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Haptic Feedback to Improve Musical Interaction

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ABSTRACT

Interaction between musicians during a joint musical performance is predominantly based on acoustic feedback. In real situations, this feedback is unfortunately influenced by a variety of interfering factors. For example, strong reverberation or additional sounds can alter or mask acoustic signals. This leads to undesirable effects, such as asynchronous playing, and thus to a reduction in the quality of the overall musical experience for the listener. This paper investigates a supportive system with vibrotactile feedback. The applied vibration signal was generated directly from the audio signal of the partner instrument and reproduced via an actuator on the lower back of the musicians. Whether this additional information helps improve the stability of timing and synchronization was investigated. For this purpose, experiments were conducted with bass guitarists and drummers. The participants were asked to learn and play a simple musical pattern, with and without vibration feedback, under different acoustically disturbed scenarios. The musical performance was analyzed in terms of the accuracy achieved with respect to the expected beat grid. Furthermore, the participants' latency thresholds between audio and vibrotactile feedback were determined in a perceptual test with kick drum sounds to determine the delay requirements for the developed system.

Keywords: Music Performance, Sound and Vibration, Tactile

1. INTRODUCTION

Musicians' performance during live concerts is critical to the audience experience. In this context, the perception of the artists often varies from that of the listeners. Poor location-dependent acoustic conditions must be handled professionally so that the audience can still be provided with an impressive experience. Occasionally, due to various factors, such as a noisy environment, musicians may lose track of the common rhythm/tempo, decreasing the overall quality of the musical experience.

Multiple systems have been developed that combine music with haptics, more specifically focusing on rhythmic feedback. Pianotouch (1) focuses on musical education. As a glove designed to improve piano students' skills, it applies vibration to the fingers that should be used when learning a new song, using eccentric rotating mass (ERM) actuators. With regard to education, there are other devices, such as the Haptic Bracelets (2) for drum students, receiving multi-limb rhythmic information from their teacher's movements or from computer playback and generating the corresponding vibrotactile feedback through voice coil actuators (VCAs). Another device, the Haptic Tutor (3) is focused on drum learning, using ERM actuators attached to each limb.

There are metronomes that also implement haptics. Giordano and Wanderley (4) investigated the effectiveness of ERM actuators for transmission of rhythmic information. Soundbrenner (5) released a commercial wristband, currently in two models, *Core* and *Pulse*, that use ERM actuators.

In this work, the focus is on improving inter-musician communication. In (2) it is already suggested that haptics may help in that regard. For that goal, a novel system, the Groovuator, is developed. In the next section, its structure, actuation system, operation and performance will be described, followed by its use in performance experiments and the final discussion.

2. Groovuator

A device focused on the improvement of dynamic rhythmic information between musicians is presented. As it focuses on enhancing musical timing between users, which in colloquial language is known as grooving, this system is referred to as the Groovuator

2.1 System

The Groovuator is a modular system designed for improving the interaction between two musicians by measuring their interactions with their instruments and providing haptic feedback to each other, as shown in Figure *1*.

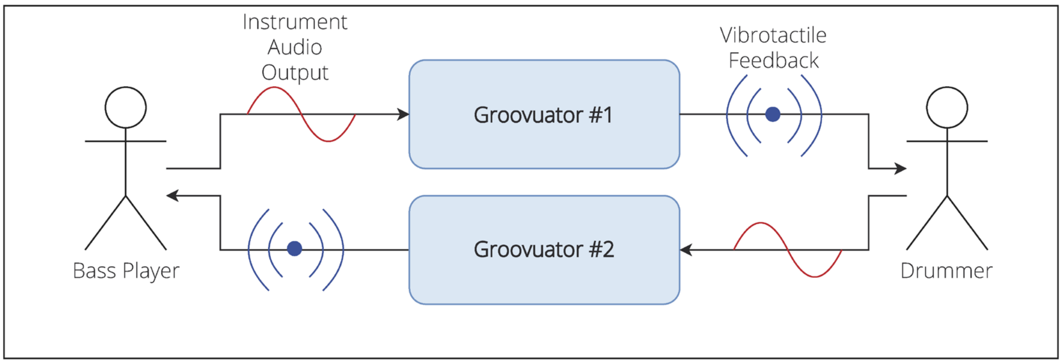

Figure 1: Block diagram of the system's intercommunication.

In order to do that, each module must be able to detect and quantify the musical signal from its corresponding musical instrument, process it, and send the haptic command to the corresponding module, as explained in Figure *2*. The sound acquisition system, however, varies from one instrument to another. Here, two different instruments were chosen: a bass guitar and a kick drum of a drum set. The additional system deployed for measuring their signals is explained in the next section.

