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Haptic Recognition System with Sensory Integration and Attentional Perception

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Abstract — The authors constructed a haptic recognition system which discriminates feel of touch based on the principles of sensory integration and attentional perception. The system is equipped with several sensor devices and can push and rub the object's surface with several values of force and speed. It integrates the sensory information iteratively with selecting appropriate sensors and measurement conditions according to the proceeding of the recognition. The algorithms of sensory integration and of attentional perception are realized by Bayes inference and by an iterative experimental design based on an information criterion, respectively.

The experimental result shows that the system can discern a subtle difference in feel of touch. It is also proved that the system selects appropriate sensors and conditions according to the situation, that is, the attentional perception algorithm realizes good recognition accuracy with fewer observations. In addition, it is shown that the characteristics used in the system correspond well to those human beings utilize in haptic perception. These results suggest that the constructed system is a faithful model for the human haptic mechanism.

I. INTRODUCTION

We human beings perceive objects not only by integrating various sensory information but also by choosing appropriate observational actions according to our purpose. Such sensory integration and attentional perception[†] are fundamental mechanisms of human sensory information processing [1], and a number of intelligent systems have been proposed based on these principles [2, 3, 4].

When perceiving an object by touch, for instance, we utilize information from mechanical receptors, thermal receptors and proprioceptive receptors buried in our bodies. In addition, we observe the surface of the object through various finger movements, such as touching, pushing and rubbing. The integrated sense brought by these observations is called "haptics", in distinction from "the tactile sense" which is concerned only with mechanical stimulus to the skin. As we can see from this definition, the mechanisms of sensory integration and attentional perception play essential roles in haptic perception [5, 6].

In light of such characteristics of haptics, the authors built a haptic recognition system which integrates appropriate sensory information selectively and simulates human haptic perception process [7].

Most of the conventional tactile sensors have been designed for detecting contact with objects or collision with obstacles. That is, their sensing principle is just confined to the field of "the tactile sense". This is because people tend to regard "the sense of touch" as a means to notice "contact with other things". In order to simulate the human haptic process, however, it is necessary to realize a sensing system based on the principles of sensory integration and attentional perception.

Here, it should be noticed that there are two purposes in this research. One is to construct a sensing system based on the principles and to prove their effectiveness in the actual system. The other, which is more significant, is to clarify the mechanism of human sensory processing with the approach of "analysis by synthesis": If the behavior of the constructed system resembles that of humans, it can be regarded that the mechanism of human sensory processing is elucidated in principle. In order to verify whether the behavior of the constructed system is similar to that of humans, the authors construct a representation of feel of touch based on the characteristics utilized in the system and examine whether the representation reflects the human feel of touch.

In the following, the authors give a brief outline of biological findings on haptics and summarize the points of realizing a haptic recognition system in Sec. II. The structure of the constructed system and the algorithm of attentional perception are explained in Sec. III. Section IV describes the performance of the system and the results of comparative experiments on haptic representation.

[†] This may be called "active perception" in general. However, the authors prefer "attentional perception" because the authors would like to put an emphasis not on making actions in observing the object but on paying an "attention" to certain sensory information according to a purpose.

II. BIOLOGICAL FINDINGS AND THEIR SUGGESTIONS

A. *Characteristics of Receptors on Haptics*

First, let us survey the characteristics of mechanical and thermal receptors in the human skin.

There are about 17,000 mechanical receptors distributed over a human hand [8]. They are divided into two groups according to the adaptation to the sustained stimulus to the skin. One is called "slowly adapting (SA) type", which responds continuously during the stimulus, and the other is called "rapidly adapting (RA) type", which responds only to the onset and offset of the stimulus.

Each group is further divided into two types according to the size of receptive field: Type I has small (2–4 mm in diameter) receptive field whose boundaries are clear. To the contrary, the receptive fields of type II receptors are larger and their boundary are vague. The density of type I receptors varies according to the position (it is the highest on the fingers) while that of type II is almost uniform. Table I summarizes the characteristics of these receptors.

As for the thermoreceptors, there are two types of receptors, "cold fibers" and "warm fibers" [9]. They respond both to constant temperature and to change in temperature. When the temperature is constant, they show static responses which forms a bell-shaped response curve around the optimal temperature (30°C for cold fibers and 43°C for warm fibers). For the change in the skin temperature, on the other hand, they show transient response for a few seconds and give way to a new static response. The intensity of the transient response depends on the step of the temperature change.

