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(Citation)
Advanced Robotics,34(11):730-743

(Issue Date)
2020-06-02

(Resource Type)
journal article

(Version)
Accepted Manuscript

To appear in *Advanced Robotics*
Vol. , No. , , 1–17

FULL PAPER

Tactile Feedback System of High-frequency Vibration Signals for Supporting Delicate Teleoperation of Construction Robots

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(*Received 00 Month 201X; accepted 00 Month 201X*)

This study proposes a methodology to deliver contact information on construction robots to the remote operator by transmitting measured collision vibrations, which are often beyond the human perceivable range. We focus on the human capacity to discriminate the envelope of high-frequency vibrations as an essential cue to perceive contact materials and collision conditions. The proposed method preserves the envelope shapes with amplitude-modulated waves with a single carrier frequency in the human sensitive range. In the preliminary experiments, a miniature shovel digging experiment confirmed that the proposed method improves the discriminability of the contact materials and sliding velocities. A psychophysical experiment also showed that the participants could discriminate the envelope differences irrespective of the carrier frequency. The proposed method was applied to the tactile transmission system for a construction robot developed in the ImPACT program. A vibration sensor was attached on the robot arm, and the vibrotactile feedback was applied to the operator's wrist. Performance evaluations under a delicate teleoperated task (insertion of a bar into bricks) showed that the peak force was reduced by the proposed method significantly for two out of the three participants. The results show that our proposal could improve the maneuverability of teleoperation.

Keywords: Haptic feedback, Haptic display, Vibrotactile feedback, Teleoperation

1. Introduction

The teleoperation of a construction machine is expected to be effective for early restoration after disasters such as earthquakes, landslides, and volcanic eruptions. For example, in disaster environments that are dangerous for human operation, teleoperated excavators are often used to remove debris while keeping the operator away from the disaster site. However, the usability/maneuverability of teleoperated machines is not high, and the working efficiency is lower than that of a directly controlled construction robot [1]. The limitation of visual information during teleoperation tasks is one of the factors that can reduce the efficiency of the tasks; therefore, visual supporting systems have been developed in some studies [2, 3]. Furthermore, the lack of haptic feedback is a serious drawback of teleoperation because a construction robot usually involves haptic interactions such as digging and handling of heavy loads. This paper focuses on the haptic feedback system to support the teleoperation of a construction machine.

To support the teleoperation of construction machines, many researchers proposed force feedback systems [4, 5]. Although these force feedback (kinesthetic feedback) systems are useful because operators understand the application of forces and the presence of contact with the environment, it is not easy to measure the precise contact force under heavy tasks for ordinary construction machines. In contrast, tactile cues such as high-frequency vibration caused by contacts are also important to provide information about collision conditions. Humans usually perceive environments using both tactile and kinesthetic cues, and it has been reported that the realism of contacting materials is improved by adding tactile cues

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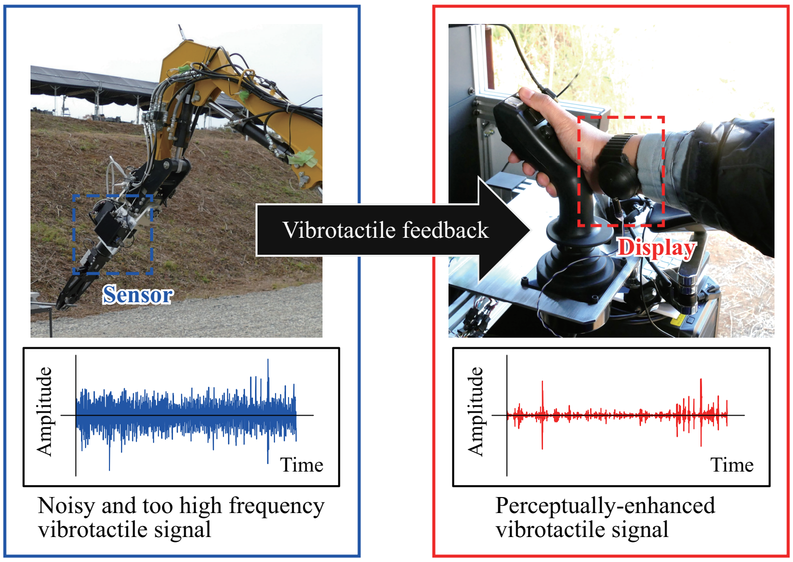

Figure 1. Transmission system of high-frequency vibration generated on construction robot with perceptually enhanced signal processing

to kinesthetic ones [6]. Several researchers have reported that by providing high-frequency vibration, humans perceive the properties of contact environments [7–9]. For example, Okamura et al. modeled the collision vibration characteristics of different materials and showed that modeled collision vibrotactile sitmuli could represent the hardness of virtual objects. The frequency spectrum of the collision vibrations can effectively represent material properties [10, 11]. For supporting telerobotic surgery, the feedback of contact vibration has been proposed and qualitatively evaluated [12], which is an example of the use of vibrotactile cues to support teleoperation. In the teleoperation of construction machines, the detection of collisional events plays several vital roles in ensuring situation awareness. For example, although visual feedback is the primary cue for teleoperation, limited sights result in difficulty in depth perception to confirm the timing of collisions with environments. Visual cues are not available when a machine collides with a buried object in the ground or objects at blind spots. Immediate vibrotactile feedback will provide another cue to detect such collisions to avoid applying excessive force to the contact objects. Vibrations at the end effector also change depending on soil properties and colliding speed. Such vibration feedback may guide the operator to adjust the operation speed and force according to the environment.

However, there is a critical problem that a simple transmission of the vibration recorded on a heavy robot could lose important contact information. The frequency range of vibrations measured on heavy steel-body robots such as construction machines is often beyond the human-perceivable range, which is approximately up to 800 Hz [13]. For example, we observed that the measured vibrations on the metal arm while digging soils using an excavator contained frequency peaks of over 2 kHz [14]. Therefore, it is important to develop a methodology to extract important collision information and modulate the vibration signals into a perceivable range as effective vibrotactile feedback for humans.

In this study, we develop a vibrotactile transmission system (Figure 1), which comprises vibration sensors attached to the robot and a vibrotactile display for the remote operator. We focus on the methodology for extracting haptic information from high-frequency vibratory signals and modulating signals that can provide operators information on contact properties. The idea is based on the human capacity to discriminate the envelope components of high-frequency vibrations, which are also considered important cues for perceiving the characteristics of contact materials and collision conditions as described in Section 2.

