thermal flow are the thermal difference between the finger and the environment, area distribution of contact surface, and thermal conductivities of both the finger and the environment. The existing thermal sensors are only measuring the current temperature. Neither contact area distribution nor thermal conductivities is measured. The lack of these information make the displaying of temperature difficult.

Source: Sensors, Focus on Tactile, Force and Stress Sensors, Book edited by: Jose Gerardo Rocha and Senentxu Lanceros-Mendez,
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2. Tactile sensors in human

Human has some receptors beneath his/her skin. The known receptors are listed as follows; mechanoreceptors, nociceptors, thermal receptors, and muscle and skeletal mechanoreceptors. Each receptor has its own distribution and network; e.g. lateral inhibition. So the mapping and the network of the sensor is also important for tactile sensation.

2.1 Cutaneous receptors

First, there are some receptors in human skin (Kandel, et al. 2000) (Fig. 1). As mechanoreceptors there are Merkel cells, Meissner's corpscules, Pacinian corpuscles, and Ruffini endings. As nociceptors there are mechanical ones, thermal-mechanical ones, and polymodal ones. As thermal receptors there are cool receptors, warm receptors, heat nociceptors, and cold nociceptors. In addition, as muscle and skeletal mechanoreceptors, there are muscle spindle primary, secondary, Golgi tendon organs, joint capsule mechanoreceptors, stretch-sensitive free endings. By using these receptors human translate the physical phenomena to some electric signals.

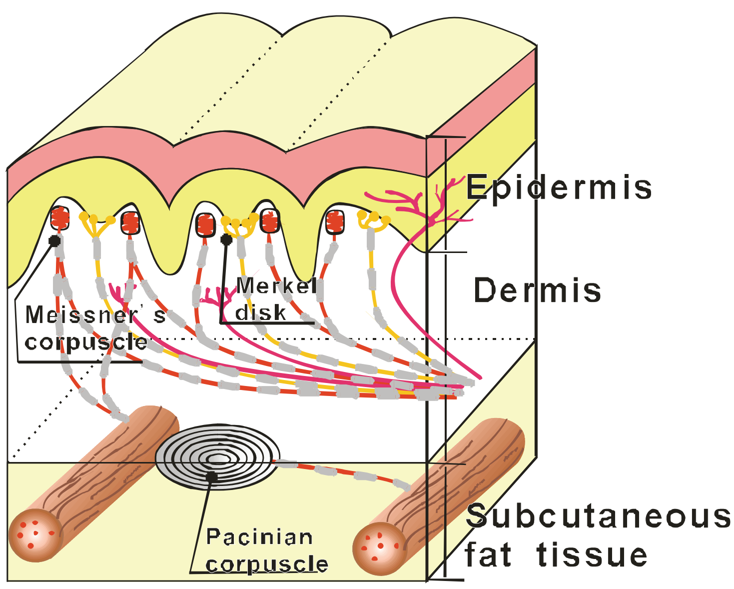

Fig. 1. Structure of skin (adapted from Kandel, et al. 2000)

Each receptor has its own unit density and responsibility. For example, the mechanoreceptors which measures mainly deformation and stress distributions have various densities and responsibilities. Merkel disks have its responsibility about 5 - 15Hz and has 70 units/cm square distribution, Meissner's corpuscles have its responsibility about 20 - 50Hz and has 140 units/cm square distribution, and Pacinian corpuscle have its responsibility about 60 - 400Hz and has 20 units/cm square distribution (Fig. 2).
These density and responsibility suggests that human processes the higher frequency signals with not so high density, but processes the lower frequency signals with high density.

2.2 Networks of receptors

In addition, each receptor has its own networks in the cortex, dorsal column nuclei, ventral posterior lateral nucleus of the thalamus, or cortex itself.
For example, there is convergent excitation, Surround inhibition, and lateral inhibition.

- Convergent excitation
- Surround inhibition
- Lateral inhibition

By using these networks parallel processing is exerted. Through the process the simple many signals became more extracted meaningful some signals.