B. *Roles of Receptors in Haptic Perception*

The above findings give us some hints as to building a haptic sensing system.

First, mechanical receptors convey the following two kinds of information. SAI, RAI and RAII receptors detect local deformation or vibration of the skin when a finger touches or rubs the object's surface. On the other hand, SAII receptor detects shear stress of the skin. Accordingly, human beings get "microscopic deformation and vibration" from the former receptors and "macroscopic friction" from the latter one.

TABLE I

CHARACTERISTICS OF MECHANICAL RECEPTORS

Type	Receptor	RF	Optimal Stimulus
RAI	Meissner corpuscle	Small	Vibration of 40Hz
SAI	Merkel cell	Small	Sustained pressure
RAII	Pacini corpuscle	Large	Vibration of 100–300Hz
SAII	Ruffini ending	Large	Shear stress

The density of the receptors gives an interesting suggestion. It is about 150 receptors/cm^2 on the index finger where it is the highest. This means that there exists only one receptor in each 1mm^2 at most. Nevertheless, human beings can tell a subtle difference in texture by touch.

This fact suggests that such delicate discrimination is not realized from the information of static contact to the object's surface: Instead, dynamic stimuli such as vibration and friction during finger movements are essential.

In addition, we choose appropriate finger movements according to what property we want to know. When we want to know whether the object is rough or smooth, for instance, we rubs the surface of the object. When trying to know whether the object is hard or soft, on the other hand, we push the object and observe its deformation. Moreover, our finger movements changes as the recognition proceeds.

Above discussion can be summarized as follows:

1. It is essential to utilize sensors which detect various dynamic stimuli to the skin. Static sensors are of no use even if their density is high.
2. Efficient recognition can be realized by selecting appropriate observational movements according to the purpose and the proceeding of recognition.

As for thermoreceptors, the transient change in the skin temperature is useful for material discrimination because it reflects thermal capacity and conductance of the objects. However, it cannot be definite key to the discrimination since it depends not only on the material but also the absolute temperature of the object. It seems to play a supplementary role in reducing the candidates in the process of recognition.

Feelings of reaction seems to be another key to haptic perception. However, it is not discussed to the detail here.

III. HAPTIC RECOGNITION SYSTEM

A. *System Structure*

Based on the consideration in the previous section, the following actuators and sensors are required to simulate the human haptic process.

1. An actuator which applies various force to the object.
2. An actuator which rubs the surface of the object.
3. A sensor for detecting contact with the object.
4. A sensor for measuring vibration when the system rubs the object.
5. A sensor for measuring shear stress when the system rubs the object.

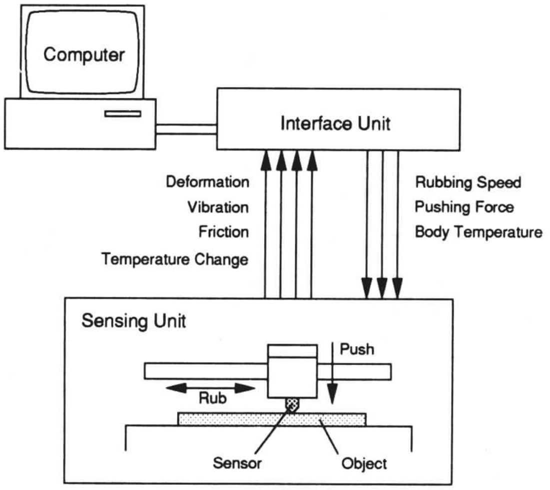


Fig. 1 Schematic Structure of Haptic Recognition System

6. A sensor which catches deformation when the system pushes the object.
7. A sensor which catches the change in temperature of the sensor.

The authors designed and built a system equipped with these mechanisms. Fig. 1 shows the general scheme of the constructed system.

The system consists of a stage and a sensor head (Fig. 2). The stage holds an object on itself and moves up and down. A load cell (force sensor) is attached at the center of the stage and monitors the force to the object's surface. A potentiometer under the stage measures the displacement of the stage.

The sensor head slides horizontally along a rail and measures the state of object's surface. It is equipped with a vibration sensor, a friction sensor and a thermal sensor (See Fig. 3).

The vibration sensor is a small microphone whose top is covered by silicon rubber. It detects the vibration of the rubber while the sensor tip rubs the object's surface. A thermistor is buried in the rubber and measures the change in its temperature. A small heater is also set on the head for keeping the temperature constant.

