The Hapstrument: A Bimanual Haptic Interface for Musical Expression

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ABSTRACT

In this paper, we present the Hapstrument:[1] a bimanual haptic interface for musical expression. This DMI uses two low-cost 2-DoF haptic force-feedback devices, one for each hand. The left device controls pitch selection, while the right device controls excitation by simulating the feeling of bowing or plucking a string. A user study was run to evaluate the effectiveness of the Hapstrument. This evaluation received a wide range of reviews, from excellent to poor. Ultimately, the musical backgrounds of the participants greatly impacted their experiences with the Hapstrument. For participants whose expectations aligned with what the instrument could provide, it was an effective DMI that uses force feedback to enhance musical expression.

Author Keywords

haptics, haptic feedback, digital musical instrument, musical expression

CCS Concepts

•**Human-centered computing** → **Haptic devices;** •**Applied computing** → *Sound and music computing; Performing arts;*

1. INTRODUCTION

Digital musical instruments (DMIs) have given musicians many alternative methods for musical expression. However, the majority of them are expensive and inaccessible to the general public. In accordance with the theme of NIME 2023, "Frugal Music Innovation", we see an opportunity to use the Haply 2diy [12], an inexpensive DIY pantograph-inspired device, to create a new DMI capable of musical expression. The Haply 2diy contains easily-replaceable 3D-printed mechanical parts and uses open-sourced firmware, making it an ideal tool to create a simple, low-cost, and lightweight DMI.

We are interested specifically in implementing haptic feedback for our novel DMI. Haptic feedback is an important aspect of musical instruments and can greatly improve the affective and expressive experiences of a musician [13]. In the past, the haptic feedback of instruments was closely tied to the physical structure needed to produce a specific sound. However, modern DMIs often lack force feedback because the acoustic properties of the instrument are replaced with digital alternatives. The Haply 2diy is capable of providing haptic force feedback which we can leverage to enhance the musical expression that a musician can produce during a performance.

The contribution of this paper is the exploration of whether low-cost 2-DoF force-feedback devices may be used to model bowing and plucking with a continuous transition between the two. This technique was developed within the context of a DMI that supports other requisite functionality such as pitch selection. We also explored to what degree this interaction paradigm can contribute to musical expression. To address these questions, we conducted a user study with musicians, working with the novel bimanual haptic interface we developed for this purpose.

2. RELATED WORK

The relevant literature to this project is mainly from the NIME community and consists of force feedback in DMIs. A force-feedback musical system used a brake-augmented ball pen stylus on a sticky touch-sensitive surface [8]; an enhanced handle for a Phantom Omni combined vibrotactile feedback with force feedback to simulate bowing [5]; and a 1-DoF force-feedback device used various haptic illusions, such as a slope or clutch illusion, to simulate various terrains and map them to audio parameters [11].

Sheffield et al. used two rotational force-feedback knobs to convey physical models for various musical applications [9]. One of the inspiring applications provided in this paper was the use of knobs to simulate plucking harp strings.

Howard et al. created a music synthesis system that allows virtual instruments to be controlled by a force-feedback joystick and force-feedback mouse [7]. Inspiring our own design, the authors used force feedback to simulate various excitation methods, such as plucking and bowing a string.

Steiner created a DMI by using a haptic joystick and hap-

[1]A short video showcasing a sample performance with the Hapstrument can be found at `https://www.youtube.com/watch?v=WpKuaUBec8M`.

NIME'23, 31 May–2 June, 2023, Mexico City, Mexico.

tic mouse [10]. The joystick was used to select the timbre and the mouse was used to select the pitch and amplitude. Haptic feedback assisted with note and timbre selection.

Berdahl and Kontogeorgakopoulos created the FireFader [3], a 1-DoF force feedback device that has been used in several projects in the NIME community [2, 4, 1].

3. DESIGN

Inspired by the aforementioned literature, we decided to set one Haply 2diy to control the pitch of the instrument, and the other 2diy to control volume and timbre through physical models that use force feedback to simulate plucking and bowing.