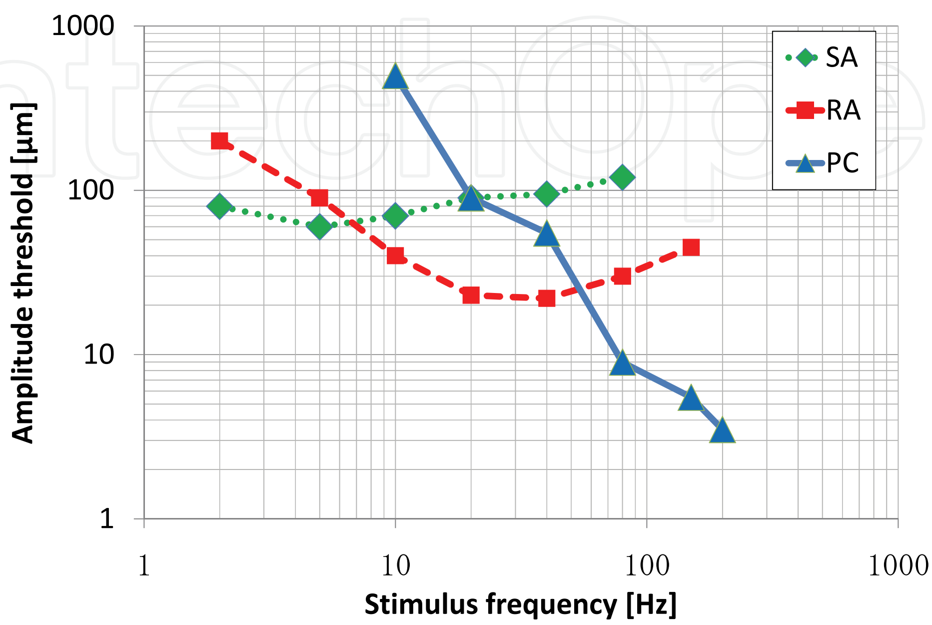

Fig. 2. Responsibility of each receptors (adapted from Freeman & Johnson, 1982)

2.3 Additional sensation

Furthermore, from clinical psychology's view, some sensations, such as pain, itchy, tickle, feel good, have their special dimension. Each of them is linked to one another, so the sensory information is more complex than what the conventional sensor can acquire. In order to detect and record and transmit tactile sensation of human, the tactile sensor should also have these complex sensitivities.

2.4 Feedbacks from cerebella

The complexities of these sensations are mainly caused by the cerebral feedbacks. These sensations are strongly affected by the emotion, knowledge or other information. These information also change the sensing ranges dynamically. In addition, as sensor hardware, the wirings of the sensors are also important for these sensations.

For example, the signals of pain sensation has time lag. These are the first pain and the second pain. The difference between the two is the transmitted path and the transmission speed. The first pain use A δ fiber which has myelin sheath, 13 - 22 µm gauge, and 70 - 120 m/s transmission speed, the other hand the second pain use C fiber which doesn't have myelin sheath, 0.2 - 1.0 µm gauge, and 0.2 - 2.0 m/s transmission speed.

By Melzack & Wall the gate control theory has been proposed according to these difference of transmission speed (Melzack & Wall, 1962). When the information is captured by the skin the signals are transmitted by between Aδ and C fiber and go into the spain. First, the signal going through Aδ fiber is transmitted toward the cerebellum. The arrival of the signal induces the search of memory. The processed information is transmitted to the T cell in the

spinal dorsal corn, and closes the gate of C fiber. Then the information of pain becomes difficult to be transmitted to the spine.
In tickle sensation, self tickling is not effective. This is because human uses his efferent copy in his tickle sensing. That is, the efferent copy is also a part of sensing information.

3. Conventional mechanical sensors using physical principles

3.1 Force sensors

Conventional tactile sensors have been created from some principles of physics. They record the phenomena of the contact status using some physical principles. In order to record the deformation or stress information, many tactile sensors have been developed. Strain gauge, piezoelectric effect, pressure sensitive rubber, diaphragm, photometric pressure gauge, and SAW force sensor, et al.

3.1.1 Strain gauge

A load cell usually uses a strain gauge. Through a mechanical arrangement, the force being sensed deforms a strain gauge. The strain gauge converts the deformation (strain) to electrical signals. The electrical signal output is typically in the order of a few millivolts and requires amplification by an instrumentation amplifier before it can be used.
A strain gauge takes advantage of the physical property of electrical conductance's dependency.

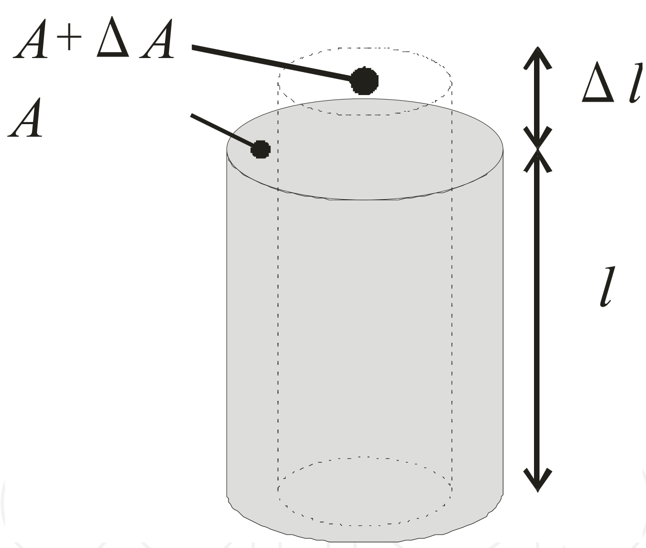

Fig. 3. Deformation of a conductor

$$R = \frac{\rho l}{A} \tag{2}$$

By differentiate the equation, we get

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta l}{l} - \frac{\Delta A}{A} \tag{3}$$