The head is connected to the mount by parallel links and can rotate around the mount. Leaf springs give a force to keep the head position around the center. Since the rotation angle reflects the amount of friction force between the sensor tip and the object's surface, this mechanism works as a friction sensor and is expected to simulate SAII type receptors.

The system can set the force to the object and the speed of the horizontal movement as variable parameters, and collect information through assigning appropriate values to these parameters.

The procedure of the measurement is as follows:

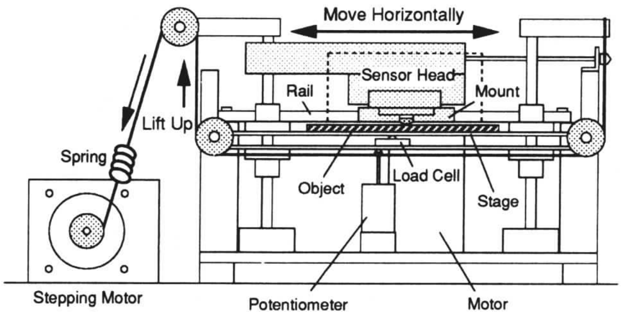


Fig. 2 System Structure

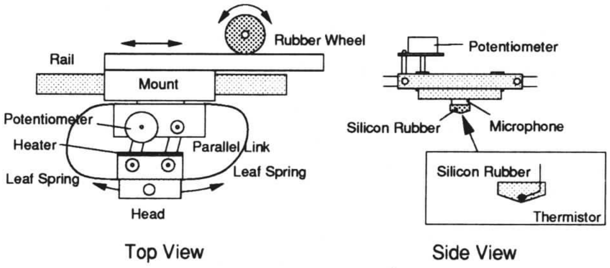


Fig. 3 Sensor Head

1. Set an object on the stage.
2. Lift up the stage until the force to the object reaches a specified value. The instant that the sensor tip touches the surface is detected by the microphone. Then, the system follows the change in temperature and observes the deformation of the object.
3. Move the sensor head at the specified speed. The microscopic vibration and macroscopic friction are measured by the microphone and by the rotation angle, respectively.

B. *Algorithm of Attentional Perception*

The recognition was performed according to the following algorithm [10].

A mathematical model to explain the algorithm is illustrated in Fig. 4 . This model consists of a sensory part, which receive signals from the object through various sensors, and a perceptual part, which integrates the sensory signals and forms the "internal image" of the object. It should be noted that the "sensors" in this model do not correspond to physical sensors but to observation methods. That is, the output of each sensor means a signal which the system observes the object in a certain manner. When the system utilizes an identical sensor in various manners, therefore, each manner is regarded as a "sensor". In the following, it is assumed that the perceptual part selects the sensors one by one and forms the internal image iteratively.

Based on this model, an algorithm of sensory integra-

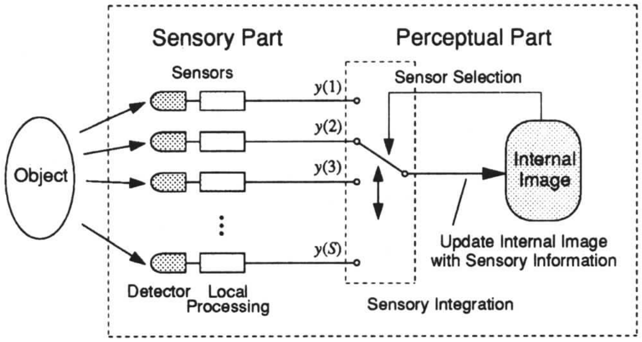


Fig. 4 Mathematical Model for Attentional Perception

tion can be formalized as follows.

Take an internal state space Ξ as a set of objects and put a probability $\pi_t(\xi)$ to each element $\xi \in \Xi$. The probability distribution $\pi_t(\xi)$ corresponds to the internal image after t-times observation. Let Y_s denote a set of signals $y(s)$ detected by sensor s $(= 1, 2, \cdots, S)$. The conditional probability of signal $y(s)$ conditioned on object ξ is represented by $p_s(y(s)|\xi)$. It is assumed that these conditional probabilities have been obtained beforehand and that there is no mutual interaction among the signals of the sensors.