We chose pitch to be controlled by the left-hand 2diy and excitation to be controlled by the right-hand 2diy because this division of tasks is the standard configuration for most stringed instruments, such as violin and guitar.

As illustrated in Figure 1, the end effector positions of the two Haply 2diy devices are passed from the *Haply hAPI* library to Processing through serial communication, and force feedback is calculated and delivered. Processing generates visuals for both devices, which are presented through a graphical user interface (GUI). Sound control commands from Processing are passed to *Pure Data* as Open Sound Control (OSC) messages, and external speakers play the synthesized output.

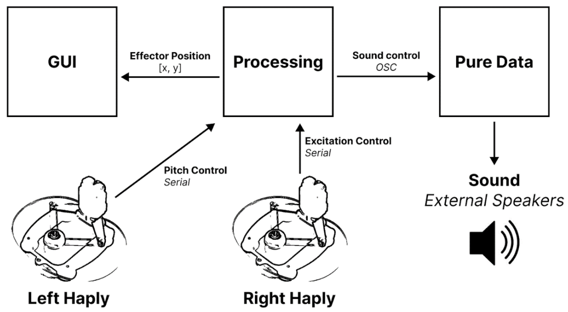

Figure 1: Block diagram of the prototype.

3.1 Pitch Selection Interface

The purpose of the pitch selection interface is to provide musicians with an easy way of selecting a pitch/frequency for the synthesized sound. Through an iterative design process, a number of pitch selection interfaces were created and tested.

The first design employed a piano layout, as illustrated in Figure 2. Unlike the quantization of a conventional piano to discrete notes, pitch could also be modified continuously by moving the end effector horizontally below the representation of the keyboard. This was inspired by the Haken Continuum [6], which supports continuous pitch selection using a keyboard-like interface. While moving the end effector above the piano, pitch remained constant, thus permitting the musician to transition between non-adjacent notes. The ability to have both discrete and continuous notes provided the musician with multiple ways of expressing themselves. Finally, with this design, the Haply 2diy generated a haptic "bump" when moving over a line, giving musicians force feedback to help them move from note to note.

We tested this design and discovered some significant limitations. Most notably, it was very difficult to quickly move from a note to any note not directly beside it. A piano interface ultimately has its design because, from an ergonomic perspective, it fits the affordances of human hands very well. For a single end effector, a keyboard representation is not the ideal interface. As a result, we replaced the piano interface with a 2-octave circular layout, as shown in Figure 3.

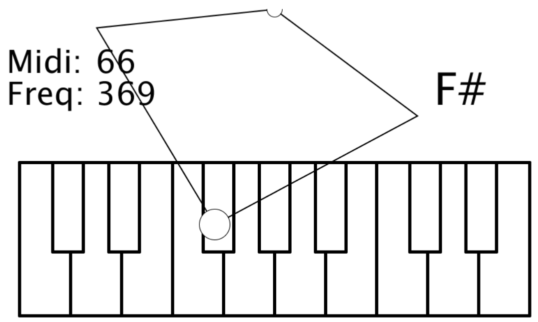

Figure 2: Piano-like interface for pitch selection.

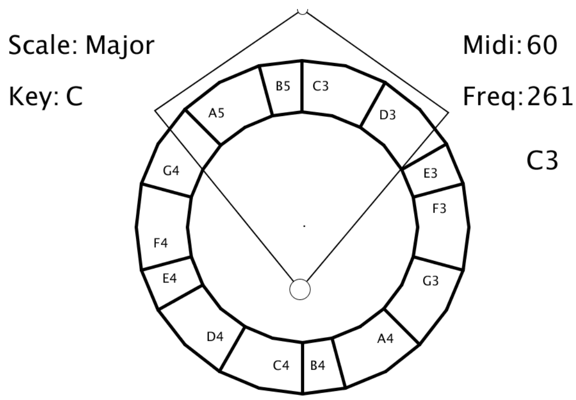

Figure 3: Two-octave circular layout used for pitch selection.