$$= (1 + 2\sigma)\frac{\Delta l}{l} \tag{4}$$

ρ: Resistance ratio,
R: Resistance value
l: Length
A: Cross section
σ: Poisson's ratio
This (1+2σ) is called as gauge factor.

3.1.2 Piezoelectric device

A piezoelectric device uses a piezoelectricity effect. Piezoelectricity is the ability of some materials to generate an electric potential in response to applied mechanical stress. That is, this effect translates the strain information toward electric voltage. A PVDF also has a piezoelectricity. By using this characteristic some force sensors are created.

$$\frac{\Delta\rho}{\rho} = \pi E \frac{\Delta l}{l} \tag{4}$$

With the equation (2) and (4) we get;

$$\frac{\Delta R}{R} = (\pi + 1 + 2\sigma)\frac{\Delta l}{l} \tag{5}$$

π: Piezoresistance coefficient,
E: Young's modulus
This (π+1+2σ) is called as gauge factor.

3.1.3 Pressure sensitive rubber

A pressure sensitive rubber has been developed for the sheet-switch of the electronic circuits, and has a unique property in that it conducts electric current only when compressed, and acts as an insulator when the pressure is released. This patented material is a composite of an elastomer and specially treated carbon particles, and is available in gray-black flexible sheet form, 0.5 mm in thickness.

3.1.4 Optical diaphragm

There is an interferometer sensor with optical diaphragm. Using the micro electro mechanical system technology the sensor has been made.

3.1.5 SAW force sensor

A SAW (Surface Acoustic Wave) force sensor measures the force in the frequency domain. If the force is applied to a SAW device, the phase shift occurs on the SAW signal. By recording the frequency shift the sensor can measure the force.

3.2 Thermometer

In general use, thermometer is not treated as tactile sensor. However temperature is also important information for tactile sensation. There are some contact type thermometers that are able to use as a tactile sensor; e.g. bi-metal, thermistor, thermocouple, thermal-diode, and optical fibers, et al.

3.2.1 Bi-metal

A bi-metal is a thermal dilation type sensor. This sensor is made of two kinds of metals which have different thermal dilation modulus. By the roll bonding of these metals this device can deform with thermal changes.

3.2.2 Thermistor

A thermistor is a type of resistor with resistance varying according to its temperature. With a first-order approximation, the relation depends on the equation;

$$\Delta R = k\Delta T \tag{6}$$

ΔR = change in resistance
ΔT = change in temperature
k = first-order temperature coefficient of resistance

3.2.3 Thermocouple

A thermocouple is a thermal electromotive force type sensor. When any conductor is subjected to a thermal gradient, it will generate a voltage. This phenomenon is known as Seebeck effect. Thermocouples measure the temperature difference between two points, not absolute temperature. In traditional applications, one of the junctions—the cold junction—was maintained at a reference temperature, while the other end was attached to a probe.

3.2.4 Thermal diode

A thermal diode is a semiconductor junction type device. The p-n junction has 1 - 2 mV/K voltage drop characteristic. By using this phenomenon the temperature is measured. By keeping the electric current to constant and by using the relation between the orthodromic voltage and current the sensor can measure the temperature.

3.2.5 Thermometer using optical fibers

An optical fiber can be used as a thermal sensor, too. There are two types of thermal sensor using an optical fiber. One is an interferometer type thermal sensor, and the other is a polarization type thermal sensor. An interferometer type sensor is using the phase shift against the thermal changes. A polarization type sensor is using double refraction characteristic and the refraction index is changed by the thermal changes. By monitoring the oblations the sensor can measure the thermal changes.

3.3 What is measured by conventional tactile sensors?

Conventional pressure /force/thermal sensors measure information by using some physical laws. These laws are mainly linked to electronic signals. Some of them use resistance shift and the others use electromotive force shift. This is because the signals are easily picked up by the electronic signals and integrated with other actuators. A few of them uses optical fibers for the safety of electric free system and for the accuracy of measuring. The sensors which use electronic signals has amplification problem in itself. This is because the acquired original electronic signals are often small and S/N ratio may be problem. The optical systems are free from these electronic amplification problems in itself.
Though the sensors are useful for the tactile sensor in part, the sensors are not designed for the tactile sensor. So there are some defects for tactile sensor. In the next session we talk about the defects of conventional sensors as tactile sensors.

