Analysis and Modeling Based on Cepstrum for Haptic Presentation Considering Frequency Features of Vibration in Rubbing Motion

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This paper proposes a modeling method for the haptic information from the environmental characteristics of a plane. A human obtains much haptic information by touching an object. For the haptic information derived from a rubbing motion, this paper particularly focuses on the vibration components of the friction force. Although there are many methods to describe the friction force, it is difficult to treat them quantitatively. This paper proposes applying Cepstral analysis to haptic information to easily extract and treat unique features of the environment. A technique for representing the extracted frequency features is also presented. An experiment was performed using a 2 DOF system to show the validity of the proposal.

Keywords: haptics, cepstral analysis, environmental surface, feature extraction, haptic presentation

1. Introduction

Until today, the systems to support the human work have been much studied (1) (2). Conventionally, industrial robots to perform high-precision and high-speed work compared to humans have been developed. However, there are many skillful techniques relying on human delicate motions and senses. Therefore, technology transfer from person to person is necessary.

When a person wants to tell things to another person, in many cases, techniques using text, oral, and visual are taken. In technology transfer, a trainer had better tell skill by not only audio and visual but also force adjustment information to a trainee. For this reason, expert skill transfer is not easy, and requires a lot of time and cost. Furthermore, reduction of engineers and lack of successors due to the declining birthrate and aging society is serious. It is also anticipated that the skill transfer to multinational engineers is required in the future (3). Though the technology transfer with character and visual have been performed, technical tradition in other countries is more difficult from differences in culture and languages. In addition to the conventional information such as characters, word, and video, if the use of force adjustment in expert motion and haptic information that engineers feel is possible, more efficient technology transfer will be realized (4). As described above, utilization of haptic information is expected in the industrial society.

Although haptic information is attracted attention as a new media, it has different properties from the audiovisual information. While audio and video are unidirectional information, tactile sensation is bidirectional information, which is governed by the law of action and reaction with contact target. In addition, it is self-reference information affected a lot by individual’s subjective. Recently, many approaches to evaluate haptic information have been proposed (5)–(8). Nevertheless, due to the characters of this bidirectionality and self-reference, there is no unified method to handle haptic information clearly.

From the above, study of haptics is organized; studies to evaluate quantitatively the haptic information are made actively. As one of them, environment-copying system (9) (10) is proposed. It is a system to store and reproduce a real-world environmental haptic information corresponding to any position and velocity of the system. This method has been successful in the quantification of haptic information in the push-pull motion.

Haptic information includes the information with rubbing motion on environmental surface such as “slippery” and “gritty” in addition to the hardness or softness of the environment with the push-pull motion. The tactile that human feel from environmental surface in rubbing motion include much information, it is important in today’s industrial scenes. Based on the importance of haptic information, reproduction the haptic feel of human is performed. Techniques such as the human illusion of tactile generated by vibration actuators have been proposed (11)–(13). However, these methods are according to a qualitative sense of human in many cases. In order to utilize haptic information for communication between people such as technology transfer in addition to audiovisual information, it is necessary to evaluate quantitatively haptic data obtained from the real world.

Human can acquire a lot of information from the haptic information in rubbing motion. Skilled people, such as metal processing, are able to determine features of worked surface with high accuracy by the haptic information. To replace human technology based on haptic, not the audiovisual information is still difficult. This is one of the areas that the robot system cannot enter. Therefore, it is an important research subject to evaluate quantitatively by analyzing the haptic information on actual environmental surfaces.

In this paper, the method to evaluate quantitatively the
friction force in rubbing motion is proposed. This paper focuses on the vibration component of the friction force as the haptic information in rubbing motion. For the modeling of the friction force, many approaches have been suggested in the past. Since they have complex models and non-linearity, handling them is very difficult. In addition, many parameter identifications are required. By using the proposed method, evaluation of the vibration component in the frequency domain is possible without going through complicated steps. Cepstral analysis is applied in order to extract the features of vibration components due to differences of environmental surfaces. Cepstral analysis is one of the frequency analyses used for speech analysis, which is a method to express the variation of the amplitude spectrum in frequency domain as the spectral envelope. The proposed method let the friction force in rubbing motion be evaluated and modeled accurately without complication and difficulty to treat the model. There are some techniques to evaluate signals not voice information using the Cepstral analysis. In conventional methods, Cepstral analysis has been used to detect envisaged frequency features contained in the signal.