This layout made it much easier to move between different notes, with the pitch remaining constant inside the circle, and continuous pitch selection occurring outside the circle. Furthermore, a feature was implemented which allowed a specific key and scale to be selected so that only the relevant notes would be available to play. Similar to the piano design, all of the lines in this interface provided force feedback as "bumps", so that users could tell when they moved from one note to another.

This layout was refined and a few more features were introduced, resulting in our most recent design, shown in Figure 4. Three columns were added to the interface. Moving the end effector over column 1 selects the desired key, while doing so over column 2 selects the scale.

Column 3 shows the saved key-scale combinations. A user can move the end effector over one of these segments to select it, and then any change to the key or scale will be saved there. This allows a user to easily switch between three key-scale combinations, without needing to manually select the key and scale each time.

The ability to implement vibrato was added to the pitch selection interface. When the end effector is inside one of the discrete ring segments, the user can shake it back and forth, and the amplitude and frequency of the movement will map to the properties of the vibrato.

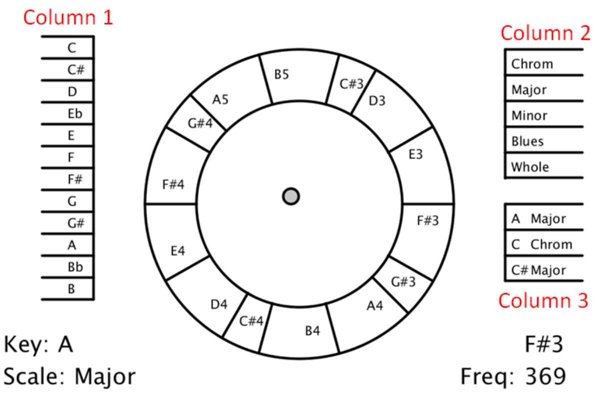

Figure 4: Refined circular layout, with red annotations added to each of the columns.

3.2 Excitation Interface

While the left Haply 2diy focuses on pitch selection, the right 2diy focuses on note excitation. For this purpose, two approaches were selected: the simulation of a pluck, such as when playing a guitar, and the sensation of moving a bow across a string instrument such as a violin or cello. For the plucking simulation, a vertical line was drawn to represent a string, and the haptic response was modelled as extending a spring. However, past a threshold distance away from the center of the string, the force will be removed suddenly, and the user can feel the plucking effect. This was made more realistic by adding a subtle vibration at the moment after the pluck, to simulate the resonance of an acoustic instrument. In the GUI of the plucking model, a representation of the string bends and vibrates to imitate the characteristics of a real acoustic string as it is plucked.

For the bowing approach, we note that users playing a real violin or cello experience a resistive force, dependent on how hard the bow is being pressed against the string. Unfortunately, the Haply 2diy does not have a sensor to detect how hard the handle is being pressed against its surface. However, among stringed instruments, there is often a correlation between the speed of the bow and its force against the string. Therefore, we chose to calculate the resistive force as proportional to the speed of the end effector.

To produce the rough haptic sensations that are ordinarily associated with bowing, we introduced small, random variations in the force feedback to the Haply 2diy. Finally, to prevent the force from changing too quickly and being too volatile, we set the force to be a weighted sum of the current and previous values. By adjusting the weights, we found a mix that produces a believable and enjoyable bowing model.

Based on encouraging initial feedback from the members of the research team, we incorporated both models into the Hapstrument, with the top half of the Haply 2diy workspace being used for plucking and the bottom half for bowing. As the end effector moves between the zones, there is a smooth interpolation between these models for haptic feedback, GUI display, and sound output.

At first, a linear interpolation was used; however, it was difficult to only pluck or bow because unless the end effector was at the very top or bottom, it would be a combination of the two. To address this issue, a sigmoid interpolation was chosen, which yielded better results.