4. Required ranges for tactile sensors

Previously discussed sensors have not enough ability for tactile sensor. This is partially because the range of the sensor is not enough. For the tactile sensing, we should not consider the sensor based on some physical principles but the sensor design based on the required functions. There are at least three lacked range, the lack of the spatial distribution, frequency distribution, and force distribution.

4.1 Spatial distribution

The spatial distribution means that the tactile sensation has two dimensional sensing distributions. The tactile itself is a boundary between human and the environment. Based on simple topology, the boundary of human whose body has three dimensions must be two dimensional distributions (Fig. 4). Many conventional sensors only measures force/temperature toward one point. This is because the sensor is not developed for the tactile sensor, and the applications often require only one point sensing information. However, in order to detect the changes of environment toward human, position information is also very much important. If there is some large pressure/thermal change information without position, human can detect the hazardous information but cannot understand which way he/she should escape (Fig. 5). In smaller range if there is rubbing movement of some object on the finger, human can detect some time varying information without position information (Fig. 6). Though he/she can detect the changing information, he/she cannot detect the direction of the movement of the object. Without the spatial information human cannot detect the changing direction of the signals.

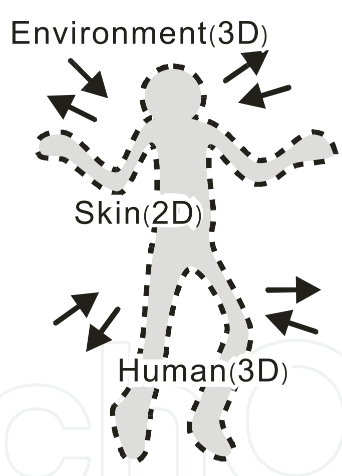

Fig. 4. Topology of human, environment and skin

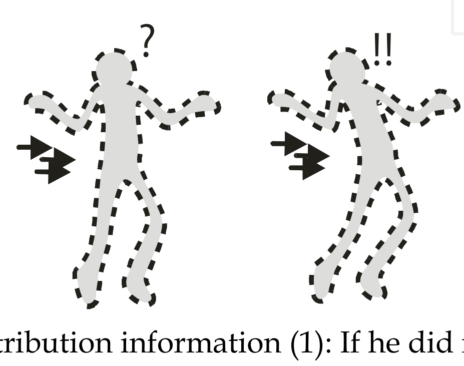

Fig. 5. With/without the distribution information (1): If he did not know the position of the hazardous information, he cannot understand which way to escape.

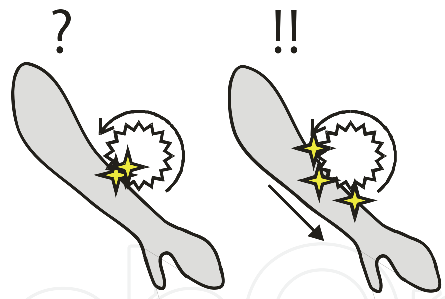

Fig. 6. With/without the distribution information (2): If he didn't acquire the position information, he cannot distinguish which movement occors.

Of course some distributed tactile sensor exists. For example, Pliance (Novel corp.), Tactilus seat type sensing (Sensor Products LLC.), and Flexi force (Nitta corp.). These are composed of small sensors unit and arranged in two dimensional arrays (Fig. 7). They can measure the distribution of added forces. Each of unit is independently connected. To analyse the contact state by many methods from the input data, the independency of the signal is useful. If we use these devise for tactile sensing application, the independency may cause some problems. In creating phase, the number of wirings may be a problem. In measuring phase, because of the independency there is no network for signal processing. In order to acquire the position or movement information, we have to integrate and analyse the information after acquiring the input.