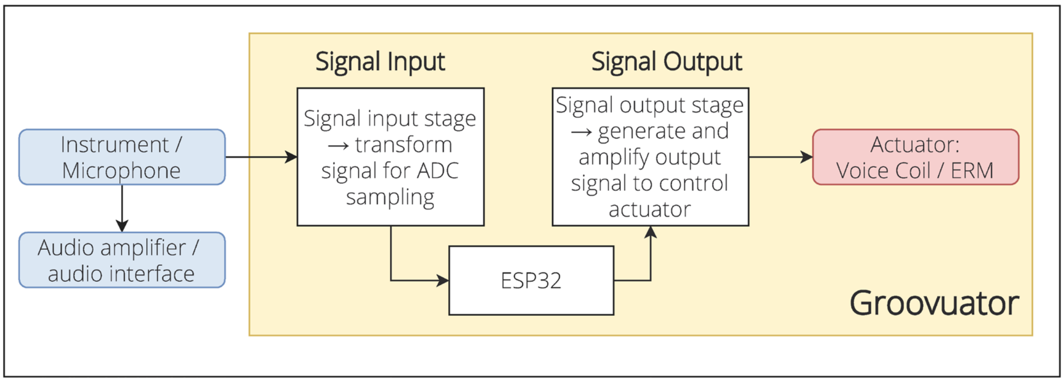

Figure 2 – Block diagram of Groovuator's modular operation.

Each module is composed of an ESP32 microcontroller as the core processing unit, an input stage where the input signal from the musical instrument is connected and converted with a TL072 operational amplifier to a readable value for the microcontroller's ADC, and an output stage to drive a vibrotactile actuator. This output stage is prepared in such a way that it can drive different technologies, in this case ERMs and voice coil actuators (VCA). For the first, the ERMs, the circuit consists of a BC547 transistor, and for the second, the voice coil actuators, a Class-D audio amplifier, the PAM8403, is used.

2.2 Signal Processing

Once the adjusted signal from the musical instrument is read by the ESP32, it is processed. As the read signal is produced by a musical instrument, it is expected to follow the amplitude trend of an ADSR model (Attack, Decay, Sustain and Release). It describes the envelope of an audio signal exclusively according to its amplitude, disregarding its frequency. Therefore, this model is used for detecting new events from the musical instrument. However, before applying the ADSR model for event discrimination, the envelope of the signal must first be generated from the input AC signal. For that purpose, an envelope-detector-model, shown in *Figure 3,* is used. Based on the model from Sethares et al. (6), it rectifies the input AC signal, using exclusively absolute values, and applies a low pass filter which, in this case, is done by applying a moving average algorithm.

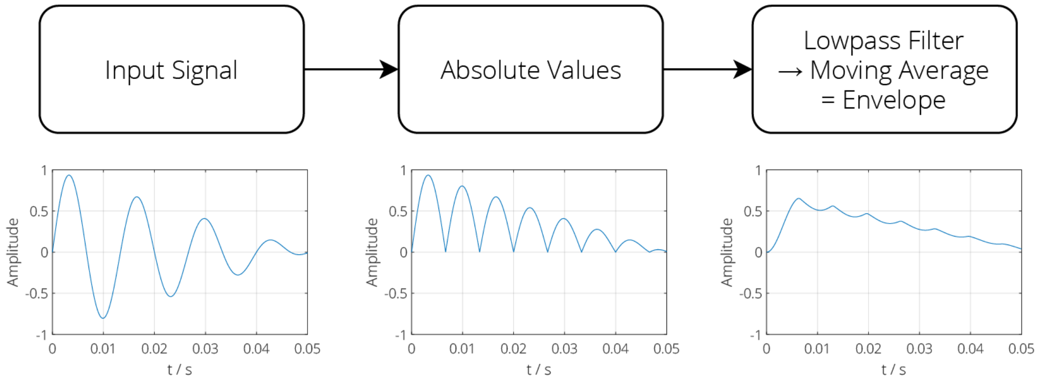

Figure 3 – Envelope detector algorithm used prior to the ADSR model.

To output vibrotactile feedback, two appropriate stimuli were created according to the input events produced by the bass guitar and the kick drum. While the ERM was controlled by an on-off signal with a fixed duration, the VCAs were controlled by a sinusoidal amplitude sweep at their resonance frequency of 70 Hz. In *Figure 4,* the vibrotactile feedback stimuli are displayed over time. The kick drum stimulus was chosen to last for 150 ms, according to the duration of an audio kick drum sample, while the bass guitar stimulus was adjusted to 250 ms.

