Recording & Rendering High-Frequency Vibrations Through a Deployable System

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By

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List of contents

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***Abstract*—In dangerous environments, teleoperation is needed to enable humans to execute tasks remotely. To assist in these tasks, *haptic* teleoperation systems provide the human operator with the sense of touch of the telerobot. One way to provide this sense of touch is through high-frequency vibration feedback. State-of-the-art solutions generally rely on integrated hardware, which limits their application to specific telerobots and master devices.**

The aim of this study is to develop a deployable high-frequency vibration feedback method through an add-on setup. In the presented system, both the vibration recording device and vibration feedback display run on a single microcontroller. Furthermore, all components are small in size and portable by the robotic or human hand.

Spectral analysis of the replicated vibrations shows that the presented system is capable of mimicking textures. To evaluate the effectiveness of the texture imitations, a human factors experiment is conducted. Twenty participants executed a texture identification task for two conditions: a manual condition with direct tactile feedback and a teleoperated condition with tactile feedback displayed by the presented system.

Results show that 75-85% of the textures were correctly identified in the teleoperated condition. These correctness rates are close to the results of the manual condition (96% correct) and outperform the chances of random guessing by a factor three. In the teleoperated condition, participants took on average 67% longer than in the manual feedback condition.

Based on these results, it is concluded that the presented add-on system enables humans to accurately feel high-frequency vibrations in teleoperation.

Keywords—Teleoperation, vibration feedback, texture identification

I. INTRODUCTION

Robots excel in repetitive tasks and are therefore mostly installed in the manufacturing industry [1]. However, in more complex tasks, human creativity is irreplaceable. In some applications, e.g. in dangerous environments or when the tasks demands physical capabilities beyond the human capability, physical human presence is not feasible or not desirable [2]. In these situations, teleoperation is applied, allowing a human operator to control a telerobot remotely.

To adequately control the telerobot, the human operator needs feedback on the state of the telerobot and its interaction with the environment. Most systems control the position of the robotic arm through a master input device and rely on visual feedback through camera's. Some systems also add *haptic feedback* to the master device. Haptic feedback provides the human operator with a sense of touch, e.g. through force feedback [3]. To avoid instabilities in force feedback systems, higher frequencies are typically filtered or dampened out [4]. However, high frequencies do encode valuable information on contact, contact transitions and textures [5]. Therefore, teleoperation without high-frequency vibration feedback results in contacts feeling indistinct and objects feeling soft.

To add high-frequency vibration feedback to the low-frequency force feedback systems, various researchers added an open feedback loop to the bilateral force feedback loop. To compensate for the master device's limited response in the higher frequencies, researchers applied either a crude *inverse master model* [6] or a more sophisticated one [7]. These solutions account for the dynamics of the master device, but result in a device specific method that only works with specific master devices capable of reproducing high-frequency vibrations.

Other researchers have used dedicated vibration actuators that can render complex vibration waveforms with higher fidelity. Some of these systems use complex dedicated sensor systems to mimic human finger sensing [8]–[10]. Other systems combine dedicated vibration sensors and actuators that are specific to the used telerobot or master device respectively [11], [12].

This paper describes a novel, standalone, add-on system to record and render high-frequency vibrations which can be deployed in different teleoperation systems, see Fig. 1.

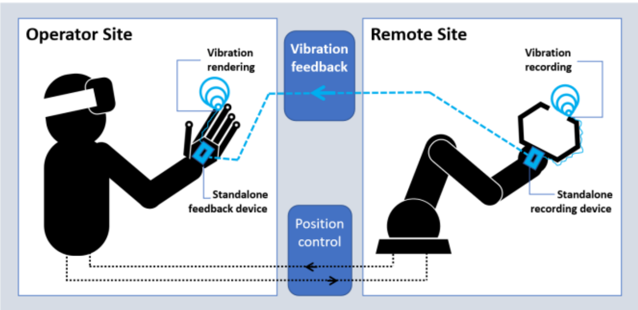

Fig. 1: A novel, independent system to render high-frequency vibrations through standalone devices, deployable to teleoperation systems.

To prove the effectiveness of the novel system, a human factors experiment was conducted that had participants perform a texture identification task. The results are compared to random guessing, as assumed to be the baseline of teleoperation without high-frequency vibration feedback. Furthermore, results are compared to manual operation, which is assumed to be the perfect score.

Therefore, the experiment tests the following hypotheses:

1. Teleoperation with the presented high-frequency vibration feedback system performs better than random guessing regarding texture identification correctness.
2. Manual operation with direct feedback performs better than or equal to teleoperation with the presented high-frequency feedback system regarding texture identifications correctness.
3. Manual operation with direct feedback performs better than or equal to teleoperation with the presented high-frequency feedback system regarding texture identification time.

II. Recording & Rendering of High-Frequency Vibrations through a Deployable Setup

A. System components

The primary objective of this thesis was to develop a system that can be deployed in teleoperation to provide high-frequency vibration feedback. To achieve this deployability, the system consists of a standalone device that can be attached to a telerobot to record vibrations and a vibration feedback display that is wearable on a human finger.

1) Vibration Recording

To record the vibrations at the remote site, a vibration sensor should be placed on, or close to, a gripper's finger tips. A MEMS accelerometer is best practicable for various reasons. Firstly, such sensors are very deployable due to their small size and low operating voltages. Secondly, this type of sensors measure accelerations rather than contact displacements. Therefore, it can be attached onto the more distant components of the gripper, instead of onto the fingertips where it could impair the movements and functionalities of the gripper.

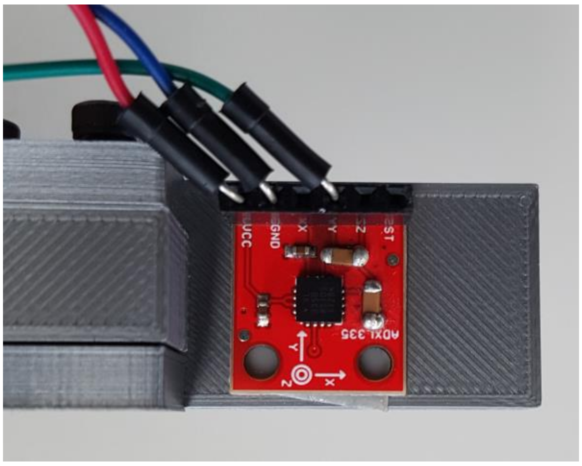

Fig. 2: The vibration sensor: an accelerometer with pin headers to easily select one axis (green wire, here selecting the y-axis). Capacitors on the y- and z- axes are replaced to increase the bandwidth to 1600Hz.

Mounted on the 16 x 18 mm breakout board from SparkFun, a triple-axis ADXL335 accelerometer from Analog Devices provides a range of at least ± 3g. An integrated analog (RC) filter results in a bandwidth of up to 1600 Hz. As shown in Fig. 2, pin headers are soldered onto the breakout board allowing the user to easily select one of the axes to record the vibrations on.

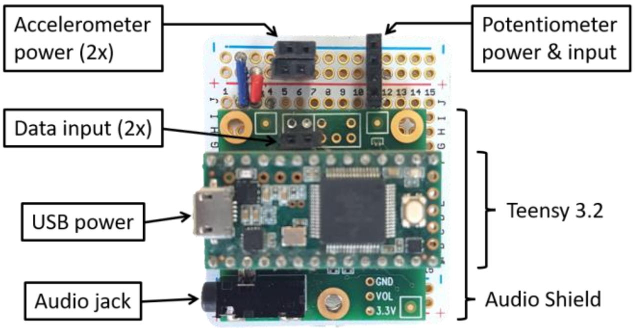

Fig. 3: The microcontroller: a stacked Teensy 3.2 and Audio shield, and its connections that enable left and right vibration data streams and one potentiometer for volume control. Power is supplied through a USB.

2) Microcontroller

The whole system runs on a single microcontroller: a Teensy 3.2 by PJRC. The Teensy is powered by a USB cable at 5 V, which it converts to 3.3 V for use by the internal and external components. Soldered to the Teensy is an Audio Adaptor Rev C, also from PJRC, and together this setup can receive analog data, impose digital filtering, and output analog data with the benefits of well-developed audio processing techniques. The stacked devices are soldered onto a proto-board of 44 x 55 mm to connect additional external devices, see Fig. 3.

A schematic of the signal processing of the vibrations data is shown in Fig. 4: the accelerometer data is read from 0 - 3.3 V with 16-bit resolution and is converted to digital at 44.1 kHz by the Audio Adaptor's Analog-to-Digital Converter (ADC). It is then sent to the Teensy for digital processing with the I2S protocol. After filtering and setting the gain, the digital audio is sent to the Audio Adaptor's 16-bit Digital-to-Analog Converter (DAC). The analog output signal drives the actuators through a headphone audio jack with 0 - 3.15 V.

The digital filtering is performed using Teensy's pre-programmed *state variable filters* (Chamberlin's digital version). This type of filter can provide the high-pass, band-pass and low-pass responses simultaneously, each with a second-order transfer function controlled by only two parameters: the corner frequency and the resonance [13].