On the other hand, in this research, the Cepstral analysis is applied not only to evaluate but also to model the friction force in rubbing motion. In the proposed method, we will add a term indicating the characteristics of the vibration component obtained from the actual environment to the simple linear mode. It is a simple structure without the complexity, such as non-linear model.

In addition, haptic presentation based on the real-world information is performed by reproduction the frictional force using the extracted features. This paper also introduces a method to present operator haptic information represented in frequency domain by the Cepstral analysis. The results of the reproduction experiments will show that the adequacy of the proposed modeling method.

This approach is a frequency analysis with a logarithmic transformation and a filtering of the signal spectrum. Unlike simple Fourier transform, it is effective to modeling and evaluation because the fine structure of the spectrum is removed and weak information in frequency domain is enlarged. In addition, the proposed method to capture vibration components as only a spectral envelope is effective when we consider the reproduction of haptic information. Against the conventional methods, using the spectral envelope as friction model explicitly is the chief aim of this paper.

This paper is organized as follows. The following section shows the proposed method for feature extraction of environmental surface. Cepstral analysis, the analytical method used in this paper, is described in this section. Extraction experiment results are also shown. A process for reproduction of haptic information using proposed model is written in Sect. 3. Finally, this paper is concluded in Sect. 4.

2. Feature Extraction of Environmental Surface

2.1 Haptic Information at Environmental Surface

This subsection explains the method of haptic information at environmental surface. A human can take much haptic information when he or she recognize the state of the environmental surface in rubbing motion. Major haptic information received from the environment is minute irregularities on the surface and friction force on the rubbing motion. This paper focuses particular on the friction force of haptic information. The features of environmental surface are evaluated quantitatively by analyzing this information.

Physical property of the object surface for rubbing motion is described as follows:

\[ F^{\text{fric}} = \text{sgn}(\omega) \mu F^{\text{ver}} + D_0 \]  

(1)

where \( F^{\text{fric}}, F^{\text{ver}}, \omega, \mu, D \), and \( \text{sgn} \) indicate friction force, vertical force, rubbing motion velocity in horizontal direction, Coulomb’s friction coefficient, viscous friction coefficient, and signum, respectively. In (1), the environmental surfaces are characterized by coulomb’s friction coefficient \( \mu \) and viscous friction coefficient \( D \). However, minute vibration is also important information in addition to the friction force given by (1) when actually human recognize the state of the environmental surface. The mathematical model shown in (1) cannot express the vibration characteristics of the friction force depends on the environment. Different environments have different vibration properties, they are key elements to evaluate environmental surface quantitatively. It is necessary to evaluate friction force in frequency domain in order to describe the friction force that human feel exactly. However, friction force has not been elucidated its generation mechanism, accurate modeling is difficult. Of course, many physical models that are more complex than a basic formula such as (1) for friction force have proposed. There are some methods such as stick-slip model, complex spring-damper model, and so on. Although they are accurate models, it is difficult to handle due to their nonlinearity and need to identify a number of parameters.

As described above, many friction models have been proposed so far, not limited to the haptic information. However, there is a trade-off between accurately and simplicity of the model. A simple model like (1), that is constructed two parameters, can only describe linear components. Though accuracy of the friction model is improved if the modeling is complicated, the parameter identification and design is not easy. This paper proposed a method considering vibration components that can not be expressed in a liner model, even while maintaining the simplicity of the model.

2.2 Cepstral Analysis

This subsection explains cepstral analysis using extraction of vibration characteristics. Cepstral analysis is one of the analytical methods used for the analysis of voice information. Cepstrum is defined by

\[ C_s(m) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \log |S(e^{j\omega})| e^{jm\omega} d\omega \]  

(2)

where \( S(e^{j\omega}), \omega, C_s(m), \) and \( m \) denote Fourier transform of signal \( s(t) \), frequency, cepstrum of signal \( s(t) \), and quefrency, respectively. Fourier transform of a signal that is a function of time, after that applying the inverse Fourier transform so that the dimension of the cepstral domain is time. It is called quefrency to distinguish from ordinary time \( t \).