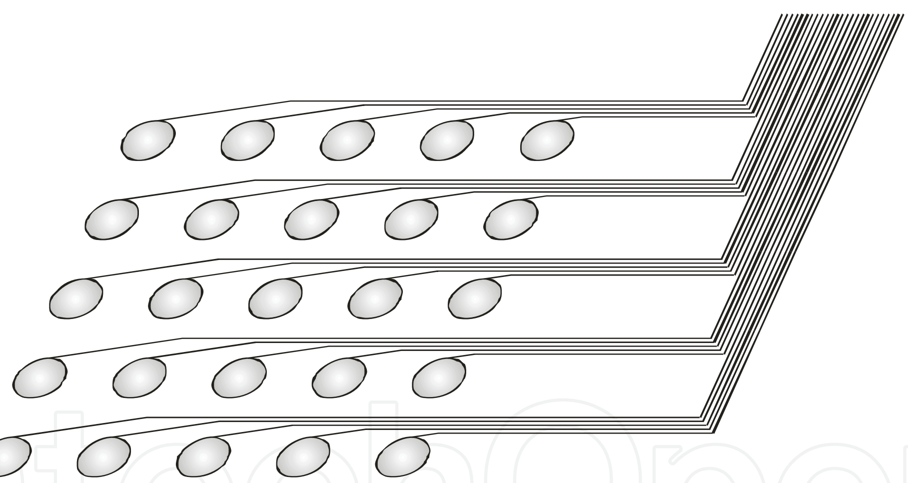

Fig. 7. Array type tactile sensor (ex. Pliance (Novel corp.), Tactilus (Sensor Procucts LLC.), Flexi Force (Nitta corp.))

4.2 Frequency distribution

The frequency distribution means that, from the figure 2, the receptors of human have their own responsibility toward frequency domain. For example, Merkel disks have their responsibility about 5 - 15 Hz, Meissner's corpuscles have about 20 - 50 Hz and Pacinian corpuscles have about 60 - 400 Hz. From this fact the tactile sensor should be able to measure at least the range of 0 - 400 Hz. Many kinds of conventional tactile sensors have such measurement range. So the frequency distribution seems sufficient for the tactile sensor. This is because the sensor often measures only one point. Sampling with few points will make the responsibility of the sensor faster.

4.2.1 Information transfer problem

If we treat the frequency distribution and the spatial distribution at the same time, the frequency distribution becomes difficult problem to solve. Though the ability of the sensors toward the frequency distribution is high, the multiple sensors arranged in two dimensional arrays requires some data collecting method, such as scanning or matrix switching.
Methods of acquiring two dimensional discrete data are critical for frequency distribution. Simple scanning method requires $n \times n$ ordered wirings and $n \times n$ switching device. Matrix switching method requires $2n$ ordered wirings and $n \times n$ switching device. Each method requires $n \times n$ ordered scanning speed. This is because each method aims to get all of the acquired information.

4.2.2 Imaging devices for information transfer

Here, the imaging device also has such switching technology, CMOS (Complementary Metal Oxide Semiconductor) imaging sensor and CCD (Charge coupled device) imaging sensor. CMOS imaging sensor is known as an active-pixel sensor (APS), also commonly written active pixel sensor. It is an image sensor consisting of an integrated circuit containing an array of pixel sensors, each pixel containing a photodetector and an active amplifier. There are many types of active pixel sensors including the CMOS imaging sensor used most commonly in web cameras. This imaging sensor is produced by a CMOS process, so it is also known as a CMOS imaging sensor. Because of its simplicity CMOS imaging device can realize block scanning. By separating the imaging area to some blocks, the device can scan each block simultaneously. In recent years Sony Inc. create fast scanning chip by specialized design (Barth, et al. 2007). CCD itself is an analog shift register, enabling electric charges to be transported through successive capacitors controlled by a clock signal. Charge coupled devices can be used as a form of memory or for delaying analog, sampled signals. By using this device CCD imaging sensor is created for serializing parallel analog signals.

4.2.3 Other novel devices for information transfer

Another communicating device, Two-Dimensional Signal Transmission (2DST), is developed by Shinoda, et al (Shinoda, et al. 2007). This device realizes the communication between each element without wiring them independently. The device is made from some layered conductive sheets and by using microwave confined around the surface it realize the low power and high security communication. This technology is designed for the use of tactile information, and now developing. By using the special transmitting protocol, this device may realize high speed transmission of information and compression technology.
Some methods are compressing sensing information without losing important aspects for tactile information. The soft tribo-sensor using PVDF Film is created by Jiang, et al (Jiang, et al. 1999). Though this sensor has only one dimensional measurement point, it can measure high frequency pressure change. By scanning the sensor itself on skin surfaces, it can measure the difference of them. Another thin and flexible tactile sensor is made of ordinal pressure-conductive rubber, though, the wirings of the sensor is very few (Shimojo & Ishikawa. 1990). Furthermore the sensor itself is flexible sheet. These sensors have been used as skins of some robots. The measurement information of the sensor is limited only the position of center of mass and the mass itself. By limiting the information the sensor require only four wirings for each area. For example, manipulation of some object with robot arm requires only this information. That is, the application decides the required information of the sensor, so the limitation of information matters little.

4.3 Force distribution

4.3.1 Range, dimension and material

The force distribution means that tactile sensor should measure the required force range and force vectors. Some sensors have their specific sensing ranges owing to their physical law.