This study uses two consecutive state variable filters: the data is first subjected to a low-pass filter with a corner frequency of 500 Hz, followed by a high-pass filter set at 40 Hz. The resulting bandwidth is similar to the perception band of the *Pacinian Corpuscles* (or '*FAII receptors*') the human uses to detect high-frequency vibrations [14]. The

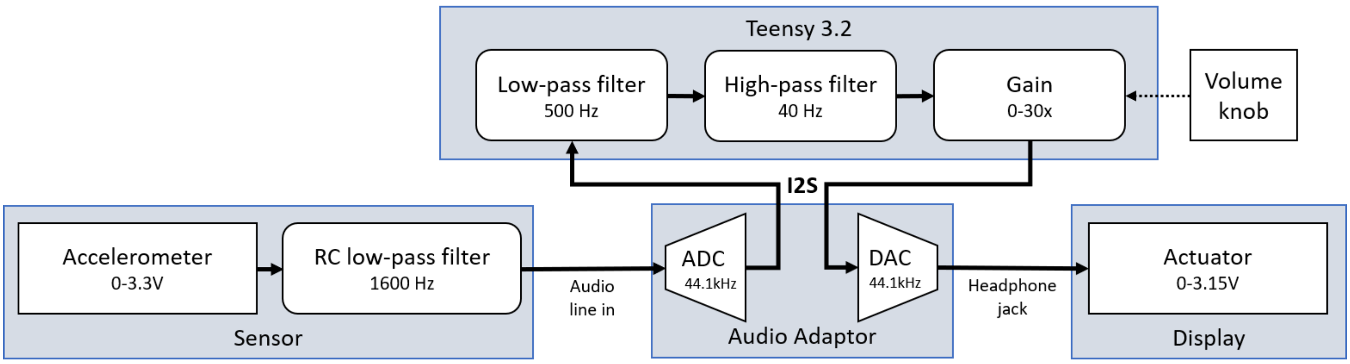

Fig. 4: Schematic overview of the vibration data flow.

high-pass filter also cancels out the low-frequency movements of the telerobot.

Subsequent to the filtering, a gain is imposed to the digital output to compensate for differences between humans regarding perception sensitivity [15], user impedance [16] and personal preferences [11]. The human operator can set the gain from 0 to 30 through an external potentiometer to adjust the volume of the vibrations rendered by the actuator.

3) Vibration display

The actuator that renders the vibrations is the TEAX14C02-8 Compact Audio Exciter from Tectonic. This voice coil actuator has a footprint of 37 x 20 mm, about the size of the fingertip of an adult index finger. Its resonance frequency is around 600 Hz, outside the range of the vibrations excited, and beyond human perception [14].

As shown in Fig. 5 the actuator should be placed with the moving mass towards the inside of the fingertip, but outside any force-feedback mechanisms of a haptic glove. Activation of such mechanisms would subject a mechanical impedance onto the actuator, resulting in weaker vibrations.

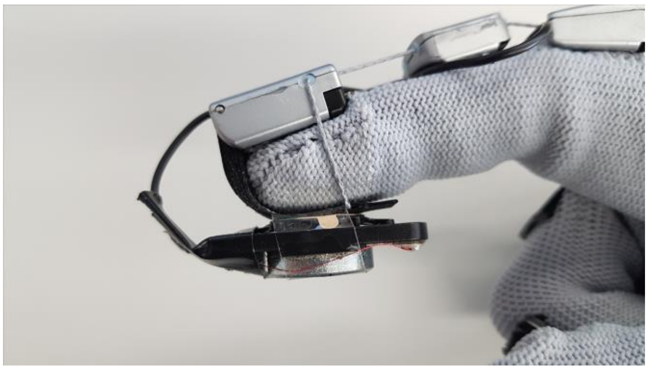

Fig. 5: The vibration display: a voice coil actuator placed on the inside of the fingertip of the haptic glove SenseGlove Nova.

B. System behaviour

To unveil the system behaviour, the rendered vibrations were recorded by a second, identical accelerometer which was placed between the actuator and the human's finger. Recordings of these output vibrations are compared with the original input vibrations recorded by the system's first accelerometer. Analysis of this data in the time domain showed a delay of 9 ms between the recording and the rendering of the vibrations. This delay is below the human tactile temporal discrimination threshold (~30 - 50 ms) [17].

The system behaviour is also evaluated in frequency domain, as spectral matching drives the realism of the vibration feedback [18]. Shown in Fig. 6, several power spectral density plots show that the measured output vibrations match the original vibrations well during interactions with various textures, but show more noise when stationary. This noise is largely caused by the digital-to-analog conversion. Considering the logarithmic scale, the noise level is low compared to vibrations of interaction with the different textures, with exception of the smooth paper.

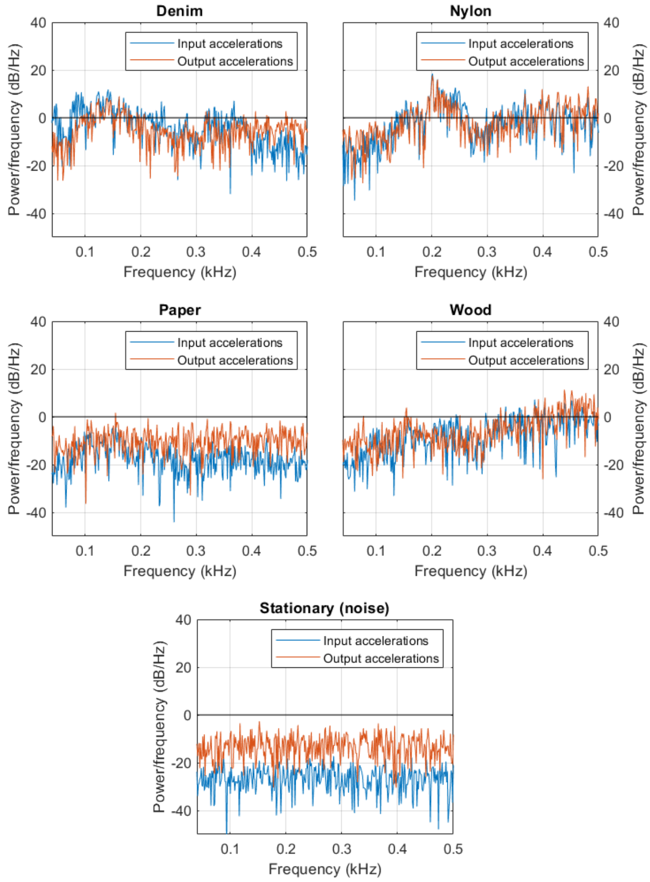

Fig. 6: Power Spectral Density plots of interactions with different textures (Denim, Nylon, Paper, Wood) and while stationary.

III. Experimental Method

The system behaviour was assumed to be appropriate for providing high-frequency feedback in teleoperation. To validate the system, a human factors experiment was performed, which explained in this chapter.

A. Participants

Twenty participants (15 male, 5 female) took part in the human factors experiment. One participant was 46 years of age, others were all within the range of 20-32. Although many had prior experience with teleoperation and/or haptic gloves, none of the participants had notable experience with high-frequency vibration feedback.

Participation was voluntary and no compensation was given for partaking in the experiment. Participants were briefed on the task and the data collected. Then, all participants gave their informed consent before the start of the experiment. The experiment was approved by The Human Research Ethics Committee of the Delft University of Technology.

B. Apparatus

The experiments were performed with a turntable with four removable panels for different textures, with a passive robotic gripper as telerobot, and with a stripped SenseGlove Nova as master device, as shown in Fig. 7. The haptic feedback components of the SenseGlove Nova are not used in this experiment and are therefore removed.

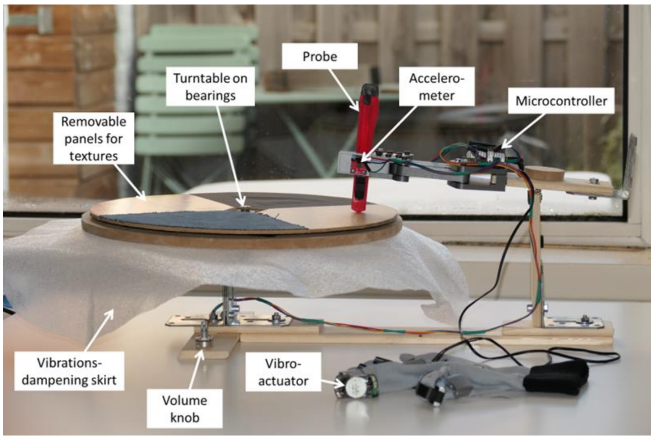

Fig. 7: The textures turntable and all its components as used in the experiment.

The robotic gripper is a parallel gripper, 3D printed from PLA, and is equipped with the vibration sensing hardware: the accelerometer is attached the back of the fingertip with TESA double-sided tape and the microcontroller is screwed onto the back of the gripper's wrist. Between the gripper's fingers is a probe, which is a plastic snap-off blade knife with the blades removed. This probe has a flat and pointy tip, like human fingernails, and is held perpendicular to the direction of rotation. Together with its low mass, these properties make the probe susceptible to small bumps and irregularities in the surfaces, without leaving permanent marks on the textures.

The turntable is designed without motors, as the choice for motor type and control mode could influence the performance heavily. Instead, the participants spin the wheel themselves. This is done through pulling a skirt, which is attached to the bottom part of the turntable's wheel. The foam wrap skirt dampens all high-frequency vibrations, but does allow the participants to control the order, direction and speed by which they examine the textures.

Furthermore, the device is constructed with passive elements that mimic human interaction. By hinging the gripper with neglectable friction, the contact force between the probe and texture panels is around 0.30 N. To hold the probe between the fingers, a spring provides a grip force of 1.8 N. Both forces are similar to statically holding a pen [19].

C. *Texture panels*

The turntable has four slots for removable quarter-pie panels and can therefore be equipped with a variety of textures, as shown in Fig. 8. For the human factors experiment, the following four textures were selected:

- *Denim*, made from a piece of jeans. The woven textile creates a pattern of parallel ridges, but also shows some irregularities. The texture is oriented so that the ridges are parallel to one straight edge of the quarter-pie panel, and thus perpendicular to the other straight edge.
- *Nylon*, made from a watertight fabric of PVC on polyamide textile. This material is also a woven textile, creating a checked pattern of ridges with higher density than the Denim.
- *Paper*, made from the softcover of a paper notebook. This paperboard is glossier and sturdier than standard copy paper, but it is less sensitive to scratches than photographic paper. It is the smoothest texture of the four.
- *Wood*, without any added material, this texture is the smooth surface of the hardboard panel itself. This texture is slightly less smooth than the Paper texture and contains small irregularities.