In our previous paper, we reported the feasibility of the proposed method with a normal excavator [15]. The main contributions of the present paper are as follows. First, we provide detailed discussions on the proposed method considering the human perceptual characteristics of high-frequency vibratory signals and the guidelines of the vibrotactile transmission system (Section 2 and 3). Second, we adopt the guidelines to the vibrotactile feedback system of the construction robot developed in the ImPACT

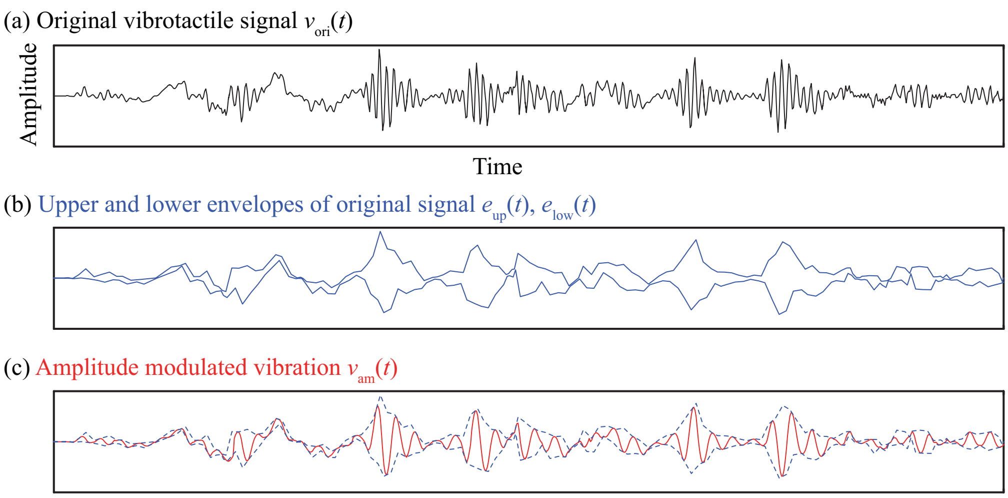

Figure 2. Process of modulation of high-frequency vibration

Tough Robotics Challenge (TRC) Program [14] (Section 4). Third, to the best of our knowledge, this is the first report on the performance evaluation of the maneuverability in delicate teleoperation using the ImPACT-TRC construction robot, which has a greater potential for precise motion control than conventional construction machines (Section 5).

2. Modulation methodology of high-frequency vibration

2.1 *Proposal*

As described in Section 1, high-frequency vibrotactile feedback has a high potential to deliver rich contact information. Reality-based modelings, which replicate collision vibrations based on the measured data, can represent the realistic contact feelings of materials by adjusting of the parameters of decaying sinusoidal wave [7] and the acceleration-matched model [6]. The vibrotactile transmission of acceleration on a tool demonstrated realistic feedback for telerobotic surgery application [12].

The major problem of the present study is the mismatch of vibration frequency ranges between the measured vibration on a heavy steel robot and the human-perceivable vibration, as described in Section 1. In this study, we assumed that the envelope shapes of the high-frequency vibrations could contain the contact information, and the envelope information could be delivered effectively by amplitude-modulated (AM) vibrations with a constant carrier frequency in the perceivable range. We had noticed empirically that the envelope shapes could contain contact information such as the impact and sliding conditions of collisions. The present study aims to verify our assumption experimentally (Experiments 1-1 and 1-2).

Although the human perceptual mechanism of collision vibration has not been clarified thus far, multiple studies suggest the possibilities of our assumption. First, the amplitude and decay rate of the collision vibration in the reality-based modeling [7] can be regarded as parameters to determine the envelope shape of vibrations. It is also known that humans can discriminate small differences in the decay rate (time constant) of damped sinusoidal waves [16]. Second, humans can also detect the envelope vibration of AM vibrations [17, 18]. Third, FA II type receptor, which is known as the receptor to perceive high-frequency vibrations, does not the waveform itself but detect the energy of vibrations [19, 20]. Thus, the envelope shape of the AM vibrations can reflect the energy changes if the carrier frequency is constant.

Figure 2 shows an example of the modulation process for high-frequency vibrations. Figure 2(a) is the original vibration measured on a robot, which often contains higher frequency components than the human-perceivable range (approximately up to 800 Hz [13]). Figure 2(b) shows the upper and lower envelopes of the original signal. The frequencies of the envelopes become so small that humans are more sensitive to the envelope signals compared with the original. Figure 2(c) shows the AM vibration within the envelopes with a constant carrier frequency. If the carrier frequency is selected in the most sensitive frequency range (200–300 Hz [21]), the perceived strength can be increased and humans can clearly perceive the contact information better than the original and envelope signals. We confirm the effect of the carrier frequency in Experiment 1-2.

2.2 *Preprocess: Subtraction of noisy vibration*

Measured tactile signals usually contain noisy vibrations such as engine vibration and driving vibration depending on the operation of the construction robot. Therefore, before the main process, the noisy vibration will be extracted from the measured signal using a noise subtraction technique. McMahan et al. proposed a method in which the spectrum of vibration in the non-contact condition is subtracted from that of the measured vibration when the robot is active [22]. In this method, the measured signal is transformed into frequency domain information (power spectral) using a short-term Fourier transform (STFT), and then the power of the noise signal, which is defined previously, is subtracted from that of the measured signal. The calculated frequency domain information is then transformed into time domain information using an inverse short-term Fourier transform (ISTFT), which we use as the original vibrotactile signal $v_{\mathrm{ori}}(t)$ as shown in Fig. 2(a).

2.3 *Main process: Envelope extraction and amplitude modulation*

The process flow is shown in Figure 2. An upper envelope $e_{\mathrm{up}}(t)$ and a lower envelope $e_{\mathrm{low}}(t)$ are extracted by finding the points where an original signal $v_{\mathrm{ori}}(t)$ is convex upward and downward, and linear interpolation is separately applied to those points. Then, an AM signal $v_{\mathrm{am}}(t)$, which is shown in Fig. 2(c), is determined as follows:

$$v_{\mathrm{am}}(t) = A(t - 1/f_{\mathrm{stft}})\sin(2\pi f t) + v_{\mathrm{off}}(t - 1/f_{\mathrm{stft}}), \tag{1}$$

$$A(t) = (e_{\mathrm{up}}(t) - e_{\mathrm{low}}(t))/2, \tag{2}$$

$$v_{\mathrm{off}}(t) = (e_{\mathrm{up}}(t) + e_{\mathrm{low}}(t))/2, \tag{3}$$

where $A(t)$, f, f_{stft}, and $v_{\mathrm{off}}(t)$ are the amplitude of the modulated vibration, frequency range that can be sensed by humans as the carrier frequency, frequency to apply STFT, and offset of the signals, respectively.

3. Experiment 1: Preliminary experiments

3.1 *Experiment 1-1: Basic discrimination performance*

3.1.1 Objective

An evaluation experiment was conducted to investigate whether the proposed method improved the ability of humans to discriminate the properties of contacting materials and operating characteristics of a moving manipulator.

3.1.2 Participants

Eight volunteers (aged 22 to 29 years, all right-handed, and with no history of deficits in tactile processing) participated in the experiments. They were not aware of the purpose of the experiments.