Suppose that the system receives signal $y_t(s)$ from sensor s at time t. Then, Bayes theorem leads us to calculate the probability distribution after observation $\pi_t(\xi; y_t(s))$ as

$$\pi_t(\xi; y_t(s)) = \frac{p_s(y_t(s)|\xi)}{\sum_{\eta \in \Xi} p_s(y_t(s)|\eta)\pi_t(\eta)} \pi_{t-1}(\xi). \qquad (1)$$

The system integrates information from various sensors iteratively by updating the probability distribution according to (1) and answers the object whose probability is the most as a recognition result. Therefore, the sensory integration process can be realized by Bayes inference.

Next, let us consider how to choose the sensors for recognizing objects by fewer observations. Here, the authors take the entropy of the internal state space H_t as a criterion of the proceeding of recognition:

$$H_t = -\sum_{\xi \in \Xi} \pi_t(\xi) \log \pi_t(\xi). \qquad (2)$$

Since H_t has a small value when $\pi_t(\xi)$ is concentrated on a few ξ's and has a large value when $\pi_t(\xi)$ distributes over the state space, it is a good measure of the proceeding of recognition. It should be noted, however, that this criterion does not indicate "accuracy" but "certainty": The entropy may become small even if the recognition result does not agree to the true object.

Based on this preparation, let us define a method to choose a sensor for efficient recognition. Given the system receives signal $y_t(s)$ from sensor s, the entropy after observation $H_t(y_t(s))$ is written by

$$H_t(y_t(s)) = -\sum_{\xi \in \Xi} \pi_t(\xi; y_t(s)) \log \pi_t(\xi; y_t(s)), \qquad (3)$$

where $\pi_t(\xi; y_t(s))$ is calculated using (1). It is hopeful that the system selects the sensor whose $H_t(y_t(s))$ is the smallest. However, this is impossible because $y(s)$ cannot be known before the system observes the object. Here, the system calculates the expected entropy $H_t(s)$ and uses it as a criterion:

$$\begin{aligned} H_t(s) &= \sum_{y_t(s) \in \mathcal{Y}_s} P(y_t(s)) H_t(y_t(s)) \\ &= \sum_{y_t(s) \in \mathcal{Y}_s} \sum_{\xi \in \Xi} p_s(y_t(s)|\xi)\pi_{t-1}(\xi) H_t(y_t(s)). \qquad (4) \end{aligned}$$

The system selects the sensor whose $H_t(s)$ is the smallest. The system may select the sensor whose expected decrease of the entropy is the largest, instead:

$$\begin{aligned} I_t(s) &\equiv H_{t-1} - H_t(s) = \sum_{\xi \in \Xi} \pi_{t-1}(\xi) \\ &\sum_{y_s(t) \in \mathcal{Y}_s} p_s(y_t(s)|\xi) \log \frac{p_s(y_t(s)|\xi)}{\sum_{\eta \in \Xi} p_s(y_t(s)|\eta)\pi_{t-1}(\eta)}. \qquad (5) \end{aligned}$$

This amount is called "mutual information" in the field of information theory.

In the above discussion, it is assumed that the internal state space is a discrete set. Of course, we can deal with a continuous internal state space. Especially when the probability distribution of the internal state space $\pi_t(\xi)$ and the conditional probability distributions $p_s(y(s)|\xi)$ obey normal distributions, the update of the internal state space is realized by an iterative operation on the mean vector and covariance matrix. However, the details are omitted here.

Accordingly, attentional perception is formalized as an iterative experimental design based on an information criterion [4]. Also "distance" between probability distribution functions, such as J-divergence

$$\begin{aligned} J_t(s) &= \sum_{\xi_1, \xi_2 \in \Xi} \pi_t(\xi_1)\pi_t(\xi_2) \\ &\sum_{y(s) \in Y_s} (p_s(y(s)|\xi_1) - p_s(y(s)|\xi_2)) \log \frac{p_s(y(s)|\xi_1)}{p_s(y(s)|\xi_2)}, \qquad (6) \end{aligned}$$

can be used as the sensor selection criterion [11].