A signal \( s(t) \) is represented as a convolution a signal \( (t) \) with a impulse response \( h(t) \)

\[ s(t) = \int_0^t h(t - \tau) \delta(\tau)d\tau \]  

(3)

Fourier transformation of (3) is a form of the product of the
structure from high-order-quefrency. To draw a logarithmic spectrum envelope and to know the fine structure of low-order-quefrency extracted by liftering, it is possible to treat large areas of the power spectrum of the analysis method to haptic information. Cepstral analysis is used as a linear model of the vocal folds. This paper applies the analysis method to haptic information. Cepstral analysis is an analysis method with logarithmic transformation, it is possible to treat large areas of the power spectrum of the signal. In addition, it is also possible to extract only the important features from the complex frequency characteristics of the signal as a simplified form of an envelope. Therefore, this analysis is suitable for modeling frequency features of the friction force without using complex models.

Figure 2 shows the Fourier transformation results of the friction force (aluminum plate and felt) which are analyzed in this paper. On the other hand, Fig. 3 is the results of Cepstral analysis. The logarithmic transformation is included. And the filtering in the frequency domain is applied. These are the advantageous of using the Cepstral analysis. As is apparent from a comparison of these figures, it can be found that we can easily evaluate the features of the frequency band with weak power by using Cepstral analysis compared to the general Fourier transformation. Furthermore, the spectrum envelope obtained from the law data will be utilized as a model of the friction force in frequency domain.

2.4 Extraction Experiment

2.4.1 Experimental System In this paper, the three types of environmental surface shown in Fig. 4, aluminum plate, sandpaper, and felt are used for experiment. Feature extraction is performed on the surface of these environments. The experimental setup is shown in Fig. 5. This system is constructed to two linear motors and the end-effector mounted on environment surface can be carried out. The frictional force by the rubbing motion is external force which is utilized in order to extract features of the information. This analysis described in the former subsection is a method for separating log spectrum of the target data into slowly varying part and violently varying part. In the field of speech analysis, the spectral envelope and the fine structure of spectrum are associated with the individual features of the vocal cords and the basic waveform of voice, respectively (27). This is widely used as a linear model of the vocal folds. This paper applies the analysis method to haptic information.

The experimental setup is shown in Fig. 5. This system is constructed to two linear motors and the end-effector mounted on environment surface can be carried out. The frictional force by the rubbing motion is external force which is utilized in order to extract features of the information. This analysis described in the former subsection is a method for separating log spectrum of the target data into slowly varying part and violently varying part. In the field of speech analysis, the spectral envelope and the fine structure of spectrum are associated with the individual features of the vocal cords and the basic waveform of voice, respectively (27). This is widely used as a linear model of the vocal folds. This paper applies the analysis method to haptic information.
on the tip of the $y$-axis motor. The end-effector is shown in Fig. 6, which contact with environmental surface directly. The contact portion of this attachment is plane. The friction in rubbing motion is considered that the rotation force is being applied to the end-effector made with aluminum. In addition, the experimental results with different material are shown in Sect. 3.

The front end of this parts is not sharp but flat. Thus, it can be considered that the rotation force is being applied to the end-effector. However, it is assumed that there is no interference between $x$ and $y$ direction so that the experimental system was constructed with two linear motors placed horizontally and vertically to the environment, which can be considered as a rigid body. Therefore, the rotation force is not taken into consideration in this paper.

The setup parameters of experiments are shown in Table 1. The commands of vertical force $F_{cmd}^y$ and velocity of rubbing motion $v_{cmd}^y$ are shown in Table 2. To compare the effects in the vibration components due to $F_{cmd}^y$ and $v_{cmd}^y$ of rubbing motion, 4 patterns of command values is set up. Here, the velocity control is achieved by PD control with position command $x_{cmd}^y$ in Table 2.

The experiments performed for 7 seconds, and tried five times each. The fast Fourier transform (FFT) and the inverse fast Fourier transform (IFFT) are used for Fourier transform algorithm in this paper. Number of data samples to be analyzed was set to 214 for the efficiency of fast Fourier transformation. This means that the friction force of about 1.6 seconds is analyzed because the sampling time of the system $T_s$ is 0.1 ms. It was determined by considering the time required to analysis and the frequency resolution. There is a trade-off between this resolution and the time required to analyze. Enormous time for analysis is required due to the use of the general inverse Fourier transform not fast in reproduction experiments. The analyzed section is suitably selected from the interval that is not affected by the statical friction in the data of 7 seconds.