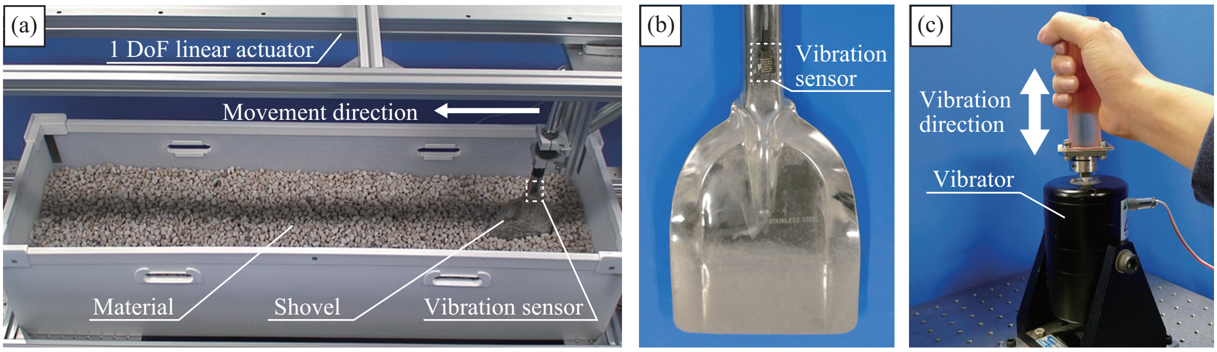

Figure 3. (a) Apparatus for recording the vibrations of the shovel digging the material with a one-DoF sliding motion. (b) Vibration sensor attached to the shovel. (c) Vibrotactile feedback device and poisitioning interface.

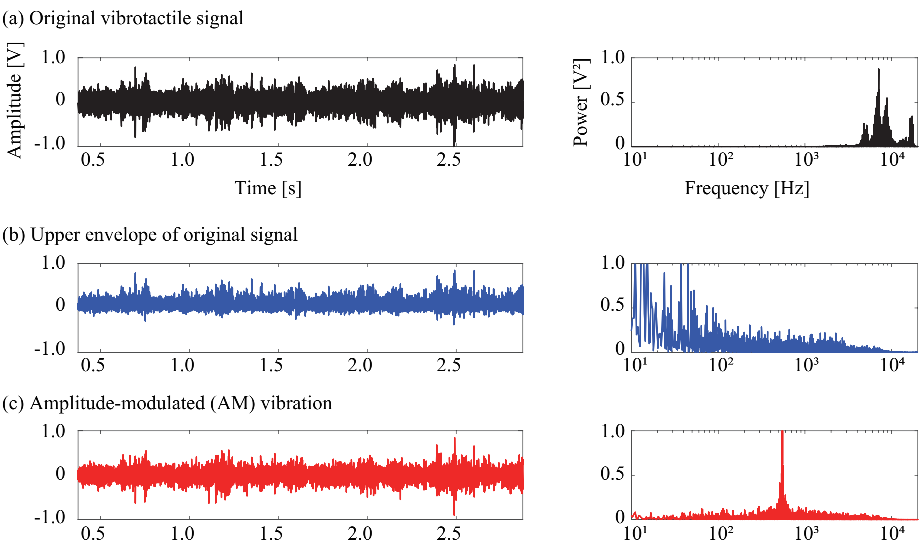

Figure 4. Examples of three types of vibrotactile signal in Experiment 1-1

3.1.3 Apparatus

The measurement apparatus is shown in Figure 3(a) and (b). A vibration sensor (NEC TOKIN, VS-BV203) was attached to the shovel used for digging the material (gravel), whose particle size affected the waveforms of the measured vibration. The sampling frequency for the vibration sensor was 50 kHz. The shovel was slided by a 1-DoF linear actuator (SMC Corporation, LEFS40B-1000).

The apparatus for generating the vibrotactile stimulation is shown in Figure 3(c). The vibotactile stimulation was delivered to the palm of the right hand by a vibration generator (EMIC CORPORATION, 511-A). The participants did not receive any special instruction about gripping force because it has been reported that the gripping force did not affect the vibration detection threshold [23]. The displacement of vibrotactile simulation was measured using a laser doppler displacement meter (KEYENCE CORPORATION, LK-H025) while activating without gripping.

3.1.4 Procedure

Six types of vibrotactile signals were measured, including three types of materials (small-size gravel, large-size pumice, and small-size pumice) and two sliding velocities (50 and 200 mm/s). From each of the six signals, five vibrotactile stimuli (2.5 s) were extracted, out of which four stimuli were used for the actual trials and one was used for the training trials. In addition, the three types of modulation shown in Figure 2 were applied to the stimuli. The carrier frequency f of method (c) was set to 550 Hz (chosen based on the human sensitive range). Examples of the three types of modulated vibrotactile stimulus are shown in Figure 4. For the noise-information-subtraction preprocess, we used the vibrations made while

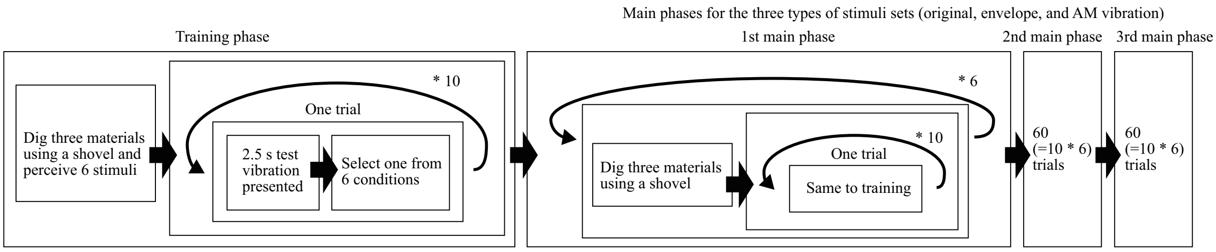

Figure 5. Schematic of the procedure in Experiment 1-1

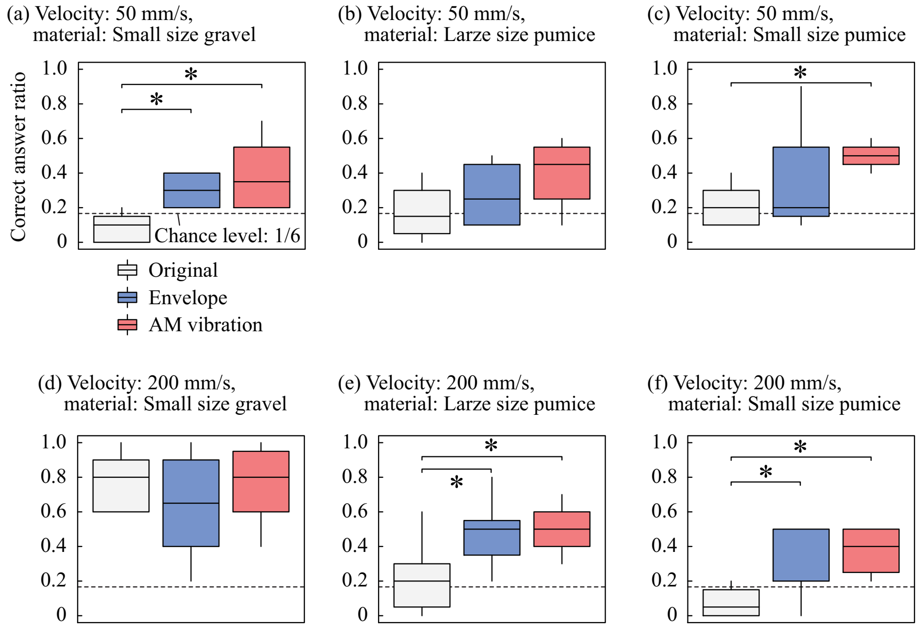

Figure 6. Result of Experiment 1-1: Correct answer ratios using three types of vibrotactile signals for each condition (velocity×material). ∗: adjusted $p < 0.05$.

the shovel was sliding around without colliding with the material.