Fig. 8: Close up of the textures: (clockwise from top-left) Nylon, Denim, Paper, and Wood.

D. *Task description*

Participants were asked to identify the textures on the panels through contact with the probe while rotating the turntable with their non-dominant hand. Without exception, the panels featured the set of textures mentioned before: Denim, Nylon, Paper and Wood. This allows for comparative texture identification, therefore, the task could be described as a texture discrimination task, although duplicate responses were accepted.

The participants were encouraged to rotate the turntable in both directions. This allows for asymmetries in the textures to be detected, but also permits the participants to decide the order of textures interacted with. Responses could be given, and corrected, at any time within the 90 seconds by holding the probe over a panel and orally provide their estimate. Once confident about the identification of all four panels, the participants could stop the time. However, it was stressed during instructions that correctness would be valued more than timeliness. After 60 seconds, a warning for time would be given and if the time limit of 90 seconds was reached, the trial would be terminated by the researcher.

E. *Experiment conditions and procedure*

The experiment was executed in two experiment conditions:

- *Manual condition*: the probe is held by the participant, providing them with direct tactile feedback. Using a pinch grip with the index finger and thumb of the dominant hand, the participant placed the probe near the edge on a panel, see Fig. 9. Participants were instructed to hold the probe with the same grip force and contact force as they would when actively stroking a texture.

- *Teleoperated condition*: the probe is held by the gripper and the participant must rely on the high-frequency vibration feedback from the feedback glove worn on the dominant hand. For better immersiveness, the participant holds a dummy probe through the glove to mimic the force feedback a haptic glove would provide, see also Fig. 9. Prior to the start of this condition, the participant calibrates the vibration feedback by adjusting the volume knob to set the gain. The vibrations of the noise should be "noticeable, yet still possible to ignore".

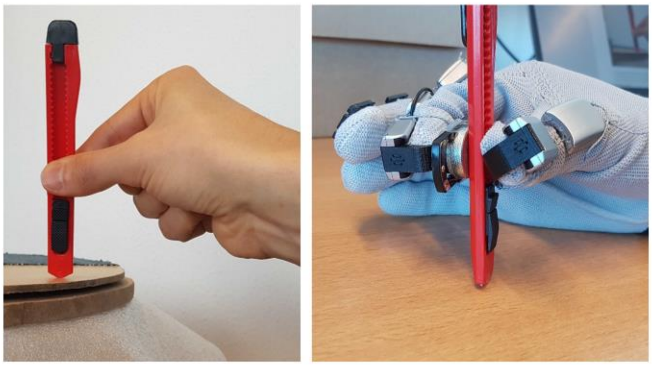

Fig. 9: Holding the probe in the manual condition (left) and holding a dummy probe in the teleoperated condition.

All participants performed the manual condition first, followed by the teleoperated condition. Results of the pilot experiment had indicated the need for extensive training prior to the teleoperated condition to overcome the lack of (lateral) low-frequency force feedback. By starting with the manual condition, the participants got prolonged familiarization with the one-handed control of the turntable, practising their spatial awareness.

Before each of the two conditions, participants were given a two-minute familiarisation phase to get acquainted with the handling of the turntable and with the sensation of textures through the probe or through the feedback glove. It was encouraged to familiarise both with and without vision and audio, as the subsequent experiment trials would be performed wearing noise cancelling headphones and with occluded vision. Between the familiarisation phase and the first trial, as well as after each trial, the texture panels were pseudorandomized by the researcher. In total, six trials were undertaken per condition. The experiment procedure is summarized in Fig. 10.

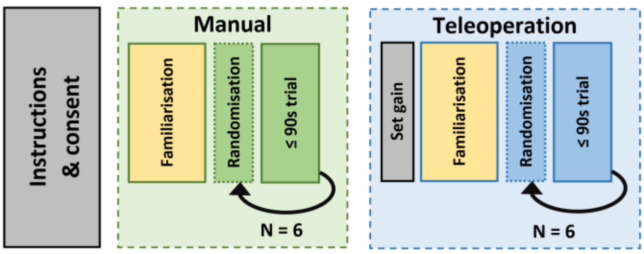

Fig. 10: Experimental procedure.

F. *Task performance metrics*

To test the hypotheses, metrics were used to examine the recorded data. The task performance was evaluated on correctness and timeliness, using the following task performance metrics:

Correct Response Rate: the percentage of correct identifications, calculated per texture.

Task Termination Time: the time until the task was terminated, either by the participant or by reaching the time limit, recorded per trial.

To interpret the results of the experiment, the following additional metrics are used:

Confusion rates: the percentage of incorrect identifications, calculated per combination of texture sample and texture estimate. This metric reveals which textures are more likely to be confused.

Empty responses: the number of textures left unidentified, evaluated per texture. This metric indicates whether there was a lack of information to identify a texture.

Mistakes: the sum of confusions and empty responses, evaluated per participant. This metric is used to reveal between-subject outliers.

G. *Data analysis*

For each trial of the experiment, the final identification of all four panels and the Task Termination Time were documented. Participants with more than twelve mistakes in the manual condition would be excluded from statistical analysis, as it could indicate a high-frequency vibration sensitivity insufficient for executing the task. However, none of the participants met this criterion.

The statistical analyses for the task performance metrics are done separately due their form of distribution. To test the Correct Response Rate against the success of guessing, the correctness was assumed to be binomially distributed. Despite the discriminative nature of experiment, the probability of correct identification by chance is assumed to be 25%. Therefore, a binomial cumulative distribution function was used to calculate the one-tailed probabilities of obtaining the Correct Response Rate or better by chance. This comparison is executed for the cumulative of all participants per texture.

For comparison between the experiment conditions, the Correct Response Rate is averaged per participant and tested for each texture separately. With an often-observed maximum the Correct Response Rate of 100%, the distribution is assumed to be non-parametric. Therefore, a paired, one-sided Wilcoxon Signed Rank test was performed to test the null hypothesis that Correct Response Rate of the manual condition minus that of the teleoperated condition comes from a distribution with zero median.

Similarly, the distribution of the Task Termination Time is also assumed to be non-parametric, as the 90-second time limit was a frequently reached time constraint. Therefore, another paired, one-sided Wilcoxon Signed Rank test was performed to test the difference in average Task Termination Time between the two conditions.

For all statistical tests, differences were considered significant if the calculated probability is below 5% ($p < 0.05$), indicated with *. P-values below 0.01 and 0.001 are indicated with ** and *** respectively.

IV. RESULTS

A. Confusion matrices

The responses of all participants are combined in the confusion matrices shown in Fig. 11. The actual textures, or samples, are shown on the columns and the estimated textures, or responses, on the rows. On the diagonal, confusion matrices show the correct responses, from which the Correct Response Rates are calculated. Outside the diagonal, the confusions are displayed, revealing which textures were more easily confused. The matrices show that Paper was among the most wrongly identified textures in the manual condition, but it was the most correctly identified in the teleoperated condition. Over both conditions, the identification correctness score of Wood was the lowest and that of Nylon the highest.

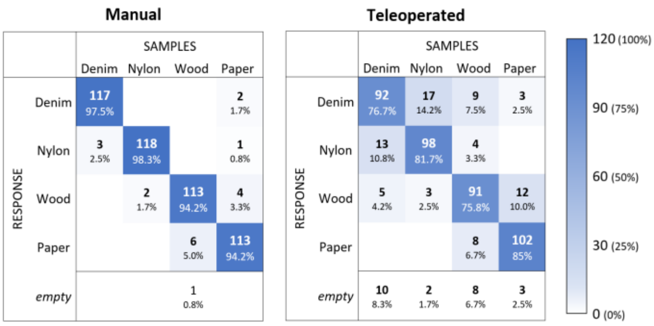

Fig. 11: Confusion matrices for the manual condition (left) and the teleoperated condition (right), cumulative over all participant trials (n=120) (zeros left out for visual aid). The correctly identified textures are found on the diagonal, confusions are found off-diagonal.

B. Correct Response Rates

The Correct Response Rates are calculated from the diagonals of the confusion matrices. On average, the Correct Response Rate is 96% for the manual condition and 80% for the teleoperated condition. For each texture individually, the Correct Response Rates are at least three times higher than the guess rate of 25% and these differences are found to be significant ($p < 0.001$). As shown in Fig. 12, the differences between the experimental conditions are much smaller, yet still significant (Denim and Nylon $p < 0.001$, Wood $p < 0.01$, Paper $p < 0.05$).

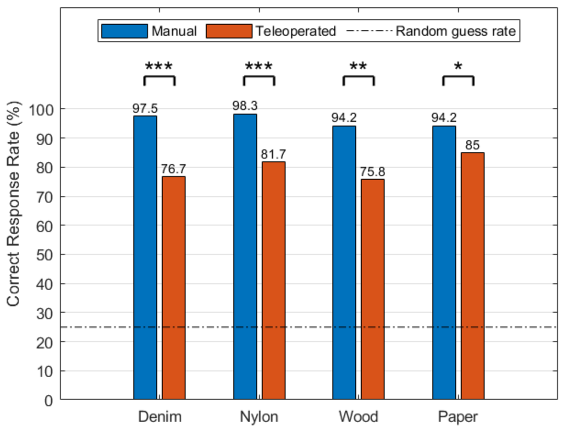

Fig. 12: Correct Response Rates per texture. Significant differences between the experimental conditions indicated with * ($p < 0.05$), ** ($p < 0.01$) or *** ($p < 0.001$). All rates are significantly higher than the guess rate of 25% ($p < 0.001$).