### 2.4.2 Results

Figure 7 shows the friction force for each environment on the condition that $F_{cmd}^y$ is 1.0 and $v_{cmd}^y$ is 0.004. Here, the friction force obtained at the start of control is not used for the analysis because it is affected by static friction. The friction force is vibrational. To accurately evaluate the friction force, the importance of taking into account the vibration components is apparent. Figures 8, 9, 10, and 11 show the experimental results with each commands. The

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**Table 1. Parameters of extraction experiment**

| Description | Value |
|-------------|-------|
| $T_s$       | $1.0 \times 10^{-4}$ [s] |
| $K_{pc}$   | 2500.0 |
| $K_{vc}$   | 100.0  |
| $f_{c}$    | 0.1 [kHz] |
| $f_{c}$    | 0.002 [kHz] |
| $f_{c}$    | 0.004 [kHz] |
| $M_{nx}$   | 1.28 [kg] |
| $M_{ny}$   | 0.33 [kg] |
| $M_{nz}$   | 0.33 [kg] |

**Table 2. Commands of extraction experiment**

| Pattern  | (i) | (ii) | (iii) | (iv) |
|----------|-----|------|-------|------|
| $F_{cmd}^y$ [N] | 1.0 | 2.0 | 1.0 | 2.0 |
| $v_{cmd}^y$ [m/s] | 0.002 | 0.002 | 0.002 | 0.004 |
| $v_{cmd}^y$ [m] | 0.002 t | 0.004 t | 0.004 t | 0.004 t |

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![Aluminum plate](image1)
![Sandpaper](image2)
![Felt](image3)

Fig. 4. Environmental surface

![End-effector](image4)

Fig. 5. Experimental setup of feature extraction

![End-effector](image5)

Fig. 6. End-effector

![End-effector](image6)

Fig. 7. Friction force
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(a) Aluminum plate.
(b) Sandpaper.
(c) Felt.

Fig. 8. Analysis results with command pattern (i)

(a) Aluminum plate.
(b) Sandpaper.
(c) Felt.

Fig. 10. Analysis results with command pattern (iii)

(a) Aluminum plate.
(b) Sandpaper.
(c) Felt.

Fig. 9. Analysis results with command pattern (ii)

(a) Aluminum plate.
(b) Sandpaper.
(c) Felt.

Fig. 11. Analysis results with command pattern (iv)

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Table 3. RMS errors by differences of environment

| Material     | Aluminium | Sandpaper | Felt   |
|--------------|-----------|-----------|--------|
| Aluminium   | 1.636     | 4.977     | 2.932  |
| Sandpaper   | 4.292     | 1.572     | 7.004  |
| Felt        | 3.052     | 5.841     | 1.255  |

Table 4. RMS errors by commands of rubbing motion

| Command | (i) | (ii) | (iii) | (iv) |
|---------|----|-----|------|-----|
| Aluminium | 1.625 | 3.333 | 2.066 |
| Sandpaper | 1.796 | 1.475 | 1.733 |
| Felt     | 1.359 | 0.946 | 1.751 |

If the aluminum plate shown in analysis result (a), the features of spectrum are lowest in the vicinity of 50 Hz and then stronger toward the high-frequency band. In results (b), spectrums show more than 40 dB up to about 20 Hz. This result indicates that sandpaper has the characteristic that many vibration components to the low-frequency range. The spectrums of felt shown in (c) are small overall, the envelope shape in the band from 40 Hz in the 80 Hz. To evaluate the differences in frequency domain, root-mean-square (RMS) errors of the envelopes between each environments are shown in Table 3. Table 3 indicates that the spectral envelopes with different features between the difference environments are obtained. RMS between different environments are bigger conspicuously than those of same environments. Diagonal elements in the table indicate RMS errors among five attempts. All of these values are smaller than other values which are errors between different environments Thus, envelopes with different characteristics are drawn by friction force with different environmental surface. The features of the environment are extracted.