Figure 5 shows the schematic of the procedure in Experiment 1-1. In one trial, a single vibrotactile stimulation (2.5 s) was presented to a participant, and the participant answered which of the six conditions was the same as the provided stimulus. First, the training phase was conducted. In the training phase, before the trials, the participants dug the three materials using a shovel and perceived the haptic sensations of the six stimuli. Then, ten actual trials were conducted without recording. Second, the main phases were conducted. Each of the six stimuli were presented to each participant ten times. Sixty trials were conducted for each set. In total, 180 trials were conducted for each participant, excluding the training trials. Before every ten trials, the participants were retrained using the three materials. The participants took a five-minute break between three types of stimuli sets. The entire experiment took approximately 80 min. The order of the stimuli sets and stimuli in each stimuli set were randomized for each participant.

3.1.5 Results

Figure 6 shows the correct answer ratios for the six conditions. To investigate which modulation methods improved the discriminability of the stimuli, multiple pairwise comparisons were performed using the Wilcoxon signed rank test with Bonferonni correction. We calculated p-values to estimate the probability of rejecting the null hypothesis of no statistical difference between the two groups [24]. For the 50 mm/s velocity and small-size gravel condition, there were significant differences between the original signals and the other two conditions (adjusted $p < 0.05$). In addition, for the results of the 50 mm/s velocity and small-size pumice condition, there was a significant difference between the original con-

Table 1. Ratios of discriminable conditions at which correct answer ratios are higher than the chance level

Type of vibrotactile signals	Ratio of discriminable condition
Original	1/6
Envelope	4/6
Amplitude modulated vibration	6/6

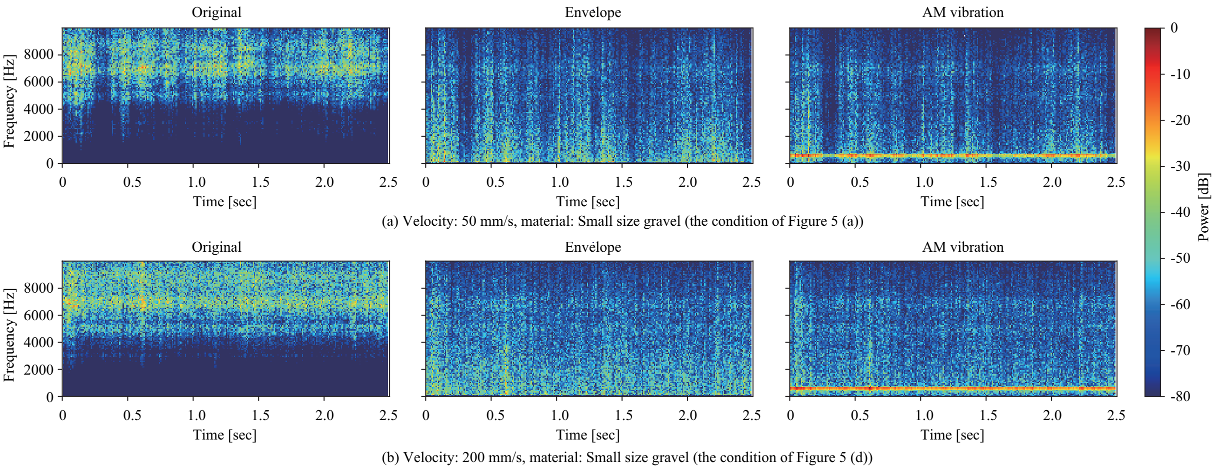

Figure 7. Examples of power spectrogram of stimuli used in Experiment 1-1

dition and the AM vibration condition (adjusted $p < 0.05$). For the 200 mm/s velocity conditions with large-size and small-size pumice, significant differences were found between the original signals and the other two conditions (adjusted $p < 0.05$).

In addition, we measured the number of discriminable conditions in which the correct answer ratios were significant higher ($p < 0.05$) than the chance level ($1/6$) of the answer ratios by using the Wilcoxon signed rank test. Chance level is the probability that the right stimulus will be selected by chance. The results are summarized in Table 1, which indicate that the AM vibration effectively improved the discriminability of the contact conditions compared with the other two conditions.

3.1.6 Discussions for Experiment 1-1

The results of Experiment 1-1 support our assumption that the envelope component could deliver the contact information. The results in Figure 6 showed that both the envelope and AM vibration conditions could improve the simultaneous discriminability of the contact material types and sliding velocities. AM vibration tends to have better discrimination performance. The result also supports our assumption that the AM vibrations with a single carrier frequency in a perceivable range provides more explicit sensation than the envelope itself.

We discuss the differences in vibration waveforms that vary with soil and impact velocity. Figure 7 shows the examples of the power spectrogram of stimuli used in Experiment 1-1. As an example, we compared the two conditions (conditions of Figure 6(a) and (d)). Figure 7(a) shows that there are occasional periods of no vibrations around 0.3 and 1.5 sec, whereas in Figure 7(b), the collision-induced vibrations are relatively continuous. It can be inferred that the number of contacts decreases as the speed decreases as a result. In addition, there is a difference in the temporal change in the power spectrum. The mean and standard deviation values of power at the carrier frequency are -21.2 ± 6.78 and -17.3 ± 3.77 dB in Figure 7(a) and (b), respectively. The properties of materials also affected the vibration, and the value was -11.0 ± 3.31 dB in 200 mm/s velocity for the large size pumice condition. These changes are also reflected in the envelope and AM vibrations.

The proposed modulation process improved the discriminable performance in Figure 6(a). In contrast, in Figure 6(d), the performance was not improved. Both Figure 7(a) and (b) show that the proposed process modulated the original signals to signals that can be easily perceived by humans, where AM

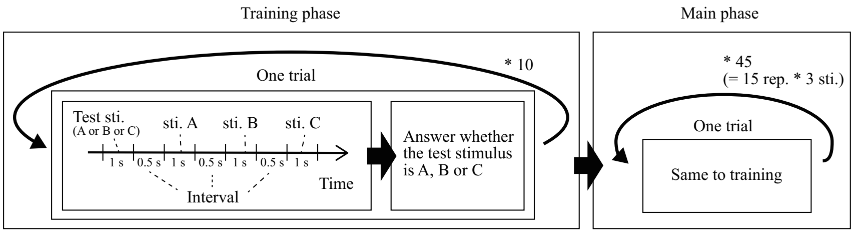

Figure 8. Schematic of the procedure in Experiment 1-2

vibration signals have a high power spectrum in the carrier frequency. As mentioned above, the power in Figure 7(a) is more variable with time than in Figure 7(b). The discrimination performance in Figure 7(b) seems to be higher because such a tendency is easy to distinguish from other conditions. In terms of the original signals of the two conditions, this difference is also observed in the high-frequency range; however, humans cannot perceive the temporal change in this range. In contrast, in terms of the AM and envelope signals, this difference is observed in the low-frequency range, which humans are sensitive to. This difference may lead to a difference in the discriminable performance between the two conditions.