Additional statistical testing, using a two-tailed Kruskall-Wallis test, gives the probability for the null-hypothesis that the Correct Response Rates of the four textures come from the same distribution. The test shows that the differences between the textures are not significant (manual: $p = 0.29$, teleoperated: $p = 0.71$).

C. Task Termination Time

To compare the experiment conditions on timeliness, the Task Termination Time is averaged per participant over all trials. These averages, plotted in Fig. 13, show an increase for nineteen out of the twenty participants for the teleoperated condition. The median Task Termination Time was 26 seconds longer, a 67% increase compared to the manual condition. This difference is rated significant ($p < 0.001$) with the Wilcoxon Signed Rank Test.

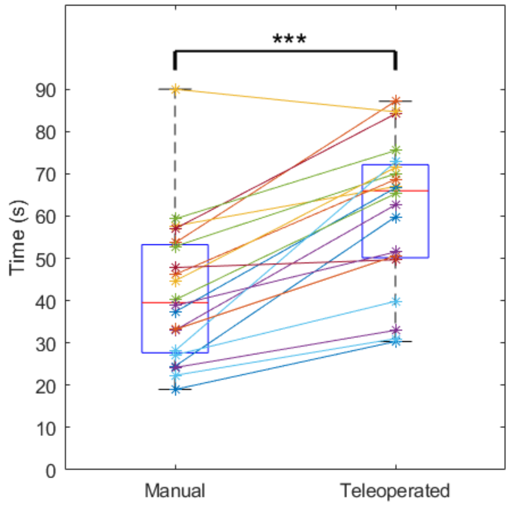

Fig. 13: Boxplots of the Task Termination Times. Data points are the average time per participant. Significant difference ($p<0.001$) indicated by ***.

V. DISCUSSION

The confusion matrices show that most of the responses are on the diagonal for both the manual and teleoperated conditions, meaning that most participants correctly identified the textures. The most common confusions are found between Denim and Nylon, and between Paper and Wood. This can be explained by the similarities in their power spectral density plots as shown in Fig. 6: Denim and Nylon share a peak above the zero decibel in the 100 - 200 Hz range, whereas Paper stays well below zero decibel throughout the whole range and Wood only shows a peak above the 400 Hz where the bandwidth of the human perception trails off.

Furthermore, the matrices show that Paper was among the most difficult textures to identify in the manual condition, but it was the easiest in the teleoperated condition. This could be explained by the use of the gain in the teleoperated condition, which raises the signal output above the human detection threshold making it easier to discriminate between Paper (no signal) and the other materials. It should be noted that the differences between the textures are not significant.

In general, the Correct Response Rates confirm the hypothesis that the presented deployable system for high-frequency vibration recording and rendering works: the correct response rates of 75 - 85% for the teleoperated condition are much higher than the random guess rate, just lower than 94 - 98% for the manual operation. Also, the Task Termination Time for the teleoperated condition is significantly longer, indicating that the rendered feedback is not as intuitive as in manual operation. However, as manual operation is often not an option, e.g. in dangerous environments, the presented system can be a useful addition in teleoperation applications.

A. Evaluation of the experimental apparatus and procedure

This study was performed with an experimental apparatus and procedure that were designed to exclude external influences and to limit variables and subjective influences as much as possible. However, this might introduce new influences that would not occur in real-world teleoperation.

This was encountered when, instead of controlling a motorized telerobot to stroke textures with the probe, the participants moved the textures while the robot holds the probe passively. The participants moved the textures by pulling a skirt attached to the turntable's wheel. The foam wrap skirt dampens high-frequency vibrations, but may still transmit low-frequency friction forces. Similarly, force feedback in real-world teleoperation could also display friction forces. With this information, the chance of guessing textures correctly might be higher than the chance of luck at 25%. However, during the teleoperated condition in the conducted experiment, participants often missed the uneven transitions from one texture to another. This suggests that there is little information to obtain from the skirt.

Without the feedback on the transitions, the participants occasionally lost track of the orientation of the turntable: they thought they rotated the turntable for 360 degrees, while in fact they rotated for 720 degrees, resulting in empty responses. This was already observed in the pilot study. However, the spatial awareness showed to increase with extended use of the turntable. Besides, this problem did not occur in the manual condition, because the lateral low-frequency forces of the transitions were very noticeable when holding the probe in the human hand. Therefore, all experiments started with the manual condition.

Retaining a fixed order might improve the performance in the latter condition due to possible learning effects. However, an analysis of the data per trial shows that there is a learning curve in the teleoperated conditions with similar features as the learning curve observed in the manual condition, see Appendices. Therefore, aside from the improved handling performance, the influence of learning effects regarding task performance is assumed to be low. Moreover, the lack of spatial awareness stresses that vibration feedback should be used in addition to force feedback for proper spatial control of the telerobot, a recommendation shared with literature [10], [18], [20].

B. Implications for deployment in teleoperation

When deploying the high-frequency vibration recording and rendering system to real-world applications, several factors will have to be taken into account. Discussed in the order of the vibration data flow, the following aspects should be considered:

- *The control of the telerobot.* The experimental setup was designed without motors to avoid interference by the motor’s vibrations. In telerobots, the motor’s vibrations will be recorded by the accelerometer and can drown out recording of the interaction vibrations under movement. Eliminating these *ego-vibrations* is feasible through spectral subtraction of the noise. However, this very computational technique requires a much more extensive system [21].
- *The performed interactions.* This study focussed on a texture identification task. To investigate the applicability to real-world teleoperation, future research should also engage in experiments with real-world scenario’s. With the presented system deployed to real teleoperation setups, such studies could also focus on object manipulation tasks, investigating the system’s value in initial contact detection, slip detection, and indirect transient contact detection.
- *The objects interacted with.* The experiment used a specific probe compatible with the range of textures to be interacted with. As vibrations are dependent on the tool and surface interactions, the choice for a different probe, or for no probe at all, will influence the excited vibration patterns [22].
- *The directions of the vibrations of interests.* The experimental setup used acceleration feedback from a single direction, perpendicular to the textures surfaces, although the system allows for selecting any single axis by choice. Single-axis recording is adequate when the vibrations are dominant in only that direction, but for more complex movements, a spectral reduction technique could be used [23].
- *The dynamics of the telerobot.* The grip force and the normal force in the experimental setup were passively kept constant by a spring and mass respectively, selected to provide force levels similar to holding a pen [19]. The surface, the probe, and the telerobot form a spring-damper system with a specific eigenfrequency that depends on these forces, the mass of the gripper, and the compliance in the gripper [22]. Different forces will therefore influence the vibration spectrum recorded.
- *The dynamics of human operator.* Similarly to the telerobot’s grasp, the human interaction with the vibration display depends on the dynamics. In the experiments, participants were instructed to hold a dummy probe, identical to the real probe, in the same way as in the manual condition to create similar dynamics. However, some participants used a too high pinch force, making the vibrations become less noticeable. This effect can be explained through the difference in user impedance, as was already illustrated by [16], [24]. Such a mismatch

between the system dynamics of the master and the slave would lead to a spectral mismatch of the vibrations recorded and rendered. This mismatch could be counteracted by implementing a High-Frequency Acceleration Matching method, as proposed by [4].

- *The need for a wireless connection.* The experimental method runs on a single microcontroller for both the recording and feedback components, resulting in a fully wired connection. For a generically deployable use in true teleoperation, extension of the setup to two microcontrollers, and possibly a wireless connection, would be more appropriate. However, this will lead to higher delays.

C. Future work

The current study provides reasonable indications for follow-up work, taking into account the considerations and implications mentioned in the previous section. The referenced literature provide solutions to enhance the performance. However, not all solutions might be applicable (yet) to a deployable system.

Examples of solutions not yet applicable are the spectral processing techniques for axis reduction and for ego-vibrations subtraction. These methods require significant computational power or it would imply high delay, e.g. 70 ms delay for 1024-point FFT with a 100 MHz processor [25]. However, computers are increasing in processing speed rapidly: the implemented Teensy 3.2 runs at 72 MHz, while the Teensy 4.0 runs at 600 MHz. Therefore, it is expected that implementations of these spectral processing techniques with acceptable delays may become feasible in the future.

VI. Conclusion

This thesis describes a novel, deployable system for providing high-frequency vibration feedback in teleoperation. It is investigated whether this system can provide the human operator with accurate vibration feedback.

Spectral analysis of the input and output accelerations shows convincing replications of the vibration waveforms of various textures. The usefulness of the feedback was assessed for a texture identification task in two conditions: with the presented teleoperation feedback and with manual feedback. The experiment results show that:

- The teleoperated condition yields a high texture identification correctness rate, close to that of the manual condition.
- Texture identification takes longer in the teleoperated condition compared to the manual condition.

The experiment shows that the presented system provides the human operator with essential vibratory information of textures. Where manual operation would not be feasible, the system can be deployed to equip the teleoperation setup with high frequency vibration feedback to make teleoperation nearly as capable as manual operation.

Acknowledgments

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APPENDIX A: ELABORATE RESULTS

1) Learning curves

Despite the 2-minute training session, there is a strong learning effect up to trial 5 in Task Termination Time for both conditions, see Fig. 14. This shows that, despite always doing the manual condition first, there is limited skill transferred to the second condition.