Table 4 presents the RMS errors between results of command (i) and commands differ from (i). It is shown in order to examine the correlation of feed rate, pushing force of the rubbing motion, and the spectral envelope. The results by command pattern (i) and the others are compared. The values are close to the diagonal in Table 3 in any combination. There is no significant change due to the difference of the command values. Therefore, the friction force does not depend on vertical force and rubbing motion velocity as conventional friction model. The spectral envelopes can be seen that their dependence on the rubbing motion pattern is small.

From above results, it is found that the spectral envelope obtained by the Cepstral analysis of the friction force is highly dependent on the contact object, and the change by the rubbing motion is negligible. This paper utilized 4 type commands to check the relationship the vibration component and rubbing motion. In order to confirm the relation between \( G_{\text{env}} \) and motion commands, complementary experiments have been performed \(^{(29)}\). They were constructed using 10 parameters of force and velocity command. Similar results have been obtained.

From the experimental results, the friction force by rubbing motion at environmental surface can represent using vibration components depend on the environment \( G_{\text{env}} \) as follows:

\[
F_{\text{fric}} = \text{sgn}(v)\mu F_{\text{rel}} + Dv + G_{\text{env}}. \tag{7}
\]

By evaluating the friction force with the proposed model, the haptic information that human feel in rubbing motion on environmental surface can be treated more accurately and quantitatively. Furthermore, the proposed model needs only the vibration component \( G_{\text{env}} \) obtained by experiments in addition to the basic term, viscous and Coulomb’s friction coefficient. It is very simple and does not require complex modeling, nonlinear term, and complicated parameters identification and so on.

Though it is also possible to identify the viscous and Coulomb’s friction coefficients from the experimental data, the linear portions of (7) are not treated because this paper only focuses the vibration component. The average value of the data is used instead of the viscous and Coulomb’s friction term in this paper.

3. Feature Reproduction of Environmental Surface

This section introduces a haptic reproduction method based on the frequency features modeled by Cepstral analysis, and shows experimental results. These results demonstrate experimentally that it is possible to present the haptic information on the basis of expression method proposed in Sect. 2. The adequacy of the haptic modeling by Cepstral analysis is also confirmed by feature reproduction results.

3.1 Reproduction of Haptic Information

The logarithm spectrum envelopes extracted in Sect. 2 represent the vibration characteristics of the specific environmental. It is possible to reproduce the vibration components of the friction force by the use of this. Time function of the vibration components can obtained by changing back into antilogarithm and inverse Fourier transform the spectral envelope using the phase spectrum of the ordinal signal. The transformation of this time is shown as follows:

\[
G_{\text{env}}(t) = \frac{1}{N} \sum_{n=0}^{N} |G_{\text{env}}[n]| \cos \left( \frac{2\pi n}{N} t + \text{arg} \ G_{\text{env}}[n] \right)
\]  \tag{8}

where \( G_{\text{env}}[t], N, |G_{\text{env}}[n]|, \) and \( \text{arg} \ G_{\text{env}}[n] \) denote vibration components, number of data samples, amplitude spectrum versus frequency \( \omega \), and phase spectrum respectively. As stated above, reproduction the environment specific friction force is realized by substituting the vibration components that decoded the time domain into the proposed model. The frictional force reproduced in this paper is reaction force which human receive in motion from the environmental surface. The bilateral control is a method which realizes the bidirectional transmission of action and reaction force. By using bilateral control, the force information reproduced by the proposed method can be presented to the operator.

3.2 Feature Reproduction System

In this paper, the feature reproduction system of environmental surface is constructed with applying the bilateral control \(^{(29)}\). The bilateral control was only used in reproduction experiments. However, as mentioned in the introduction, the haptic information has bidirectionality. A quantitative evaluation of not only the reaction force from the environmental surface but also the action force from human motion is required in future work. It is necessary to apply the bilateral control which can obtain the
action force and reaction force separately on this occasion. Furthermore, the presentation of the friction force according to the operator input is required due to the bidirectionality. In anticipation of the above, the bilateral control is introduced in this paper.