3.2 *Experiment 1-2: Discrimination test of AM vibrations*

An evaluation experiment was conducted to investigate whether humans can discriminate stimuli based on the difference in envelope frequency and whether the carrier frequency affects the discrimination performance. The envelope frequency is the frequency of the wave outlining the extremes in the amplitude of an original signal.

3.2.1 Participants

Eight volunteers (aged 22 to 29 years, all right-handed, and with no history of deficits in tactile processing) participated in the experiments. They were not aware of the purpose of the experiments. They were different from the participants in Experiment 1-1.

3.2.2 Apparatus

The apparatus for generating the vibrotactile stimulation was the same as that used in Experiment 1-1.

3.2.3 Procedure

The participants sat down on the chair and rested their forearms on the armrest during the experiments. To mask the sound generated by the vibrator, they heard pink noise through headphones and also used earplugs. Figure 8 shows the schematic of the procedure in Experiment 1-2.

In one trial, four vibrotactile stimuli (each 1 s) with 0.5 s intervals were provided to a participant. The first stimulus was the test stimuli, and the following three stimuli were the three references. The test stimulus was the same as one of the following three stimuli. At the end of one trial, a participant answers which of A, B, and C matches the test stimulus. The combination of the three stimuli is listed in Table 2. The amplitudes of all the stimuli were adjusted to be equal. The participants were allowed to repeat the stimuli as many times as they wanted; however, it was recommended that they repeated the stimuli less than three times (including the first time).

The orders of the stimuli sets and test stimuli in each stimuli set were randomized for each participant. In the beginning, ten trials were conducted as the training phase to help the participants become familiar with the experimental procedure, and then the actual phases were conducted. The training results were not recorded. For each of the three stimuli, 15 trials were conducted. In total, 45 trails were conducted for each stimuli set.

3.2.4 Results

The correct answer rate for each stimuli is shown in Figure 9 with a dotted line indicating the chance level (1/3). The ratios for the five conditions with different carrier frequencies seem to be higher than

Table 2. Stimulus sets.

Stimuli set	Envelope freq., carrier freq. [Hz]		
1	60, 200	80, 200	100, 200
2	60, 300	80, 300	100, 300
3	60, 500	80, 500	100, 500
4	60, 700	80, 700	100, 700
5	60, 1000	80, 1000	100, 1000

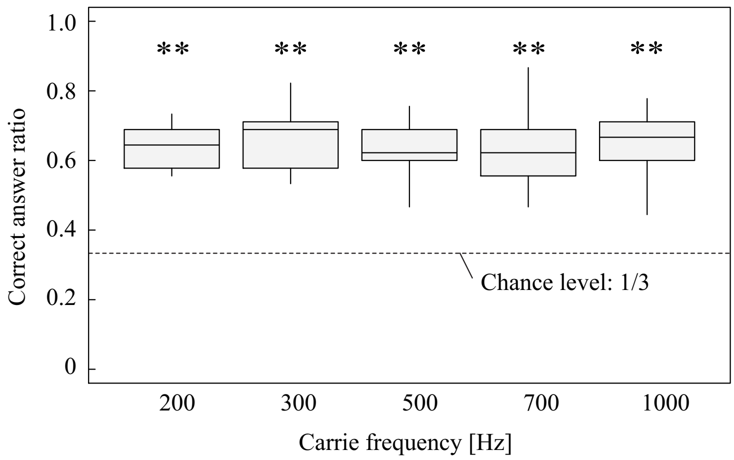

Figure 9. Result of Experiment 1-2: Correct answer ratio. $**$: $p < 0.01$.

the chance level. This is supported by the results of the Wilcoxon signed rank test, in which there were significant differences between the chance level $1/3$ ($p < 0.01$) and each of the five conditions. This implies that the participants could discriminate the stimuli set based on an envelope difference. In addition, the Friedman test revealed that there is no significant difference among the ratios in the five conditions ($p > 0.05$). This implies that the discrimination performance is comparable regardless of the carrier frequency. In addition, it was found that humans can distinguish the envelope frequencies of AM vibrations even if the carrier frequency is high, for example, 1000 Hz. This result is consistent with the reports that humans can perceive the envelope of AM vibrations [17, 18].

3.2.5 Discussions for Experiment 1-2

The results of Experiment 1-2 showed that humans can discriminate the stimuli with different envelopes regardless of the carrier frequency. The carrier frequency of the AM vibration can be arbitrarily selected from 200 to 1000 Hz. However, in this experiment, the amplitudes of all the stimuli are adjusted to be the same. The energy of a vibratory stimulus with a high carrier frequency is larger than that with a low frequency. Therefore, a high carrier frequency is not appropriate for a small vibrator to generate sufficient sensitive amplitudes. If a small vibrotactile display is necessary because of wearability and practicality reasons, high carrier frequencies should be avoided. Further, even if the same amplitude is presented at high and low carrier frequencies (e.g., 1000 and 200 Hz), the vibratory signal at the high carrier frequency is more difficult to be perceived. Because the peak frequency of human sensitivity to vibrotactile stimuli lies between 200 and 300 Hz [21].

3.3 *Examination of a body part for presenting vibrotactile stimulus*

In Experiments 1-1 and 1-2, a vibrotactile stimulus was delivered to the palm of the right hand through a grip. The palm is a good presenting part because it is highly sensitive to vibrotactile signals. However, during teleoperations, the palm is commonly used for controlling interfaces such as a joystick.

A reasonable approach is delivering a vibrotactile stimulus to the wrist of an operator. It can be used

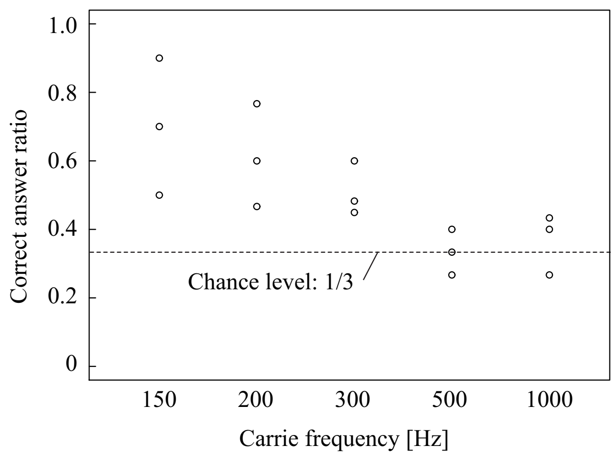

Figure 10. Results of an experiment presenting a vibration stimulus to the wrist

simultaneously with other interfaces such as a joystick or joypad. Although the sensitivity of the wrist is not as high as that of the palm, several studies have adopted the wrist as a stimulus presentation site and confirmed that the presented vibrotactile stimuli led to tactile sensation [25–27].