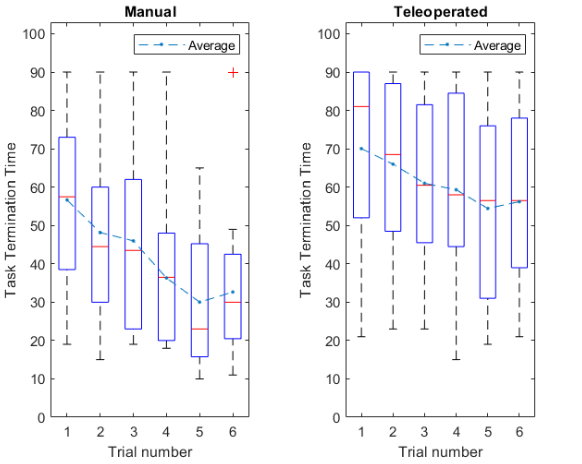


Fig. 14: Boxplots and means of the Task Termination Time per trial revealing a learning curve in both conditions.

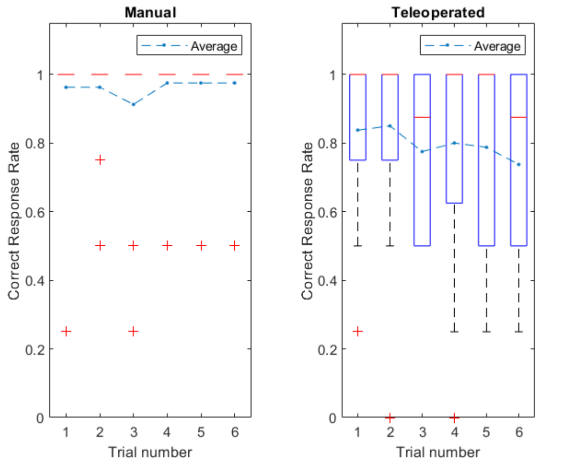


Fig. 15: Boxplots and means of the Correct Responses Rate per trial for both conditions.

There was no learning effect in the Correct Response Rate, see Fig. 15. If anything, there is a slight deterioration in performance. Possibly participants got overconfident and rushed to decrease the Task Termination Time, or they may have gotten tired to the sensation of vibrations. In the plots, each data point is one participant's score, so, there are 20 data points per box. The reason boxes in the manual condition are just one red line (indicating the median) is because less than five participants did not score 4/4, meaning the lower 25 percentile lies also at the 100% score. Similarly, the median line at 1 for the teleoperated condition indicates that at least 50% of the participants scored 4/4.

2) Correct response rates

The bar graph in the main report (Fig. 12) shows only the average correct response rates. Fig. 16 shows the same data in boxplots, revealing the median and the outlier scores of the participants. This shows that the median for the manual condition is 6/6 for all textures, and 5/6 for all textures in the teleoperated condition. The differences between the textures are not significant at p = 0.29 and p = 0.71 for manual and teleoperated conditions respectively, using a two-tailed Kruskall-Wallis test. The interval p-values are shown in Table 1.

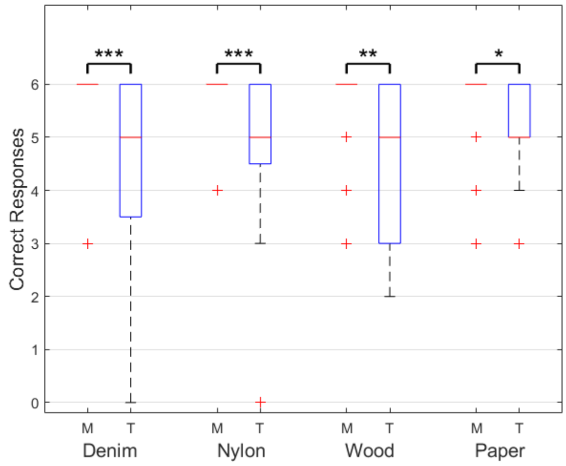


Fig. 16: Boxplots of the Correct Responses per texture. Each data point is the participants total score, so, there are 20 data points per box. The reason boxes in manual are just one red line is because less than five participants did not score 100%, meaning the lower 25 percentile lies also at the 100% score.

Table 1: Interval p-values for the Kruskall-Wallis test on differences between the textures, shown for both experimental conditions

Group 1	Group 2	Manual condition P-value	Teleoperated condition P-value
Denim	Nylon	1.00	0.97
Denim	Wood	0.53	0.98
Denim	Paper	0.53	0.91
Nylon	Wood	0.50	0.83
Nylon	Paper	0.50	0.99
Wood	Paper	1.00	0.70

Evaluating the correct response rate averaged per person results in the boxplot shown in . Except for one, all participants have an equal (n = 4) or lower (n = 16) correct response rate in the teleoperated condition. The difference is statistically significant with p < 0.001 (using a Wilcoxon Signed Rank test).

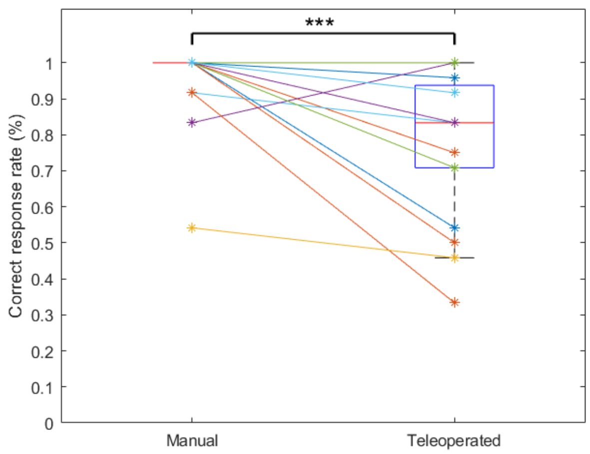


Fig. 17: The boxplot of the textures combined. Again, the data points are the participants average score, so 20 points, and the lower 25% lies also at the 100%. It shows that most participants scored worse in the teleoperated feedback condition, only 1 better (and 3 participants had 100% on both).

3) Dependency between task execution metrics

To investigate if there is a dependency between the correctness and the time needed, the Task Termination Time data is evaluated per trial and sorted by correctness. For each condition, this results in 5 sets of time data at 0%, 25%, 50%, 75%, 100%. The manual trials with a 0%, 25% or 75% score, and the teleoperated trials with a 0% score, all originate from only 2 participants. These sets should not be evaluated, as comparing these sets of trials to the other sets of trials would mean comparing these two participants to the other participants. The remaining sets are plotted in Fig. 18.

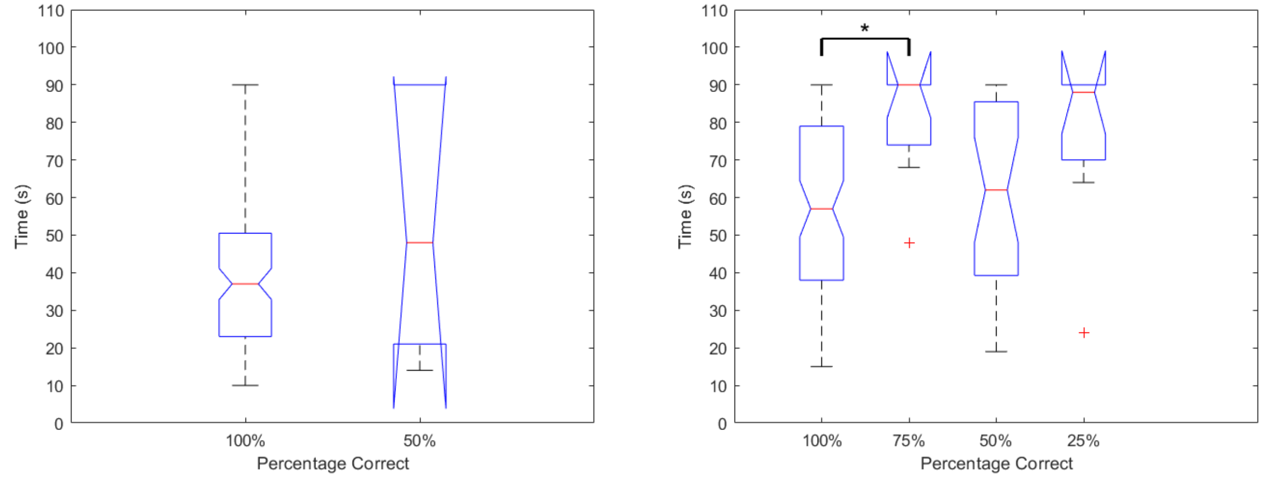


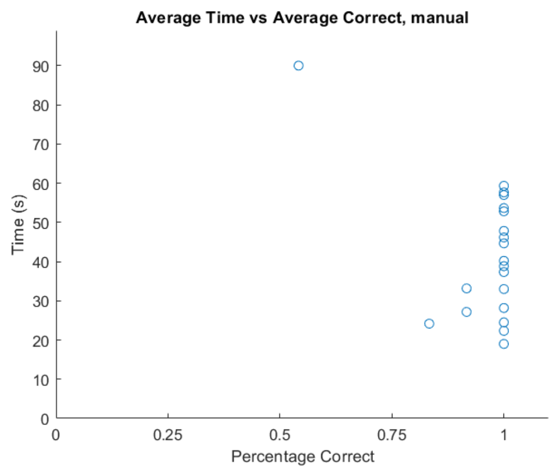
Fig. 18: Task Termination Time plotted per trial correctness.

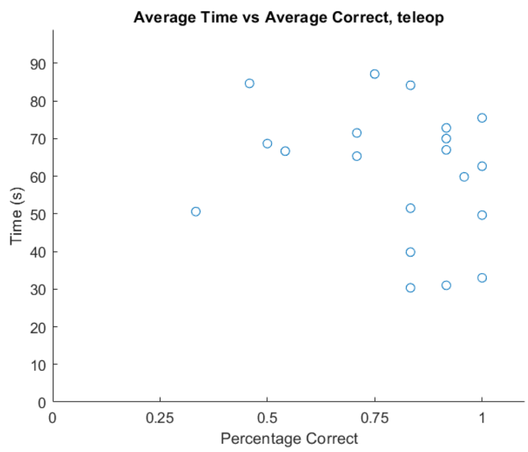
For the sets of Task Termination Time data in the manual condition, the two-sided Wilcoxon Ranks Sum test does not reject the null hypothesis that the set of trials with 50% correct and the set with 100% correct are samples from distributions with equal medians ($p = 0.43$). For the teleoperated condition, the two-sided Kruskall-Wallis test is used. The null hypothesis that the sets of trials sorted by correctness are samples from distributions with equal medians ($p < 0.01$). This indicates that the difference might not be caused by chance, but by a dependency between the metrics.