The volume of the synthesized sound in Pure Data was set to be proportional to the velocity of the end effector while bowing or at the moment of plucking, similar to the resistive force mentioned earlier. We set the default timbre of the instrument to be a synthesized sine wave. If the volume reaches above a certain threshold, a sawtooth wave is gradually introduced to add spectral content at higher frequencies. This provides more opportunities for expressivity while still focusing on the haptic interface.

4. EVALUATION

To determine how successful the Hapstrument is among musicians, we chose to evaluate it through a user study.

4.1 Procedure and Recruitment

We conducted our user study among members of the Centre for Interdisciplinary Research in Music, Media and Technology (CIRMMT) community at McGill University. Eleven people were recruited for evaluating the Hapstrument (5F, 6M, ages 22 to 36, average 28.4). These participants had a range of musical backgrounds. Some had no formal training, some grew up playing regularly, and some had a degree in music.

Before the test, participants were given an introductory survey, asking them about their musical skill, their exposure to DMIs, and their experience with haptic force-feedback devices.

During the test, participants were introduced to the Hapstrument and given a brief explanation of its functionality. They were then given time to explore the instrument and try it out. Following this, they were asked to complete several tasks, such as playing a scale, plucking, bowing, and transitioning between the two. Next, participants were given 15–20 minutes to play with the Hapstrument and prepare a performance for the end of the session, in which they would play a composition with *musical expression*. This was defined to them as the ability to invoke an emotional response or bring the music to life.

Participants played their composition and completed a post-test questionnaire, consisting of questions about what they liked and disliked, as well as eight Likert scale questions regarding the following aspects of their experience:

- Pitch selection interface
- Feeling of plucking
- Feeling of bowing
- Plucking/bowing interface
- Overall experience with the Hapstrument
- Ability to express yourself
- Impact of haptic feedback on expressing yourself
- Impact of mixing plucking and bowing on expressing yourself

4.2 Results and Discussion

The pitch selection interface received mediocre reviews overall, having an average value of 3.3 when rated from 1 to 5. The idea of using a scale/key system to select distinct tones was described by a participant as “Eurocentric”. Some participants liked this system and said that it made it easy to play a piece in the chosen key. However, other participants described it as very limiting for them.

When a scale is selected, some of the segments may be larger than others due to the distances between notes in a scale, as seen in Figure 4. Some participants liked this, saying that it is good for visualizing music scales. However, the smaller segments were often harder to select, and many participants had difficulty with this.

The haptic feedback of this interface, which consisted of "bumps" when moving over lines, had generally good reviews. Most participants liked it, saying that it improved spatial awareness. However, other participants reported that the additional force required made navigating the interface more cumbersome. Other positive aspects of the pitch selection interface included the ability to add vibrato and the presence of the continuous zone outside of the ring.

The excitation interface had slighter higher reviews, receiving an average value of 3.7. People generally enjoyed plucking but had a range of preferences for the strength of the haptic resistance, which some described as unrealistic. Some participants enjoyed the vibrational force delivered after plucking but others found it distracting and "mushy". A few participants suggested that it would be nice to be able to "lift up" the Haply 2diy handle so that you could move it across the string without plucking, although the 2diy lacks that ability.

Participants generally enjoyed bowing more than plucking. The haptic resistance made it feel lifelike, which helped users to musically express themselves. However, some of them disliked the roughness of the bowing and preferred for the force to simply be resistive.

The ability to switch between plucking and bowing was one of the novelties of the Hapstrument, and 8 of the 11 participants enjoyed this feature. However, one user disliked it because "it can't be done on a real instrument", while others found it too difficult to use while focusing on the pitch selection interface.

The Haply 2diy itself had a number of issues throughout the evaluation process. The magnetic handle would sometimes fall off, and some participants disliked its ergonomics and said that their wrists felt sore. Furthermore, the 2diy itself generated a minor rattling sound when the end effector moved across the surface, which some participants found to be distracting and irritating. Fortunately, the newest version of the 2diy eliminates the rattling issue.