If the physical law define the range which is different from humans' one, we have to prepare many types of sensing devices for the sufficient human sensing range. So the sensing method itself should not define the range. The ideal sensor should have enough range for human. However there is still no such sensor in the world. The second best sensor is a range changeable sensor by designing the sensing element without changing the sensing method.

The force vector information is also important. A force (F)/torque (T) toward one point has three dimensional components, F_x, F_y, F_z, T_x, T_y and T_z. Some conventional sensors can measure such information on only one point, but the spatial and force distribution occurs simultaneously. So the ideal sensor should measure the distribution of force vectors.

Additionally the sensor itself should have near or the same characteristics of material with the human. For example, Young's modulus, Poisson's ratio and friction coefficient are important aspects for the sensed information. This is because the stress and the strain are indivisible. So the sensing information between by strained sensing surface and by unstrained sensing surface is different. Furthermore, the friction coefficient also should be the same between the sensor and human. The most important thing in the tactile sensing is that the reproduction of the same contact state between the contact by the sensor and the contact by human skin.

4.3.2 Some devices for force distribution

Here Kamiyama, et al. proposed a tactile sensor called GelForce (Kamiyama, et al. 2005). The sensor is made of silicone rubber and imaging device. Inside the silicone rubber there is two layered marker patterns. By capturing the displacement of the markers with the imaging device, it can reconstruct the measured information. In the previous section the imaging device has well switching technology, so the use of imaging device is proper for the two dimensional sensing. The sensor can measure the force and spatial distribution simultaneously. It measures two dimensional distributions of three dimensional forces (x, y, z) and three dimensional torques (x, y, z). Furthermore the simplicity of the component of the sensor with silicone rubber, the responsibility can be changed easily. With this feature it realizes almost the same characteristics of material with human. The authors also research the similar sensor, named reflection-type tactile sensor, with the use of silicone rubber and imaging device (Saga, et al. 2007) (Fig. 8). The sensor can measure the displacement of the

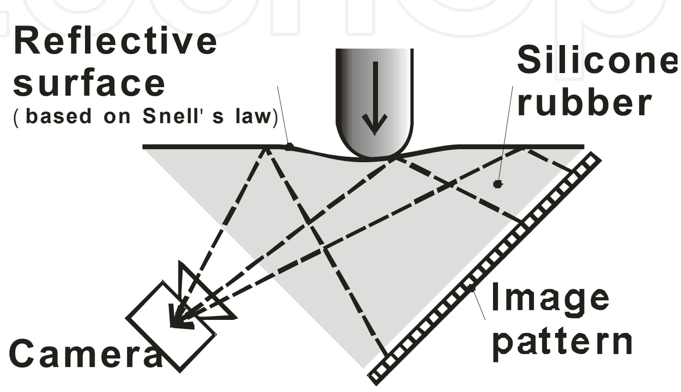

Fig. 8. Reflection type tactile sensor (Saga, et al. 2007)

sensor surface by using the total reflection of the contact surface. According to the use of the reflection image, the sensor realizes high resolution sensitivity and can detect 0.01 mm displacement of sensor surface. The same with the GelForce, the sensor can design the characteristics of the material.

4.4 Every distribution requires?

Though each of the distribution still cannot be combined now, the combination of these ranges will open the new sensing features (pain, itchy, tickle, and feel good) for the tactile sensor. Additionally, the important aspect of the tactile sensation is as follows. However we cannot compose perfect sensor with these distributions, we should well consider the application of the sensor and design it. Again, the application decides the required information of the sensor, so the limitation of information matters little.

5. Active touch for tactile sensors

The activeness of touch plays an important role (Gibson, 1962). This is a very much different thing from other sensation, such as vision and auditory. The tactile sensation uses not only the sensing information itself but also the efferent copy of arm/hand/finger movement.
In augmented reality researches, this sensing and efferent copy is more clearly examined. Nojima, et al. proposed the tool for augmented reality, SmartTool, by using a real time sensor and a haptic device (Nojima, et al. 2002). The sensor on the SmartTool measures the real environment, and the tool send the user the captured information through haptic sensation. The sensors are on the tool tip and it is the same point as the working point of the tool. Therefore, this device realizes "What the Sensors Detects is What the Tool Touches" (Fig 9, 10). So the sensing information and the efferent copy of user are integrated naturally. This discussion of active touch should be applied to tactile sensors.