The intervals, shown in the table below, show only significant difference between the 75% and the 100% sets ($p < 0.05$).

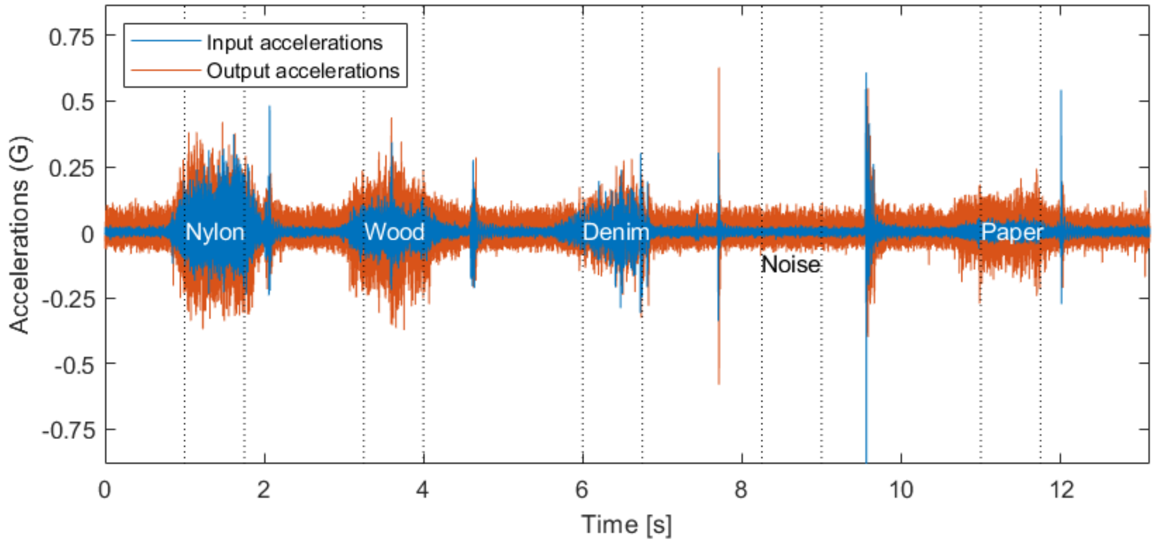
Group A	*Group B*	*P-value*
100%	*75%*	**0.0162**
100%	*50%*	0.8021
100%	*25%*	0.0781
75%	*50%*	0.1147
75%	*25%*	0.9748
50%	*25%*	0.3193

To investigate if this is caused by between-participant differences, the average Task Termination Time is plotted against the average Correct Response Rate in the Figures below. This shows there is no correlation between the participant's correctness and their timeliness. Therefore, the differences found above are due to dependencies within a participant. A possible explanation is that a confusion, where two textures are simply swapped, can go unnoticed, while a mistake, where one response is given more than once within a trial, results in a rerun of the previously answered textures.





4) Analysis in time domain

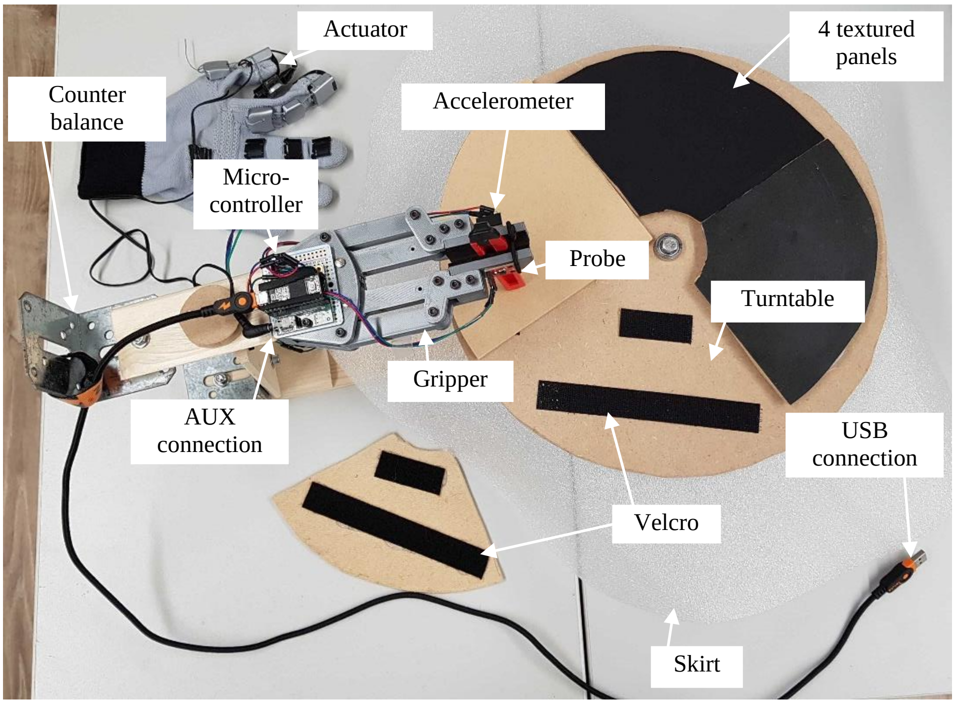


The Power Spectrum Density Plots shown in Fig. 6 are drafted from the recording shown here. While rotating the turntable with approximately 1 second per panel (= 15rpm ≈ 0.5m/s), the accelerometers are read through the Teensy's 12bit ADC's at 4kHz. Each texture sample was 3000 samples long to exclude the acceleration and deceleration of the movement. The acceleration for the Denim seems quite long, but that could be due to its asymmetry in the pattern. The large peaks after each texture are the edges between two panels, giving a significant impact. During the "noise" recording, the probe was stuck between two panels, resulting in a high impact and oscillating signal at getting out.

This time domain analysis shows that the system can also be used to encode vibratory information on impacts. Although not investigated thoroughly, this looks promising for object manipulation tasks where (indirect) contact events are of interest. The picture below is a screenshot of an early version of the setup being used to identify contact events: moving the sensor in a diagonal towards the table and the wall, the impact and sliding interactions with 1, and later 2 objects, are clearly recorded. Note, the scale is much broader than in the picture above.

APPENDIX B: DEVICE REPORT

The experiment device consists of a turntable with multiple textures, a gripper with probe, a construction that holds these two together, and a feedback glove.



The turntable is a 30cm Ø circle made from softboard, to which four MDF panels can be attached with Velcro. Three panels have added texture (*paper cover of a notebook*, *watertight fabric (PVC/Nylon)*, *denim*) and one panel is without added texture. The participants turn the turntable by gently pulling the skirt (*LDPE foam sheet*).

The gripper is a 3D printed (*PLA*) parallel gripper. The gripper does not have a motor, not for closing/opening, nor for movement in free space. The gripper is mounted on a wooden arm, which is part of the construction.

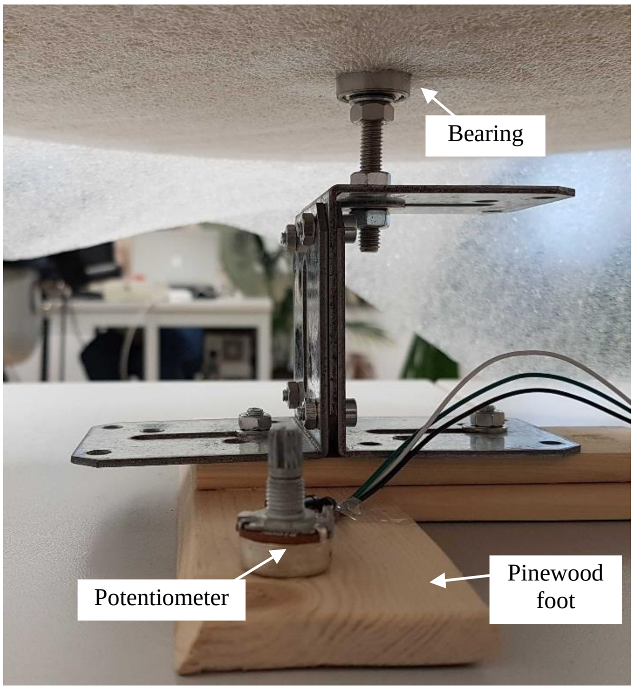
Attached to the gripper's wrist is the microcontroller (*Teensy 3.2, plus Teensy Audio Adaptor*). The microcontroller is powered by through USB connection (*5V, 0.9A*) to a laptop. In its turn, the microcontroller powers all other electronic components (*3.3V, 0.25A*).

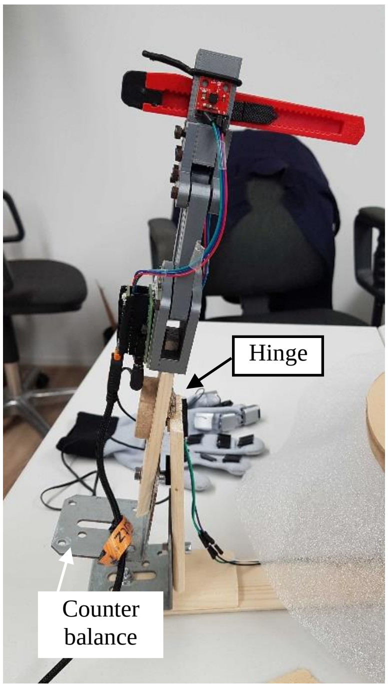
The researcher puts a probe (*a snap-off blade knife with the blades removed*) between the gripper's fingers, closed with spring (*k = 0.3 N/mm)*. Attached to back of the gripper's finger tips is an ADXL335 accelerometer breakout board using double sided tape.