Overall, the results of the post-test questionnaires exhibited significant variation across participants, with average ratings almost uniformly spread between 2 and 5 out of a maximum of 5, as shown in Figure 5. Some gave the Hapstrument high ratings across the board, indicative of promise for future development, while others consistently rated it poorly, suggesting that from their perspective, the instrument suffered insurmountable issues.

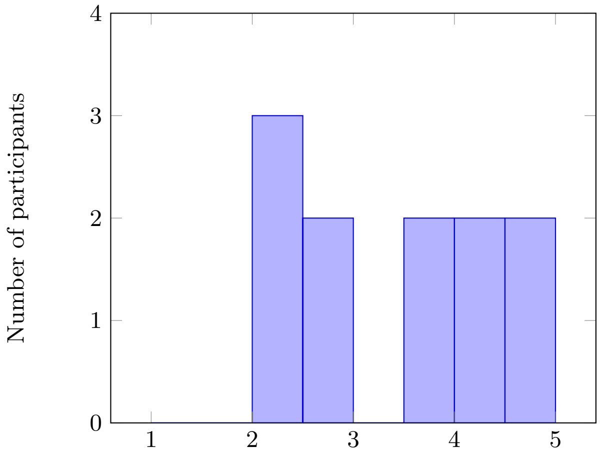

Figure 5: Distribution of ratings among participants.

Although we did not observe a correlation between the musical education of our participants and their post-test questionnaire results, the type of music they played was largely predictive of their enjoyment of the Hapstrument: those who focused on atonal composition and experimental music disliked the Hapstrument and gave an average rating of 2.5, while those who played classical music appreciated its pitch selection interface, which matched their musical expectations, and they gave an average rating of 3.8.

Similarly, participants with prior exposure to haptic devices favourably viewed the haptic sensations from bowing and plucking, whereas those who had never used such devices often found the force feedback distracting.

The main limitation of this user study was the small participant population. Future studies with larger groups may reveal additional insights into the effectiveness of the Hapstrument.

5. CONCLUSION

Returning to the theme of NIME 2023, frugal music innovation requires resources that are affordable and available. The Haply 2diy is an effective tool for this theme, due to its easily replaceable 3D-printed mechanical parts and its low cost (∼USD 500) in comparison with other commercially available force-feedback devices, which usually cost many thousands of dollars. Basic motors can be cheaper than the 2diy and can also add haptic effects to DMIs. However, they lack some of the main features of the 2diy, such as its pantograph-inspired structure, convenient API, and its ability to produce force feedback in any 2D direction.

Our main research goal in this study was to explore whether low-cost 2-DoF force-feedback devices can model bowing and plucking with a continuous transition between the two, and if so, to what degree this can contribute to musical expression. We were able to create the desired interaction paradigm and based on the evaluation we conducted, some people found it effective and realistic, although others had different preferences. Regarding musical expression, for several participants, the Haply 2diy was certainly capable of enabling them to express themselves effectively. However, the negative reviews from different participants would indicate otherwise.

Ultimately, the evaluation of the Hapstrument demonstrates that the preferences people have towards new digital musical instruments will heavily depend on their backgrounds and the expectations that they bring into their experiences with the instrument. For the participants whose expectations matched what the Hapstrument could offer, it was an expressive and effective low-cost DMI. One participant even described it as the "most successful software instrument I've seen coming out of CIRMMT for the last 4 years". However, for the participants who had different expectations, this DMI was not the right choice for them.

Future improvements to the Hapstrument, as recommended by our study participants, may include adding a button to the device's handle as an additional input, implementing more timbre parameters, and introducing new visual features to the GUI.

6. ACKNOWLEDGMENTS

The authors acknowledge the teaching team for CanHap 501, particularly Oliver Schneider, who gave valuable input to the development of the Hapstrument. Bradley Rey and Juliette Regimbal also provided helpful advice during the design process.

7. ETHICAL STANDARDS

The user study in this project received ethics approval from the Research Ethics Board at McGill University, under file #22-07-077. Participants gave informed consent and were paid once the experiment finished. This study was funded by NSERC's Discovery Grants Program.

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