IV. BEHAVIOR OF SYSTEM

A. *Experimental Conditions*

In the experiments, the system observed objects with nine combinations of force and speed shown in Table II. The obtained signals were pre-processed and a number of

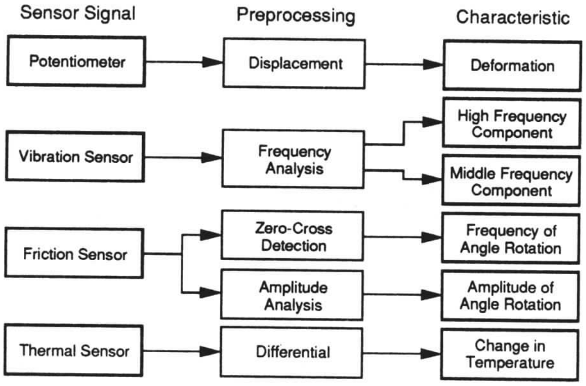


Fig. 5 Pre-processing for Extracting Characteristics

characteristics were extracted from the signals (Fig. 5). The discrimination experiment was performed on a computer after the pre-processings were finished.

The authors derived 46 characteristics from the signals and selected 16 of them which showed large variance for 43 sample objects. Table III shows the selected characteristics, where the symbols printed in the column of "condition" correspond to those in Table II. These characteristics were regarded as "sensors" in the mathematical model and the system chose them one by one based on the information criterion until the entropy became enough small (less than 0.1).

In advance of the discrimination experiments, all samples were measured 10 times, and the means and variances of the characteristics were estimated for each sample. The system used mutual information or J-divergence as the sensor selection criterion on the assumption that the characteristics obey normal distributions independently.

B. *Experimental Result*

1. Material Discrimination

First, the authors introduce the result of discrimination among 20 materials listed in Table IV.

Figs. 6 and 7 show some examples of the recognition process. As is shown in Fig. 6, characteristic #15(Slope of Temperature Change) was selected as the most informative one at the initial state. When the object was SF, the system selected characteristic #1(High Frequency Component) for the second observation. Then the entropy was reduced enough and the system judged that the object was SF. When WD1 was presented, the system put out a correct answer after three observations. This result shows clearly that the system chose different characteristics as the recognition proceeded.

Fig. 7 show the result when the object set was restricted to AC, SF, SP, CL1, RB1, CR, LT1, and WD1. In this case, characteristic #1(High Frequency

TABLE II

Experimental Conditions

Speed		Force	
S	33mm/s	1	0.23N
M	43mm/s	2	0.32N
F	60mm/s	3	0.46N
(error)	1.5mm/s	(error)	0.04N

TABLE III

Characteristics Used at Experiments

No.	Characteristic	Condition		See
		Speed	Force	Sec 4.C
1	High Freq. Comp. of Vibra.	S	2	*a*
2	High Freq. Comp. of Vibra.	S	3	
3	Middle Freq. Comp. of Vibra.	S	1	*c*
4	Middle Freq. Comp. of Vibra.	S	2	*b*
5	Middle Freq. Comp. of Vibra.	M	2	*d*
6	Middle Freq. Comp. of Vibra.	F	3	
7	Freq. of Angle Rotation	F	1	
8	Freq. of Angle Rotation	F	2	*e*
9	Amp. of Angle Rotation	S	2	
10	Amp. of Angle Rotation	M	1	
11	Amp. of Angle Rotation	M	3	*f*
12	Amp. of Angle Rotation	F	3	*g*
13	Slope of Temperature Change	-	1	
14	Slope of Temperature Change	-	2	
15	Slope of Temperature Change	-	3	*h*
16	Deformation	-	2	

TABLE IV

Test Samples

Name	Material	Name	Material
AL	Aluminum Plate	RB2	Rubber (NBR)
TL	Ceramic Tile	PP1	Paper (Plain)
CR	Cork Plate	PP2	Paper (Coated)
PL	Vinyl Resin	LT1	Leather (Cow)
AC	Acrylic Resin	LT2	Leather (Chrome)
SF	Styrene Foam	LT3	Leather (Suede)
SP	Sponge	LT4	Leather (Suede)
WD1	Wood (Cherry)	CL1	Cloth 1
WD2	Wood (*keyaki*)	CL2	Cloth 2
RB1	Rubber (Plain)	CL3	Cloth 3