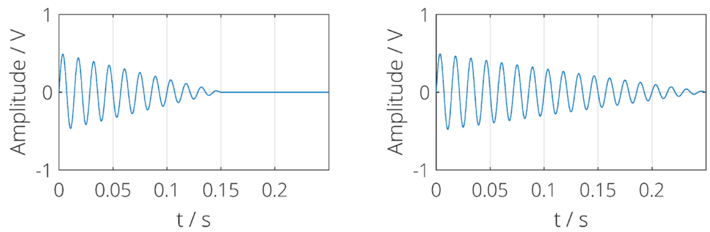

Figure 4 – Vibrotactile feedback stimuli, sinusoidal amplitude sweep, f = 70 Hz,
Left: Kick drum stimulus, 150 ms. Right: Bass guitar stimulus, 250 ms.

A voice coil actuator from Tactile Labs (Haptuator MM3C) was selected for use because of its high vibration strength and low latency.

2.3 System Latency

As the system aims to improve temporal synchronization between musicians, a controllable low latency between sound and vibration is crucial. The overall latency of the system, which includes processing the input signal, generating the driving signal for the actuator, and the actuator's start-up latency, was measured with a 3-axis accelerometer ADXL335. The resulting time delay was approximately $t_d = 2.8$ ms. As this time depends on the input signal's waveform, there can be some small changes according to the dynamic audio production of an instrument. However, it can be assumed that the latency is within a range of two to three milliseconds when using a cable connection between the input and output stages. A wireless connection was not implemented at this point but could be an improvement to increase the convenience of using the system. According to Altinsoy (7,8), the onset delay of a corresponding audio and vibrotactile feedback stimulus should not exceed ±10 ms to be perceived as synchronous. Therefore, the Groovuator's latency is under that limit.

3. Performance Experiment

To evaluate the performance of the Groovuator, experiments with test subjects were conducted. Although they presented different levels of musical experience, all of them were familiar with their assigned instruments.

3.1 Setup

For the experiment, a setup that included two Groovuator modules and two different instruments with their measurement systems was prepared, as shown in Figure *5*. A Fender Aerodyne bass guitar and a Gretsch Catalina Club Jazz drum kit were used as musical instruments. For signal acquisition, a Behringer XAIR18 digital mixer was deployed as a mixing and recording device, receiving the bass signal directly from the instrument, and the drum signal through a Sennheiser E 602 II microphone placed next to the instrument. Nine pairs of participants between the ages of 18 and 40, each consisting of a bass player and a drummer, took part in the experiment.

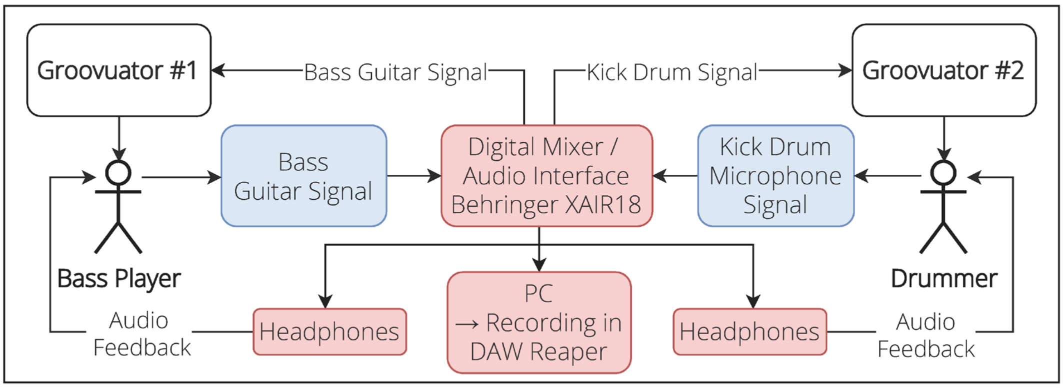

Figure 5 – Experimental setup with musical acquisition system.

3.2 First Part - Solo Play

The participants were asked to learn and play a simple musical pattern first. Following that, they played the pattern alongside playback of the other instrument. The playback was provided over headphones. Figure *6* illustrates the experimental setup.

Figure 6 – Left to Right: Bass player, Drummer, Vibration actuator placed at the lower back.