Figure 12 shows the block diagram of reproduction system. \( C_f, C_p, \dot{x}, f^e, \dot{f}^e, C_f^e, C_p^e, \ddot{x}_M, \ddot{x}_S, \dot{x}_D, \dot{\dot{x}}_S, \) and \( Q_2 \) mean force controller, position controller, position, external force, reference, response, value of master system, value of slave system, common mode, differential mode, and quarry matrix \((30)\) \((31)\) respectively. The position and force responses in the master and slave systems are transformed into the common and differential modal spaces by the second order quarry matrix

\[
\begin{bmatrix}
\ddot{x}^C \\
\ddot{x}^D
\end{bmatrix} = Q_2 \begin{bmatrix}
\ddot{\dot{x}}^M \\
\ddot{\dot{x}}^S
\end{bmatrix} \tag{9}
\]

\[
\begin{bmatrix}
\ddot{x}^C \\
\ddot{x}^D
\end{bmatrix} = Q_2 \begin{bmatrix}
\ddot{x}^M \\
\ddot{x}^S
\end{bmatrix} \tag{10}
\]

\[Q_2 = \frac{1}{2} \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix} \tag{11}\]

In this system, a virtual slave system is used instead of the system to contact the real environment. Figure 13 shows the experimental setup. In the reproduction experiment, input motor system is used for performing the rubbing motion the same as extracting experiment in Sect. 2. This input system is simulating the operator, and connected to the master system mechanically. The system performs the rubbing motion against to the virtual environmental surface, based on feed rate and vertical force shown in Table 2. We evaluate the reaction force as the friction force that human feel in the rubbing motion. This paper focuses on the vibration components of friction force. Therefore, the average value of the analyzed data is utilized instead of Coulomb’s friction and viscous friction terms in short. The friction force reproduced in this experiment is expressed as

\[
F_{\text{fric}} = F_{\text{data}} + G_{\text{env}}. \tag{12}\]

Coulomb and viscous friction are included in (7), which is the proposed friction model. Instead of these parameters, the average values \( F_{\text{data}} \) are used for simplicity of the experiments.

As above, the haptic reproduction is performed using vibration components of each environment extracted in Sect. 2. The setup parameters are shown in Table 5.

### 3.3 Results

Figures 14 and 15 present analysis results as with the extraction experiment. Solid lines indicate the spectrum envelope of reproduced force with the proposed method. The analysis results of friction force without vibration components are shown as broken lines. Actual data are described by dotted lines. Table 6 shows the RMS errors against the actual data. From analysis results, the friction force based on the proposed method includes the vibration components as extracting experiment in Sect. 2.
components similar features to the signal actually obtained. On the other hand, as analysis results in the case of reproduction without considering the vibration components, it is confirmed that the features of actual vibration components is not reproduced in frequency domain.

In this experiments, large fluctuations of friction force seen in the actual data cannot be reproduced. It is assumed that more accurate reproduction becomes possible by taking into account spatial variations in the environmental surface of Coulomb friction $\mu$ and the viscous coefficient $D$. Moreover if the calculation cost is permitted, it is possible to improve the resolution of the frequency analysis by increasing the interval using Cepstral analysis. Then, the proposed method can cope with these very low frequency features. It is an issue to be addressed in the next step.

Though this paper adopted the format using the motor system which performs the same operations as the extraction experiment, it is possible for the operators to feel the friction force with vibration component such as shown in the experimental results, even when they operates the system. Research for the relationship of human perception and human tactile information has been actively carried out\(^{(32)}\). By incorporating a virtual model of objects in addition, it is also possible to present a vibration component only when performing a rubbing motion in contact.

4. Conclusions

This paper proposes a model for haptic information considering frequency characteristics of friction force in rubbing motion. Using this method, the features of the vibration components that cannot be expressed in simple model was able to be extracted without complicated modeling. By drawing a logarithmic spectrum envelope in the frequency domain using Cepstral analysis against the frictional force, it was possible to evaluate quantitatively the haptic information that human feel in the rubbing motion. In addition, by reproducing the frictional force with extracted features of the vibration components, it was shown that haptic presentation based on the real-world information is possible.

The validity of the proposed method was shown by feature extraction experiment using three different environmental surfaces. In addition, the friction force with the same vibration components acquired haptic information was presented in reproduction experiment based on extracted features of the vibration components.

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