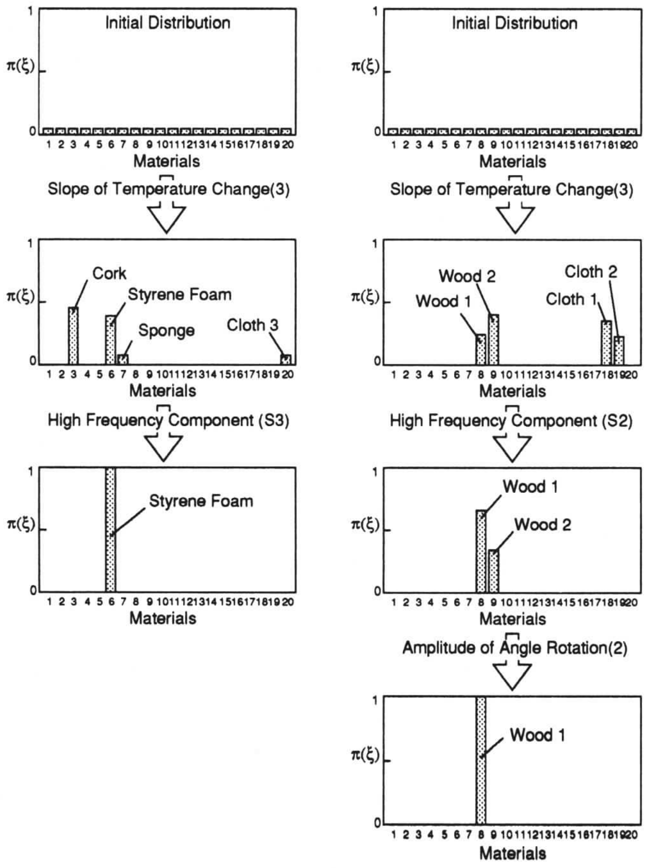


Fig. 6 Process of Recognition 1

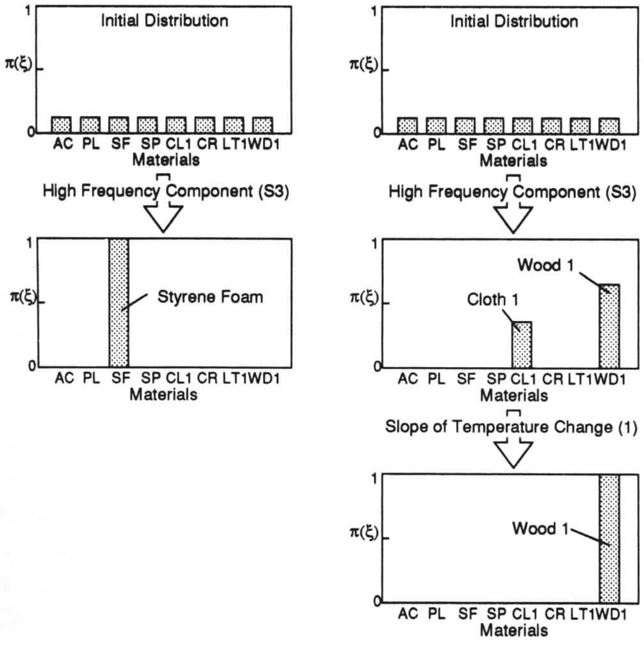


Fig. 7 Process of Recognition 2

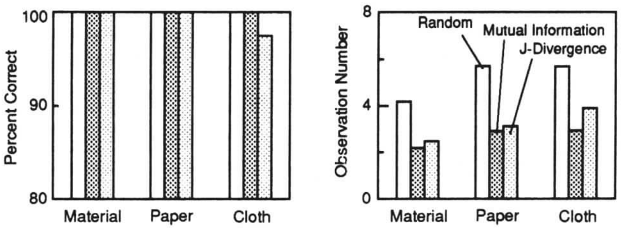


Fig. 8 System Performance

Component) was selected at the initial state. As is shown in these results, different characteristics were selected according to the object set, which illustrates the feature of attentional perception.

Fig. 8 shows the recognition accuracy and average observation number when the system selected the characteristics at random (random observation) and those when the system selected them based on the information criteria (attentional observation). As we can see from this result, the system discriminated the samples perfectly by every observation strategy, and observation number was reduced about 2 times on average by the attentional observation.

2. Paper and Cloth Discrimination

Fig. 8 shows the results for 16 kinds of paper and 16 kinds of cloth together. These objects are very similar to one another: As a matter of fact, it is not easy for human subjects to discriminate them as soon as they touch them. The result shows that the recognition accuracy was kept almost perfectly in these cases and that the observation numbers for attentional observation were about half of that for random observation.

Above results prove that the constructed system has enough ability to discriminate various objects, and that attentional perception realizes high recognition accuracy by fewer observations.