We conducted a preliminary experiment with three participants to present vibration stimulation on the wrist. Most of the procedure is the same as in Experiment 1-2; however, the envelope frequencies (64, 80 and 96 Hz) and the carrier frequencies (150, 200, 300, 500 and 1000 Hz) are close values but different. The correct answer rate of each stimulus is shown in Figure 10 with a dotted line indicating the chance level (1/3). The results show that at low frequencies (150, 200, and 300 Hz), the ratio is similar to that of Experiment 1-2. The wrist-mounted vibrator was able to reproduce sufficient vibration amplitude at low frequencies, but probably could not give perceptible enough vibration at high frequencies. Thus, the wrist showed the same trend as the palm at lower frequencies. It was also clarified that the actuator could not provide sufficient amplitude when using a very high carrier frequency.

In addition, it has been reported that Pacinian mechanoreceptors exist in the wrist and its surroundings [28, 29]. Because the proposed modulation methodology is based on the characteristics of Pacinian corpuscles, it is expected that the present method exerts a similar effect on the wrist. Because there is a difference in sensitivity to vibration stimulation between the wrist and the palm, the performance (improvement of the correct answer rate in Experiment 1-1) might have a difference.

4. Implementation of vibrotactile transmission system on construction robot

The vibrotactile transmission system adopting the modulation method was implemented for the teleoperaton system of the construction robot developed in the ImPACT Tough Robotics Challenge (TRC) Program [14] as shown in Figure 11.

As shown in Figure 11(a), the sensor box comprising a piezoelectric vibration sensor (NEC TOKIN, VS-BV203) is attached at a position slightly away from the manipulator of the robot. The sensing system measures the vibrations propagating through the body of the construction robot; therefore, the attaching position can be located at a distance from the tip manipulating position to ensure that it does not break easily. The vibration signals were sampled at 8 kHz.

As shown in Figure 11(b), the operator wore a wristband-shaped vibrotactile display containing a voice coil actuator (Vp2, Acouve Laboratory Inc.), which can reproduce vibrotactile signals in a wide frequency band. Vibrotactile stimuli were presented inside the wrist. Because, when the inside and outside of the wrist were compared, a smaller stimulus was perceived when the vibrotactile stimulus was presented to the inner side. The transmitted signal from the robot was modulated using the developed methodology. It is available with several types of interfaces such as a joystick and joypad.

The sensor and display can be applied to the existing teleoperation system of a construction robot

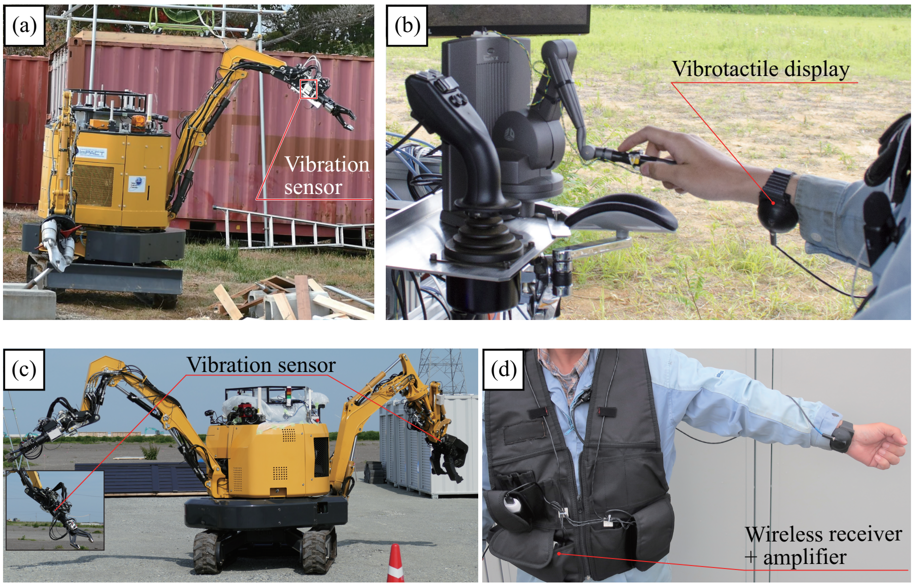

Figure 11. (a) Vibration sensor system attached on an arm of a construction robot. (b) A wristband-shaped vibrotactile display for the operator. (c) Multiple vibration sensor system for dual arms of a construction robot. (b) Jacket-type wireless vibrotactile display system for the operator.

without any altering of the system. The easily implementable sensor and display components resulted in high versatility and durability. As shown in Figure 11(c) and (d), multiple transmission systems and wireless transmission systems were also developed, which increased the versatility of the developed system.

5. Experiment 2: Evaluation of maneuverability in delicate teleoperation

5.1 *Objective*

To evaluate the effectiveness of the developed vibrotactile transmission system, the influence of the system on the maneuverability during delicate teleoperation under the remote control environment of the ImPACT-TRC was investigated. We expect the tactile transmission system to transmit contact information around the end effector and realize delicate teleoperation work. The work of inserting reinforcing bars into perforated bricks was adopted as delicate work, and we evaluated the generated forces during maneuvering and the time required for finishing a task.

5.2 *Participants*

Three males with experience in operating construction robots participated in the experiment. There were differences in their control experience. One participant had over 100 h of control experience, while the other two participants had just more than a few hours of control experience. In addition, all the three participants were given preliminary training several times to work on this experiment.

5.3 *Apparatus*

The experimental environment is shown in Figure 12. As shown in Figure 12(a), the end effector of the construction robot was a gripper capable for pinching an object. In the experiment, as shown in Figure 12(b), the rebar held by the gripper was inserted into the brick hole until it collided with the end wall. As the working environment of a construction robot, an environment such as a collapsed house where visual information cannot be obtained can be reasonably considered. Under such circumstances, tactile information is considered to be very important. Therefore, in this experiment, a situation where

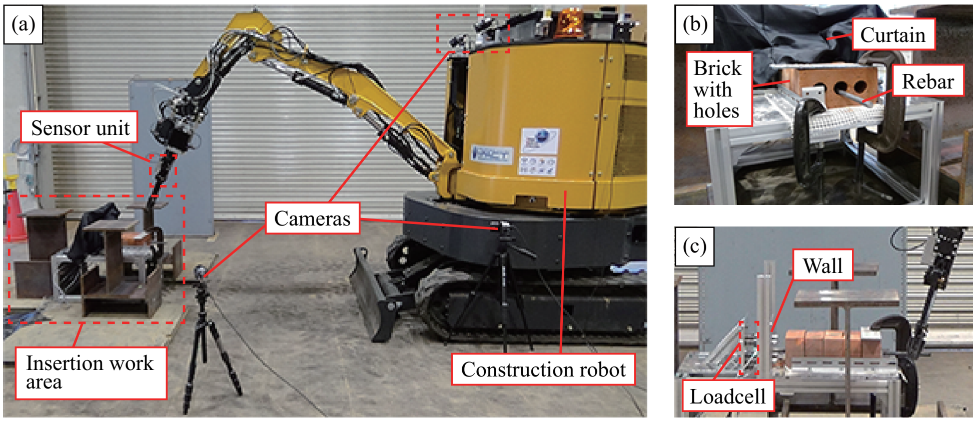

Figure 12. Experiment environment. (a) Around construction robot. (b) Around insertion work area. (c) Around measurement area.

an operator could hardly judge the collision timing by visual information was prepared by covering the end wall with a black curtain. The covered area is shown in Figure 12(c), and the load cell (Models 615, VPG Inc.) was placed on the back of the end wall. The contact force was measured with the sampling frequency of 5 kHz. Moreover, the end wall and bricks were fixed using weights so that they did not move due to the contact with the end effector.