The construction holds both the arm with gripper and the turntable and is constructed from *sanded pine wood slats*, *galvanized steel L-profiles* and *stainless steel bolts and nuts*. The turntable is clamped between two *stainless steel* ball bearings for a smooth and sealed connection. The profiles allow for linear adjustments, but this feature is not used during the experiment.

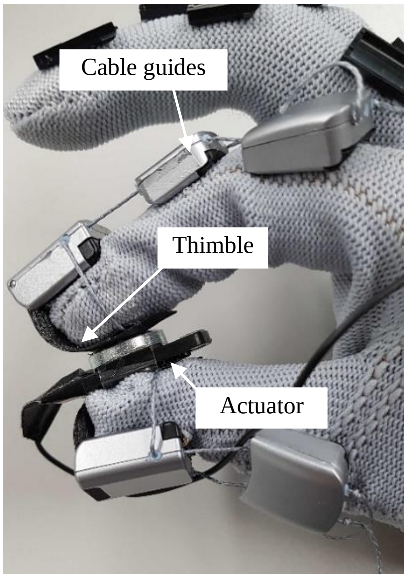
The wooden foot below the turntable prevents the turntable from falling over. On the foot, there is a potentiometer which allows participants to adjust the volume of the feedback.

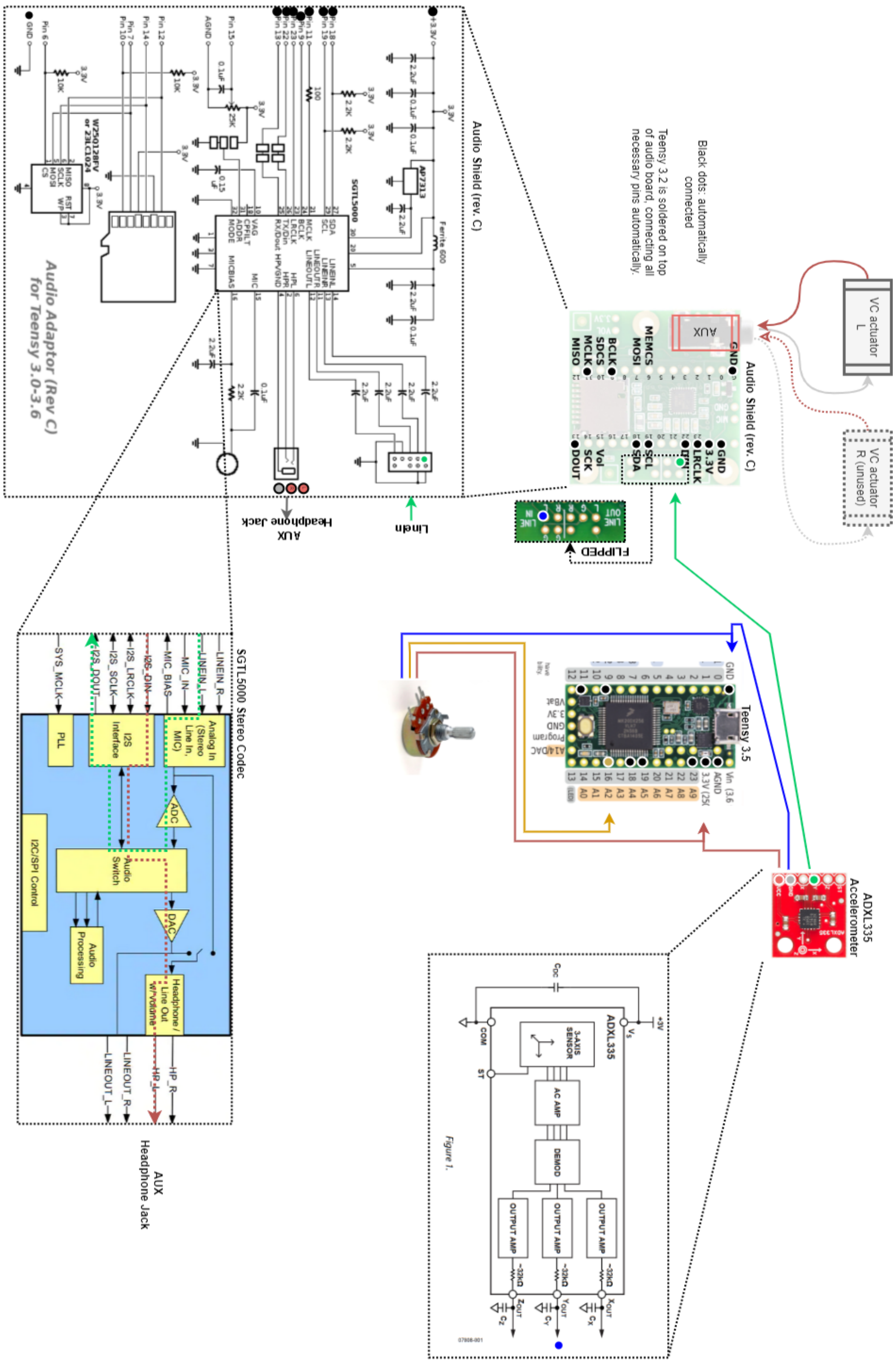
The wooden arm the gripper is mounted on is connected with a hinge (*stainless steel*, *messing*). This, together with the moveable counterbalance (*L-profile*), allows a force of 1 to 3N between the probe and the turntable, independent of the thickness of the texture.





The feedback glove is a stripped version of the commercial product SenseGlove Nova: all electronics are removed, as are most of the hard materials. The softglove (*nylon, multiple sizes*), and the cable guides (*3D printed PLA*) and the so-called thimbles (*3D printed nylon*) for thumb and index finger are remaining. The vibration actuators (*TEAX14C02, 13 grams*) are powered by the microcontroller through an AUX connection and are attached to a thimble with home-grade adhesive tape, just to keep in into place. The participants holds the actuator with a pinch grip (between thumb and index finger) with a force comparative to holding a pen.




VC actuator L
VC actuator R (unused)
ADXL335 Accelerometer
Audio Shield (rev. C)
Teensy 3.5
Black dots: automatically connected
Teensy 3.2 is soldered on top of audio board, connecting all necessary pins automatically.
FLIPPED
LineIn
AUX Headphone Jack
Audio Adaptor (Rev C) for Teensy 3.0-3.6
SGTL5000 Stereo Codec
Analog In (Stereo Line In, MIC)
ADC
DAC
Headphone / Line Out w/Volume
I2S Interface
Audio Switch
Audio Processing
PLL
I2C/SPI Control
ADXL335
3-AXIS SENSOR
AC AMP
DEMOD
OUTPUT AMP
Figure 1.

Appendix C: Pilot Experiment Notes

Procedure:
Using the presented setup, but gain set at 15. Condition variables: perpendicular (scraping) vs parallel (cutting) probe position, thumb vs index finger, y-axis (up) vs z-axis (sideways). Hand lies palm up on the table. Looking is permitted. Noise is partially cancelled with headphones.

Participant 1 (age range: 55-65)

Perpendicular + thumb + Z:	Some vibrations felt, not identifiable. Is better when pressing index finger (without actuator) to it, still not identifiable.
Perpendicular + thumb + Y:	Much better, still not identifiable. Is better when pressing middle finger to it, 35 seconds to identify all 4 textures.
Perpendicular + index + Z:	Vibrations feel okay, Denim & Nylon identifiable (although constantly, and confidently, confused), wood and paper unnoticeable. (Without pressing of another finger)
Perpendicular + index + Z:	Same as above, but pressing with thumb (without actuator): no vibrations felt. (pressed too hard)
Perpendicular + index + Y:	Vibrations feel good. All textures identifiable. (without pressing of another finger). Pressing slightly with thumb is even better.
Parallel + index + Y:	Some vibrations felt, not identifiable. Is slightly better when pressing index finger (without actuator) to it, still not identifiable.

Conclusion: Perpendicular and Y. Slight favour for index finger. Lightly pressing with second finger is better.

Participant 2 (age range: 55-65)

Perpendicular + index + Y:	(with pressure from thumb) Vibrations feel good, but only identifies 3 textures. Spins 2 full rotations, and provides two of the answers at the same location. Is completely unaware of the transients between textures and of their speed.

Participant remarks:

- Use the box you transport it in to occlude the view
- Buy noise cancelling headphones as auditive feedback is very informative
- Can the actuators be more on the tips of the finger, or slightly to the side? Difficult to grasp, especially the thumb.
- Hold the actuators upright and between thumb and index, to get proper contact
    - Squeezing to hard drastically decreases signal
- Varying the speed is important
- Varying the direction is really important! Include in instruction
- Instruct it is okay to make mistakes.
- I need more training, I have no clue what I'm doing (*w.r.t. spatial awareness*).
- Include a texture that is even more rough, e.g. a protoboard.

APPENDIX D: PARTICIPANT INSTRUCTIONS

High-Frequency Vibration Recording & Rendering for Wearable Teleoperation

Location: SenseGlove Meeting Room
Date: 12th to 23rd of December
Duration: approx. 45 minutes

Dear student, colleague, friend,

Thank you for participating in an experiment for a research study titled High-Frequency Vibration Recording & Rendering for Wearable Teleoperation. This study is conducted by Robert Heemskerk from the University of Technology Delft (TUDelft), in collaboration with SenseGlove. These instructions provide information on the topic and the experiment itself. If you have any questions, don't hesitate to ask!