The pattern was then played for one minute each with 3 different conditions: 1) clean audio feedback without Groovuator, 2) disturbed audio feedback without Groovuator, and 3) disturbed audio feedback with Groovuator. Disturbed audio meant that the audio signal had an added reverberation effect, which started approximately after 100 ms and was 12 dB louder than the direct signal. The reproduced vibrations were generated from the original audio signal.

During the musical performance, the audio output of the played instrument was recorded and analyzed in terms of accuracy with respect to the expected tempo and the beat grid. The mean value and standard deviation over 30 measuring points per participant and per mode are displayed in Figure *7* for the bass players and in Figure *8* for the drummers. A latency of 0 ms would mean that the musicians play in perfect synchrony with the second instrument. Among the bass players, it can be seen that for most data points, a low mean latency with a small standard deviation is obtained for the clean drum audio feedback (blue) and that they performed well in the expected range of latency slightly below $t_L = 0$ ms. The participants' performance varies slightly depending on their personal sense of timing. When the data points from the disturbed audio playback (red) are considered, distinct latencies in the direction of the reverberation signal can be noticed, which vary depending on the participant. The average delay is $t_{L,Mean,all}$ = 50.7 ms. When using the Groovuator (yellow), the musicians can better synchronize the onsets, similar to the clean audio condition. A latency of $t_{L,Mean,all}$ = 11.8 ms is attained on average.

After testing the prerequisites, repeated-measures analysis of variance (ANOVA) was applied for statistical analysis. The results revealed that there was a highly significant difference between the measured latency for the three feedback conditions [$F(2;16) = 19.845$, $p < 0.0005$]. To explore the significant main effect, post hoc pairwise comparisons were conducted using the Bonferroni correction for multiple comparisons. The measured latency for the condition 'clean audio' was significantly different from the condition 'disturbed audio' (average difference = 56.5 ms, p = 0.002), and the condition 'disturbed audio' was significantly different from the condition 'disturbed audio + Groovuator' (average difference = 38.9 ms, p = 0.006).

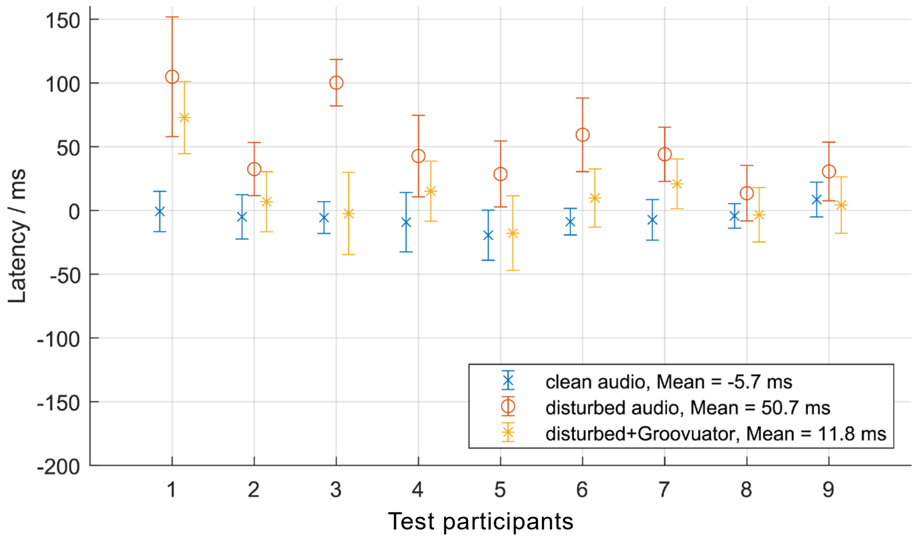

Figure 7 – Mean ±1 standard deviation of bass guitar latency measurements, each averaged over 30 measuring points.

When analyzing the timing of the drummers shown in Figure *8*, strong variation of the latency can be seen between test participants for the clean audio condition. An ANOVA did not prove any significant differences between the three conditions [$F(2;16) = 1.175$, $p = 0.334$].