As shown in Figure 12(c), the vibrotactile information from the vibrotactile sensor unit and the visual information from the three cameras were presented to the operator. A vibrotactile signal was presented by the wrist-shaped tactile display equipped with a voice coil actuator (Vp210, ACOUVE LABORATORY Inc.) as shown in Figure 11(b). In addition, as shown in Figure 11(b), the position of the end effector was controlled using a force feedback device (Geomagic Touch X, 3D System Corp.) In this experiment, a force feedback was not used.

5.4 *Procedure*

In each trial, the participant had to control the gripper to pinch a bar already inserted in a perforated brick, and then pull out and insert the bar into the same holes again. Then, the participant had to release the bar when they recognized that the bar collided with the end wall. The participants were instructed to work as quickly as possible with as little contact as possible with the blocks.

There were three feedback conditions: 1) no haptic feedback, 2) noise-reduced vibration, and 3) enhanced vibration. In the first condition, a participant worked without a haptic feedback. In the second condition, a noise-reduced vibration similar to the one shown in Figure 2(a) is presented to a participant during teleoperation. In the third condition, a perceptually enhanced vibratory signal similar to the one shown in Figure. 2(c) was used as haptic feedback information. The carrier frequency in the modulation method was $f = 300$ Hz.

A total of 30 trials were performed, 10 trials for each feedback condition. One condition required approximately takes about 25 min, and a break of 30 min or more was provided between conditions. During the trials, the participants were presented with pink noise from a headphone to intercept the auditory information from the experimental environment.

5.5 *Results*

5.5.1 Measured and displayed vibrotactile signals

Examples of the measured raw vibration waveform and the two types of presented vibration waveforms are shown in Figure 13. The vibration waveform used for the noise subtraction process was measured while the arm of the construction robot moved freely in air. Moreover, to remove the low-frequency components of the measured signal, a fifth-order high-pass filter with a cutoff frequency of 30 Hz was

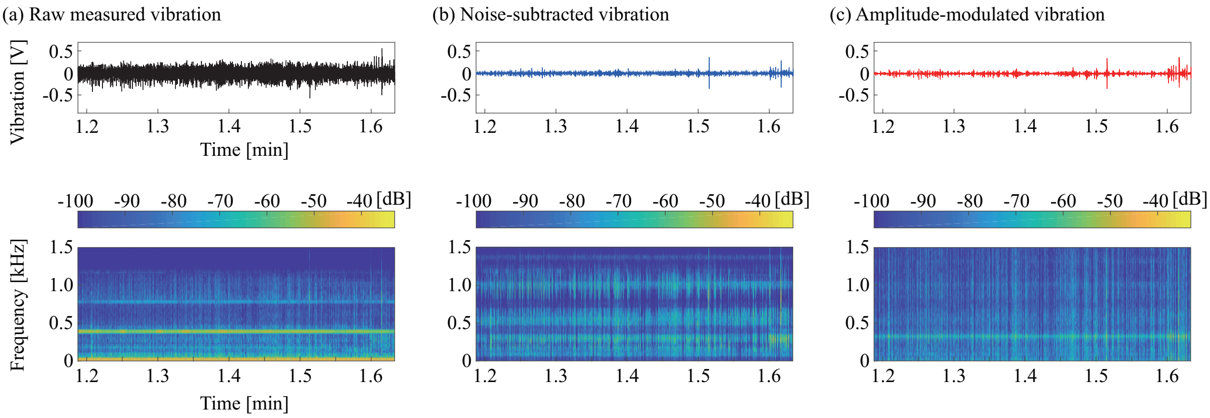

Figure 13. Examples of vibrotactile signals during teleoperation. (a) Raw measured signal. (b) Noise-subtracted signal. (c) Amplitude-modulated signal.

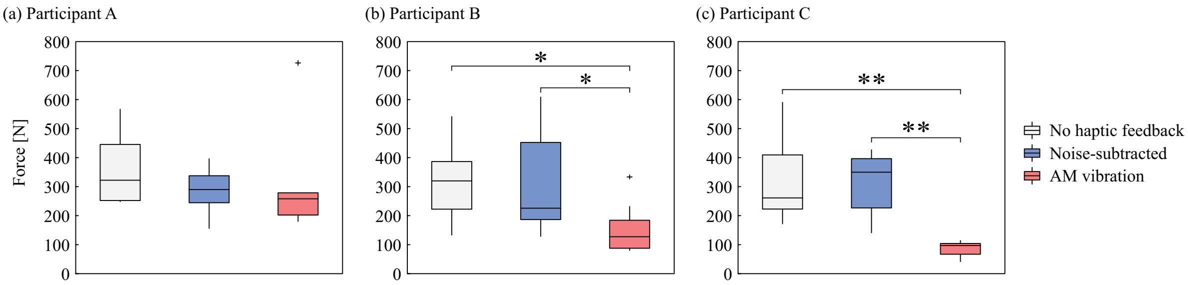

Figure 14. Peak value of collision force. (a) Partcipant A. (b) Partcipant B. (c) Partcipant C. $*$: adjusted $p < .05$ and $**$: adjusted $p < .01$.

used. The low-frequency damped vibration generated at the start and stop of arm operation was not included in pre-recorded steady-state vibration noise. In addition, it is difficult to present low-frequency vibration by the installed vibrator. Comparing Figure 13(a) and Figure 13(b), it can be confirmed that steady noise vibrations can be removed. In Figure 13(a), other vibration information is obscured by large amplitude vibrations that seem to have peaks around 400 Hz and 800 Hz, but no such peak are seen in Figure 13(b). In addition, by comparing Figure 13(b) and Figure 13(c), it is confirmed that the peak frequency can be modulated to 300 Hz (human sensitive frequency) while maintaining the envelope.

5.5.2 Contact force

The peak value of the contact force generated when the reinforcing bar collided with the end wall was calculated. To remove the high-frequency noise, a fifth-order low-pass filter with a cutoff frequency of 10 Hz was applied to the output of the load cell. The peak value of the collision force is the maximum value of the sum of the values of the four load cells. The results for each participant are shown in Figure 14. In the data of all participants, the peak value of the contact force in the enhanced vibration feedback condition seems smaller than that in the other two conditions. Pairwise comparisons using Wilcoxon rank sum test with Bonferonni correction were conducted. As a result, it was found that there was no significant difference in the data of participant A. In contrast, in the data of participant B, there were significant differences between the AM vibration feedback condition and the other two conditions (no-haptic-feedback condition: adjusted $p < 0.05$, noise-subtracted vibration condition: adjusted $p < 0.05$). In addition, for participant C, two significant differences were observed between the enhanced vibration feedback condition and the no-haptic-feedback condition (adjusted $p < 0.01$) and between the enhanced vibration condition and the noise-reduced vibration condition (adjusted $p < .01$).