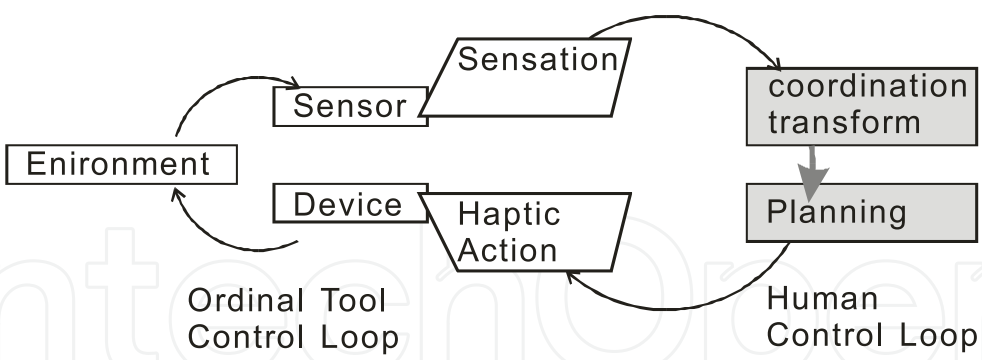

Fig. 9. Loop with ordinal tool: For human sensation and display is not the same point

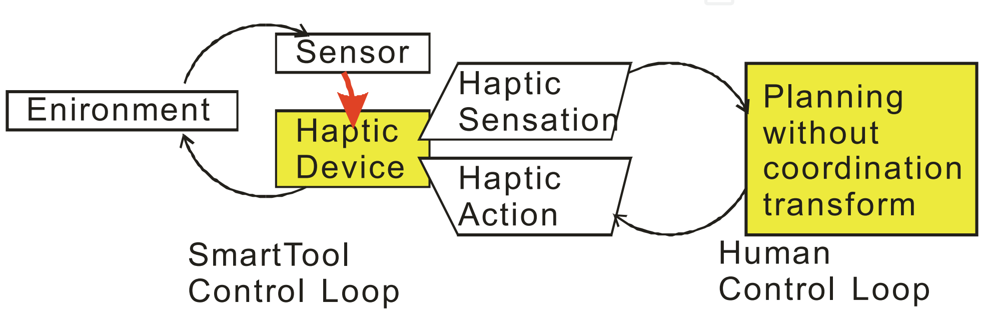

Fig. 10. Loop with SmartTool: For human sensation and display is the same point

5.1 Simultaneous sensing and display

In order to realize the active touch, sensing and display should be carried out simultaneously. (Here, the directions of sensing and display are to both environment and human in augmented reality. However to simplify the discussion we consider the direction only to human.) Furthermore, the most different thing of tactile sensation from other sensory information is their bilateral input/output. If someone touches something, the thing will always touch him/her. Touching and being touched occurs simultaneously. That is, the sensor itself has to be the display of tactile information simultaneously. In case of haptic device like SmartTools, the simultaneous sensing and display is realized by using rigid tool (Fig. 11). Because the rigid tool expands the force position to its body, the sensing point and displaying point can be separated.