C. *Likeness between Constructed System and Human Haptic Mechanism*

The previous section has described that the constructed system has similar ability for haptic discrimination to humans. In order to verify whether the mechanisms of the constructed system and of human perceptual system are alike, the author did the following two comparative experiments: One is on the characteristics used at discriminating objects, and the other on the similarity in feel of touch.

1. Characteristics Determining Feel of Touch

The authors represented the objects using the combination of eight characteristics which had been frequently used in the recognition experiments (indicated in the right column of Table III).

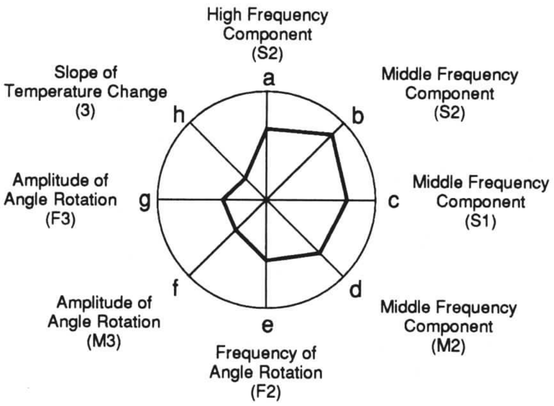


Fig. 9 Representation using Polar Diagram

Each material is represented with a polar diagram whose axes correspond to the selected characteristics. Fig. 9 shows the meaning of each axis, where the center of each radius corresponds to the mean value and the center of the circle and the points on the circle correspond to 2σ points (σ means standard deviation).

Fig. 10 shows the diagrams for various materials. We can see that each axis corresponds well to a characteristic which human beings utilize in haptic perception. For instance, things feeling "warm", such as sponge and styrene foam, have small values on axis h (Slope of Temperature Change) and, to the contrary, things feeling "cool" such as an aluminum plate have large values on the same axis. Things which pull the surface of the skin, such as sponge and suede, have large values on axes f and g (Amplitude of Angle Rotation). Rustling things such as styrene foam and carpeting have large values on axis a (High Frequency Component). Generally, rough things have large values on axes b, c and d (Middle Frequency Components), and adhesive things show large values on axis e (Frequency of Angle Rotation).

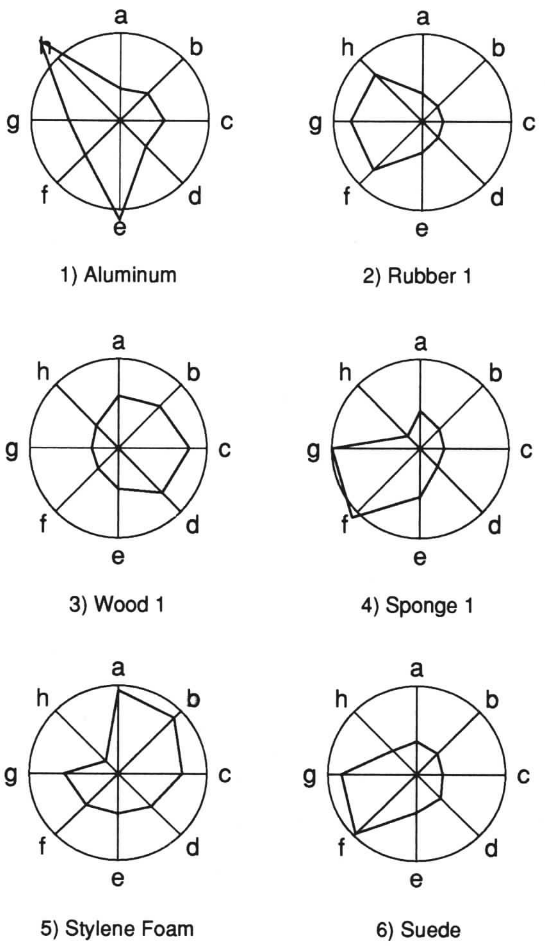
Above results show that the diagram represents faithfully the human feel of touch, and suggest that the constructed system catches the same information as humans do.

2. Similarity in Feel of Touch

Finally, let us examine whether the similarity calculated by the system corresponds to the similarity judged by human subjects.

The authors prepared ten standard samples (A, B, $\cdots$, J) and four test samples (1, 2, 3 and 4) for each of paper and cloth, and asked the constructed system and three human subjects (α, β and γ) which standard sample was the most similar to each test sample.