5.5.3 Task execution time

The task execution time was measured. Based on the side camera image, we calculated the duration from the time when the rebar tip started to enter the hole of the brick to the time when it collided with

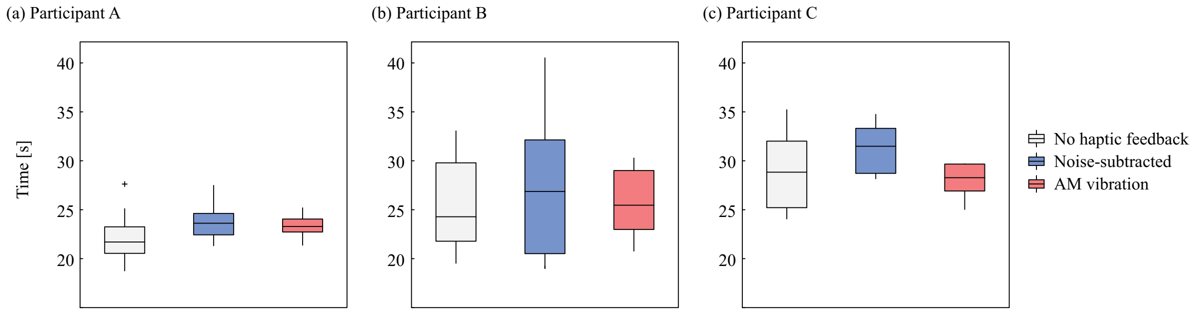

Figure 15. Elapsed time for completing the insertion task. (a) Partcipant A. (b) Partcipant B. (c) Partcipant C.

the end wall. The results for each participant are shown in Figure 15. The same analysis as the abovementioned peak value of contact force was performed. As a result, no statistically significant difference was found for any condition. However, the variation in the execution time for the condition with the enhanced vibration feedback tends to be small compared with the other two conditions.

5.6 *Discussions*

5.6.1 Effects of vibrotactile feedback and modification method

With regard to the peak value of contact in Section 5.5.2, it was confirmed that the peak contact force in the AM vibration condition was significantly reduced in the data of participants B and C. However, there was no significant difference in the data of participant A. Three participants were pilots in the construction robot operation; however, participant A was an expert and participants B and C were beginners with regard to the teleoperation of the construction robot. Considering this, it is expected that participant A is familiar with normal teleoperation without tactile feedback and that he can estimate a collision occurrence from visual information such as the movement of the end effector without depending on vibrotactile signals. Considering the positive results for participants B and C, if participant A had been trained for the teleoperation with tactile feedback or if they were beginners, their results may have been similar to the results of participants B and C.

In addition, there is an interesting point in the results of the peak value of contact. The results for the AM vibration condition of participants B and C tend to be better than that of participant A. Although participants B and C were beginners, they showed better maneuverability than the expert participant A, because they effectively relied on tactile feedback. This point also implies that participant A did not depend on the vibrotactile feedback.

Moreover, there was no improvement in performance with the noise-subtracted condition. Moreover, there was no improvement in performance with the noise-subtracted condition. The process of noise-reduction alone did not seem to enhance the feedback stimuli and lead to performance improvement, suggesting the need for the proposed concept of enhancement processing.

Regarding the results of the task execution time in Section 5.5.3, there was no significant difference among the three conditions for all participants. Although participant A did not rely on haptic feedback due to her proficiency, it is reasonable to assume that there is no difference in task execution time, as supported by the discussion of peak contact forces. For the beginner participants B and C, the tactile feedback allowed them to concentrate on the contact situations and to perform more delicate manipulations, which might be expected to result in more time-consuming and careful manipulations.

5.6.2 Comparison with force feedback

The proposed vibrotactile feedback showed better performance in reducing the peak collision force applied to the wall in Experiment 2. This is because the vibrotactile feedback delivered a collision occurrence to the operators, and the operators could stop the operation before they applied heavy loads.

Here, we discuss the possibility that force feedback could also work well for a similar task. In general, a force feedback system requires force/torque sensing, and there are many types of master-slave system that can deliver realistic contact information to the operator [30]. However, a standard force/torque sensor is too fragile for construction machines, which applies massive impulsive forces to the end effector. A hydraulic pressure that drives the construction machine could be used for estimating the contact force. The construction robot developed in the ImPACT-TRC project [14] developed a force feedback system by estimating the contact force at the end effector based on the hydraulic pressures and dynamics of the robot. However, the frame rate of the force estimation was 100 Hz, which was good for representing the static amount but not sufficient for realistic collision feeling. Hydraulic fluid could also absorb the impulsive force and weaken the initial contact information. In addition, the vibrations generated by collisions and contacts are generally high-frequency vibrations. When comparing them in the conditions that transmit them, force feedback is not suitable for the representation of the collision situation, and vibrotactile feedback has an advantage over it. However, vibrotactile feedback does not contain the directional information of the applied force. The ideal approach could be a combination of the vibrotactile and force feedback. However, our proposal has a significant advantage in terms of easy implementation.

6. Conclusions

This study developed a vibrotactile transmission system for supporting the teleoperation of construction machines. The key idea of the system is based on the modulating methodology for vibrotactile signals based on human perceptual characteristics. The proposed method involves modulating the amplitude of the human sensitive frequency vibration with the envelope of the original vibrotactile signal measured on the body of a construction robot. First, we conducted psychophysical experiments (1-1 and 1-2) to verify the proposed method in lab environments. The results of Experiment 1-1 showed that the proposed method (amplitude-modulated vibration) improves the simultaneous discriminability of the contact material types and sliding velocities while the raw vibrotactile waveform cannot convey most information required for discrimination. The results of Experiment 1-2 showed that humans can discriminate the envelope difference of high-frequency vibration regardless of the carrier frequency from 200 to 1000 Hz, which means that the carrier frequency can be selected flexibly based on the requirements of the user such as the frequency characteristics of the vibrator. Based on the above findings, we developed a vibrotactile transmission system consisting of vibration sensors and wearable wristband-shaped vibrotactile displays. Second, we conducted a performance evaluation experiment to investigate the effect of the proposed transmission system under the actual teleoperation of the construction robot. The task of the experiment was to insert a metal bar into the holes of a brick block, which requires delicate maneuvering. The performance was evaluated in terms of the peak of the collision force and the task execution time. The task execution time did not differ among the conditions. However, the peak force with the proposed method tended to be lower than those of the other conditions. The results suggest that the proposed method could improve the maneuverability of teleoperation.

acknowledgment

This work was partially supported by the ImPACT Program “Tough Robotics Challenge,” and JSPS KAKENHI Grant Numbers JP18H01401 and JP18K13722.

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