PURPOSE

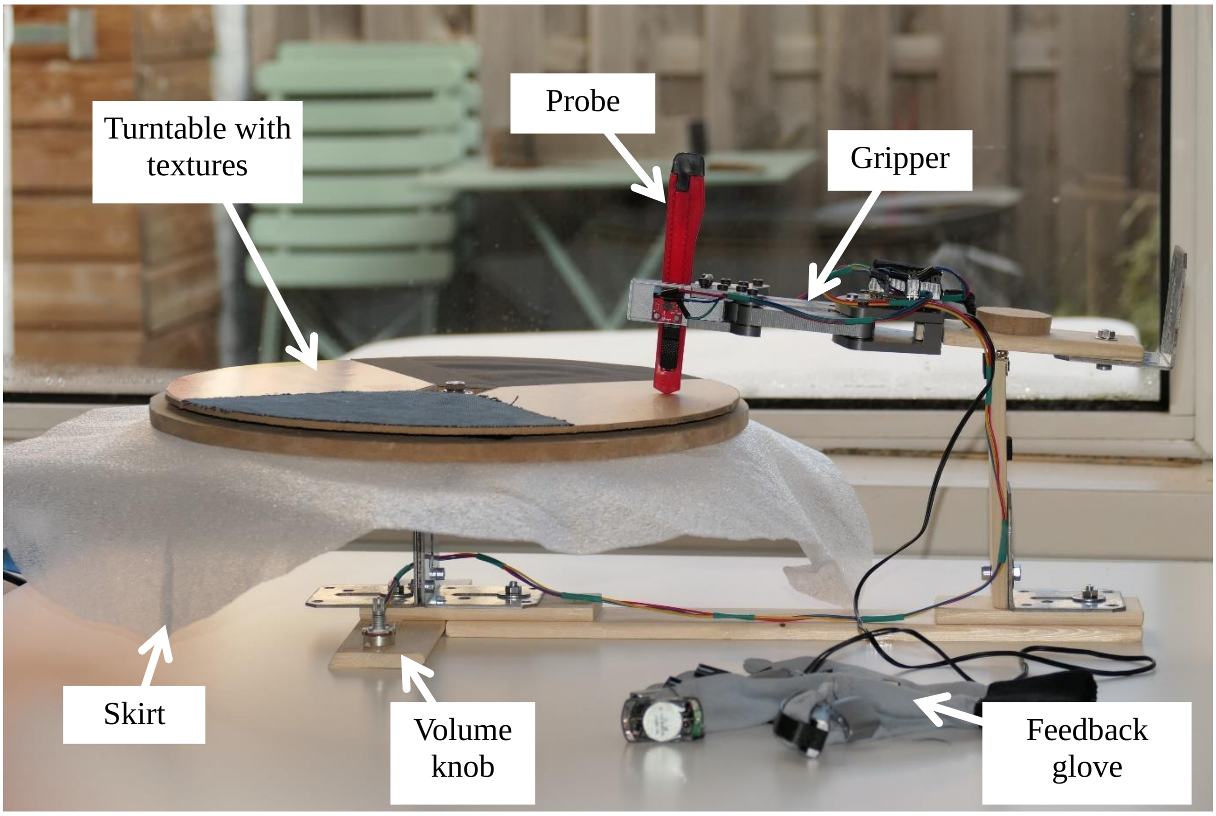
This research is about teleoperation, where a human operates a robot from a distance. Teleoperation can be very useful in dangerous environments, but there is a big downside to teleoperation: you don't feel anything! One of the things we usually feel are vibrations. Thanks to the sense of vibrations, we respond to making and breaking of contact with reflex-speed and we can determine small edges or bumps on a surface. Vibrations also play a key role in the identification of textures by providing information on hardness, roughness and patterns.

To bring back the sensation of vibrations in teleoperation, researchers worldwide have been developing many complicated hardware and software solutions. The purpose of this research study is to investigate the usefulness of a hardware solution that could be used in more generic applications. This is achieved by designing the sensing hardware to be attached to a gripper and, similarly, designing the actuating hardware to be added to a teleoperation glove.

Data collected during the research experiment will be used to investigate whether and to what extent participants are able to discriminate different texture via the remote vibro-tactile feedback. The results will be presented in a thesis report and presentations in pursue of a Master's Degree in Mechanical Engineering.

Device

The experiment device revolves around the **turntable**: the big wheel with the four panels with different textures on top. You can spin the turntable by gently pulling the **skirt** back and forth. The **probe** (in this experiment a snap-off blade knife with the blades removed) is the ONLY thing that touches the textures during the experiments. This probe is either held by you or by the **gripper**. If it is held by the gripper, you will be wearing the **feedback glove** that allows you to feel what the gripper "feels". The strength of the feedback can be controlled with the **volume knob**.



Task

There are four textures on the turntable and your task is to say which texture is which. There are four choices:

- Denim
- Nylon
- Paper / *papier*
- Wood / *hout*

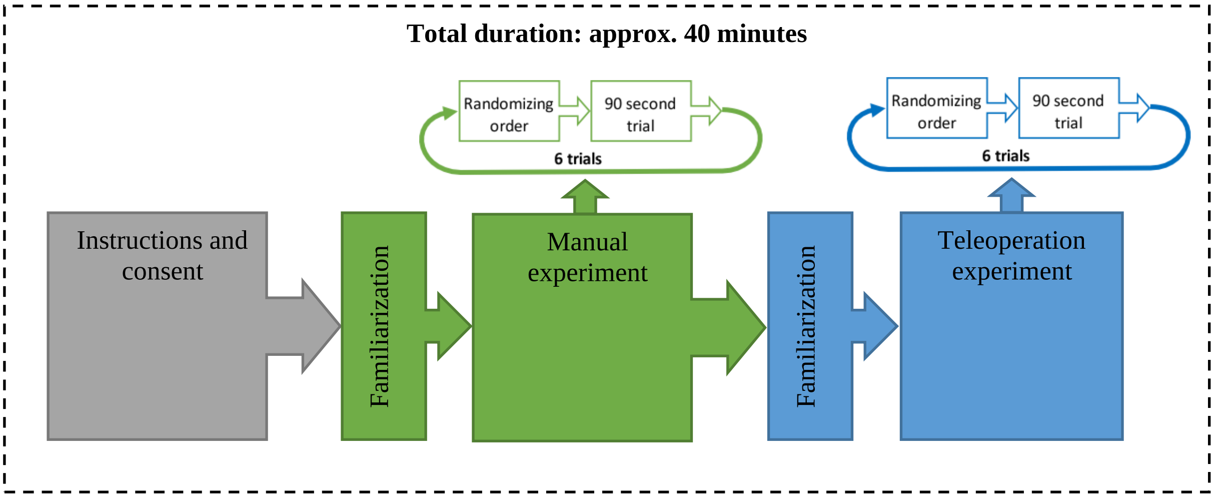
You can spin the wheel with one hand, and you will feel the vibrations on the other hand. You can choose which hand does which, but it is recommended you use <u>your dominant hand to feel</u>.

There are two experiment conditions:

- Manual: you hold the probe in a pinch grip with your own index finger and thumb.
- Teleoperation: the probe is held by the gripper and you wear the feedback glove to feel the vibrations.

PROCEDURE

After the instructions, you are asked to sign the informed consent form. Only after you consent, the experiment officially starts. It begins with the manual condition, for which you have a short familiarization phase and an experiment phase. In the familiarization phase you are instructed on how to use the equipment and you will have a 2-minute test-run. During the experiment phase you must identify the four textures in six trials, each for a maximum of 90 seconds. After these six trials, you will change equipment for the teleoperation condition. Also here, it starts with a short familiarization phase, followed by an experiment phase of again 6 trials.



For both conditions, you will be performing the task blindly. You will be sitting behind a carton wall that prevents you from seeing the turntable, but allows you to stay in contact with the researcher. You will also be wearing noise cancelling headphones to prevent you from hearing the different interactions with the different textures. There is a small break between the manual and teleoperation conditions, but if you feel like taking another break, you are always free to request one.

EXPERIMENT RULES

There are some rules to this experiment, which apply to both the Manual experiment and the Teleoperation experiment:

- You have only <u>90 seconds</u> per round to have submitted your answers, a warning for time will be given after 60 seconds.
- Within this time, you can give your answers <u>at any time</u>, for example, when you are sure about two textures, but need more time for the other two.
- Your answers are timed, but <u>correctness is valued more than time</u>. When you are sure about your answers, indicate this by saying: *I'm sure*.
- You are allowed to choose <u>the same material twice</u>, but there will always be 4 different textures. You are also allowed to pass, but know that guessing has more chance of getting it right ;)
- Pull the skirt <u>gently</u>. Please do not give it a swing, always hold onto the skirt.
- You are encouraged to spin the wheel <u>both directions</u>.
- You are encouraged to spin the wheel <u>with different speeds</u> (though keeping in gentle)

How to hold the probe

OPTIONAL READING: This will be discussed during resp. familiarization phases.

For the manual phase, you need to hold the probe yourself, preferably with your dominant hand. Pinch it between you thumb and index finger, just above the black sliders, see the photo below. This should not need to much force. Place the tip of the probe on the panels about 3cm from the edge. You can rest your elbow on the table.

For the teleoperation phase, the gripper will be holding the probe for you. The vibration feedback is received through actuators on the SenseGlove. Put on the glove (different sizes available), and make sure your fingertips are all the way at the tips of the glove. Next, like in the photo below, hold the dummy probe between index finger and thumb, just like you did without the glove: the actuator should be between your index finger and the dummy probe, and the dummy probe should be standing on the table. You can rest your arm on the table.

DO NOT SQUEEZE THE ACTUATOR, when you are having difficulties feeling the differences, this will only make the actuator do less!