In order to evaluate the similarity in the system, the authors defined the following two kinds of "distance" utilizing the eight characteristics used in the above



1) Aluminum

2) Rubber 1

3) Wood 1

4) Sponge 1

5) Stylene Foam

6) Suede

Fig. 10 Representation of Some Samples

diagrams.

$$\mathrm{dist}_a(k) = \sqrt{\sum_{i,j=1}^{8} (f_i^* - f_i^{(k)})[D^{(k)}]^{-1}_{ij}(f_j^* - f_j^{(k)})} \quad (7)$$

and

$$\mathrm{dist}_b(k) = \sqrt{\sum_{i=1}^{8} (f_i^* - f_i^{(k)})^2 / D_{ii}^{(k)}} \quad (8)$$

where f_i^*, $f_i^{(k)}$ and $D^{(k)}$ denote the ith characteristic of a test sample, the mean value of the ith characteristic of the kth standard sample and the covariance matrix of the kth standard sample, respectively. Obviously, $\mathrm{dist}_a(k)$ is standardized distance with the covariance matrix of the kth standard sample, and $\mathrm{dist}_b(k)$ agrees to $\mathrm{dist}_a(k)$ when there is no correlation among the characteristics ($D_{ij}(k) = 0$ for $i \neq j$). Since these distances satisfy neither symmetry nor triangle inequality, they are not distance in the strict sense: They indicate similarity of a test sample to each standard sample rather than similarity between two arbitrary samples.

TABLE V

SIMILARITY JUDGEMENTS BY SUBJECTS AND BY SYSTEM

a. Paper

Sample			1	2	3	4
Subject	α		A, H, I	B, A	H, A, F	H, F
	β		A, H	B, A	H, F	H, F, A
	γ		A	B	H, A, F	H, A
System	a	1	A (8.2)	J(16.0)	F (8.9)	A(16.6)
		2	F (12.6)	A(19.4)	E(12.8)	D(20.2)
		3	E (13.2)	E(23.0)	G(13.1)	J (23.5)
	b	1	A (4.4)	B (8.2)	F (5.5)	H (5.7)
		2	D (5.2)	A (8.5)	G (7.8)	D (7.4)
		3	H, J (6.7)	J(12.2)	D(10.3)	J (7.8)

b. Cloth

Sample			1	2	3	4
Subject	α		B, C	B, A	E, D, H	I, D
	β		B, C	B, A	F, D	D, I, J
	γ		B, H	B, A	I, H, E	C, D, I
System	a	1	C (50.5)	A (7.7)	E (8.2)	J (5.5)
		2	A (59.3)	C(14.5)	D(12.8)	F (9.3)
		3	F(128.0)	J(15.3)	J(15.6)	D(11.0)
	b	1	C (36.2)	A (4.9)	E (4.5)	I (3.5)
		2	A (49.1)	B (6.2)	F (7.9)	J (4.2)
		3	B (61.3)	C (8.7)	H (8.7)	D (6.7)

Table V summarizes the judgements by human subjects and by the system. Values in parentheses indicate the distance calculated by the system.

As we can see from this result, the judgements by human subjects and by the system agree to each other rather well. Moreover, the result shows that dist_b reflects the human feeling better than dist_a, which suggests that human beings do not utilize the correlation among the characteristics.

As a matter of fact, when one of the authors did the experiment as a subject, he said he paid his attention to a certain characteristic at each observation and tried to compare the objects in the characteristic. Besides, another subject said "These two samples are similar in rustling feeling but are dissimilar in fluffy feeling." These facts show that we choose a characteristic as an axis at each observation and compare the objects along the axis. The authors have not investigated what characteristic is significant when we judge of the similarity. However, such investigation will give informative suggestions to the research on representation of feel of touch [12].

V. CONCLUSION

The authors constructed a haptic recognition system which integrates various sensory information through selecting appropriate sensors, and showed that the system can discern a subtle difference in feel of touch and simulate well the human haptic process. Such a good performance was achieved by realizing a system faithful to the human haptic mechanism from the viewpoints of sensory integration and attentional perception. It can be also concluded the constructed system is a good model for human haptic mechanism.

Sensory integration and active perception are common mechanisms to all sensory information processing in the human brain. The authors would like to make models which behave like humans based on these principles and to clarify the brain mechanism with the synthetic approach.

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