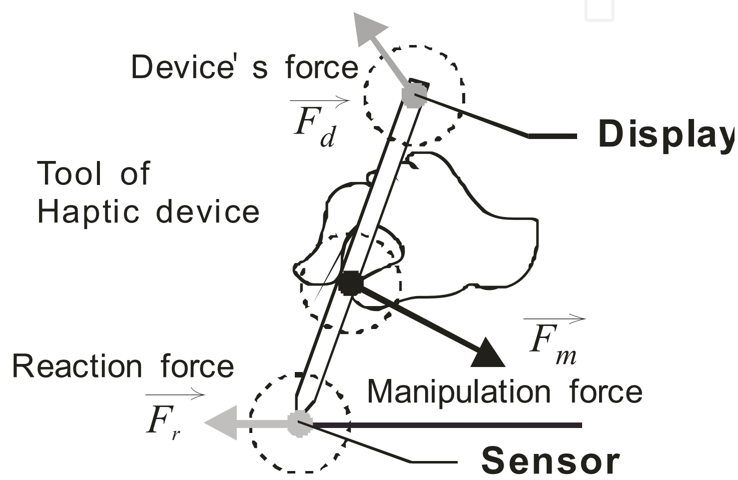

Fig. 11. Sensor & display of SmartTools

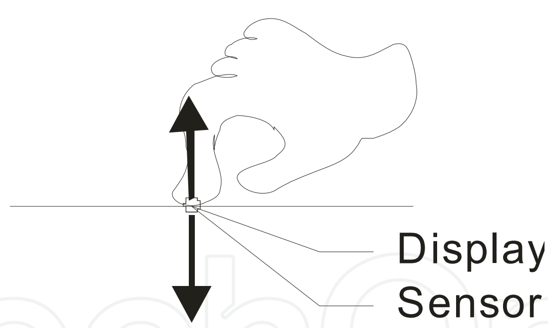

Fig. 12. Sensor & display of tactile device

However such devices are difficult to create for tactile device. This is because the contact phenomenon itself occurs in two dimensional surface. If sensor touched to some object from one side of the surface, there is no space left for the display (Fig. 12). The sensor side, there is a sensor arrays and the object side there is an object. If the sensor is created to be sparse and the displaying element is placed, the sensing and display can be realized at almost the same position simultaneously. However the resolution of sensing and displaying becomes sparse and the position is not “precisely” the same, but “almost” the same. The precise realization of simultaneous sensing and displaying is difficult in principle. So the different way of sensing technique should be realized.
In previous section, there is some new type of sensors using imaging device. These sensors are using the diffused light from the markers. So the sensing surface is free from some

mechanical devices. Especially the reflection-type tactile sensor has only transparent silicone rubber at the sensor surface. The only important things are the transparency and the deformability. So the sensor can use the transparent functional fluid such as Magneto-Rheological fluid. It may realize the sensing and displaying simultaneously at precisely the same position.

5.2 Simultaneous sensing and display

The ideal tactile sensor may be like a mirror for contact object (Fig 13). The mirror can deform and change its hardness and contact with some object with ideal shape and softness. When the contact object changes its pressure, the mirror can change according to the change of pressure. In these days there is still no such device, but the development of such device will create the new world of communication.

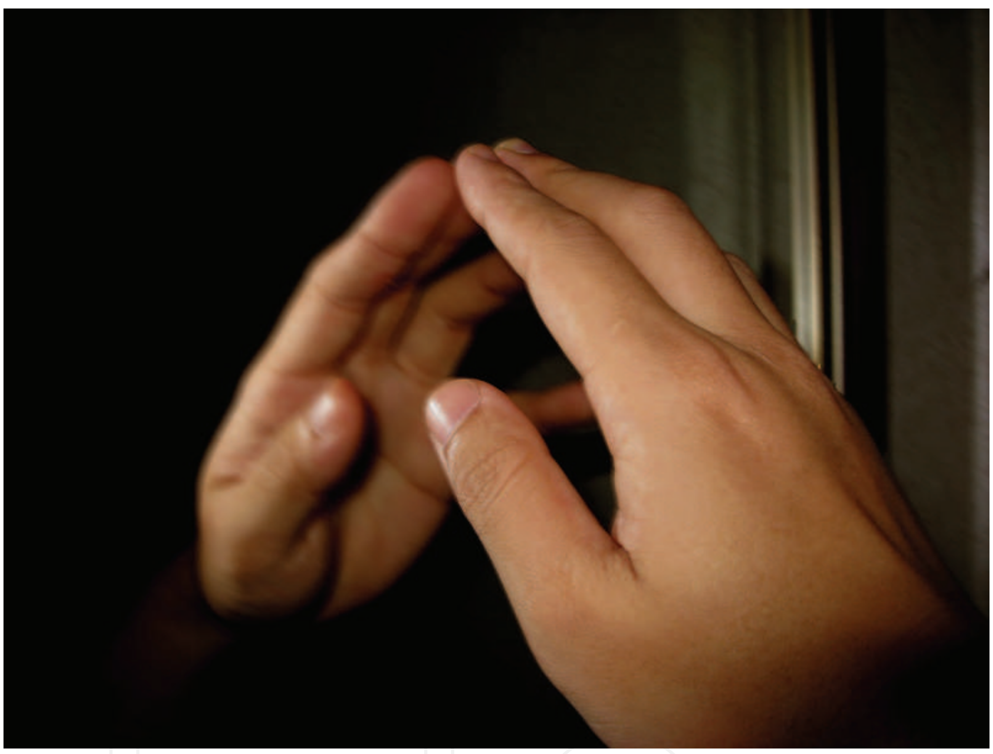

Fig. 13. Ideal tactile sensor/display?

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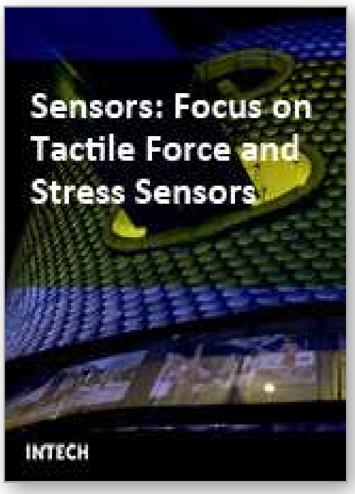

Sensors: Focus on Tactile Force and Stress Sensors
Edited by Jose Gerardo Rocha and Senentxu Lanceros-Mendez

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This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.