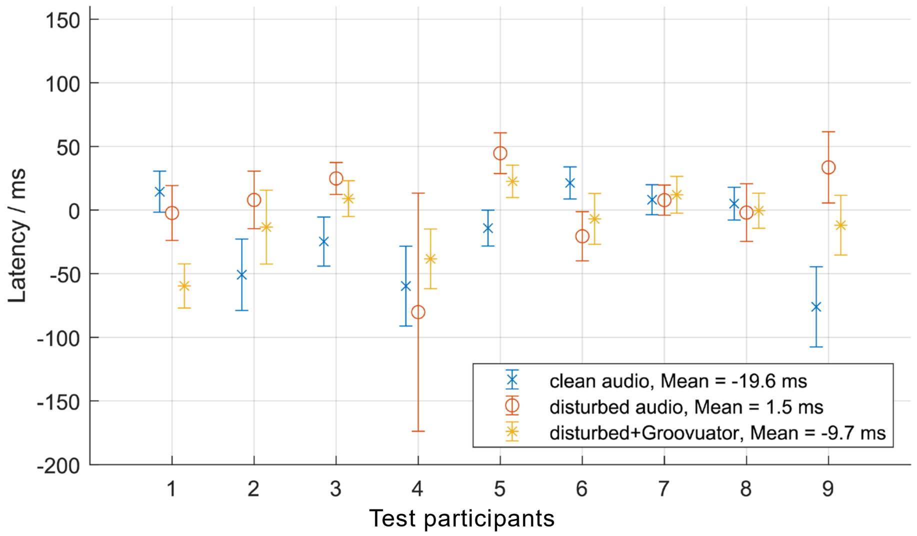

Figure 8 – Mean ±1 standard deviation of kick drum latency measurements, each averaged over 30 measuring points.

It is assumed that the strong deviations in timing were influenced by the selected sound of the bass, which was synthetically generated. Several musicians reported difficulties to follow the beat grid of this bass line.

3.3 Second Part – Just–Noticeable Latency Thresholds

In a final experiment, the latency threshold of the subjects was estimated to assess whether it is possible to work with higher latencies between audio and vibrotactile feedback in an extended system. For this purpose, a drum playback was reproduced via headphones while the Groovuator delivered stimuli associated with the kick drum to each participant. The latency between audio and vibration was increased by t_L = 2.5 ms every two pattern runs. Subjects were asked to signal after subjectively detecting a latency between audio and vibrotactile feedback. Subsequently, the experiment was repeated a second time. The averaged latency thresholds of all subjects are shown in Figure *9*. The data of the subjective latency detection threshold were confirmed to be normally distributed with two statistical tests (Kolmogorov–Smirnov $p = 0.2$ and Shapiro–Wilk $p = 0.626$). Therefore, a mean value can be used to summarize the data. The mean overall latency threshold is approximately t_L = 11 ms.

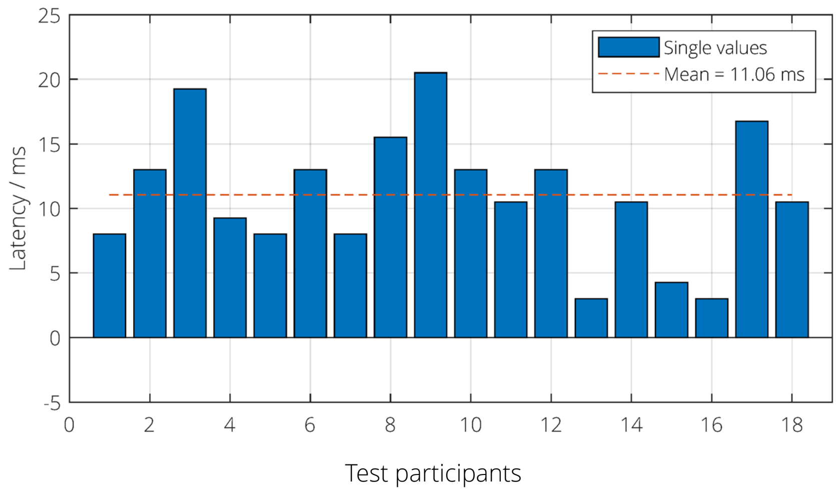

Figure 9 – Subjective latency detection thresholds for audio and vibrotactile feedback.

4. Discussion

This work investigated the development of a vibrotactile feedback device for the tempo-dynamic support of two musicians. Information on the rhythm provided to the musician was obtained from the other musician's instrument. It has been demonstrated in these experiments that vibrotactile feedback, in addition to audio feedback, can contribute to a significant improvement in timing and synchronization. Bass players in particular benefited from the feedback generated from the kick drum, implying that rhythm instruments are best suited for generating vibrotactile feedback with the Groovuator. Further improvements to the system, e.g., an improved algorithm for envelope generation, as well as a more detailed series of experiments with distinctions between amateur and professional musicians, could be conducted to improve the performance of the Groovuator and better specify its area of application.

ACKNOWLEDGMENTS

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