Resurfacing an Enactive Approach for Instrument Design: The case of the Tangible Granular Device

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ABSTRACT

This paper proposes a tangible interface for controlling a granular sound engine through the manipulation and exploration of physical materials with granular properties. The design of this Tangible Granular Device was primarily, though not exclusively, guided by the design principles of musical instruments with an enactive approach proposed by O'Modhrain and Essl in 2006, presented after the introduction of PebbleBox and CrumbleBag in 2004. Even two decades after these tactile interfaces, it remains crucial to question why a well-defined research trajectory on this subject has not been established. This places the search for new connections between granular synthesis techniques and tangible interface design at the core of this work, which aims to explore novel expressive forms of interaction with granular synthesis. To achieve this, an enactive exploration of physical materials with granular properties was conducted, followed by the implementation of an apparatus capable of capturing and recognizing interactions with these materials. Subsequently, the Tangible Granular Device was designed and implemented to facilitate interaction with these materials according to a set of guidelines of tangible interfaces and enactivism in musical instruments. Finally, the paper discusses the outcomes of the process, reflects on the current state of enactive design, and proposes improvements for future versions of this instrument.

Author Keywords

Tangible Interfaces, Granular, Enactive

CCS Concepts

•Human-centered computing → Interaction devices; •Applied computing → Sound and music computing;

1. INTRODUCTION

Granular techniques are widely employed in sound and music production. They are not only utilized for musical composition but also for video game design [19] and audio processing techniques, such as time stretching [17].

However, due to its nature, granular synthesis is difficult to excel, as its flexibility and variety in generating sound textures result from a high number of parameters. This complexity can be challenging to control without a comprehensive understanding of the underlying theory, especially during live performances [17, 3].

Based on this premise, this paper proposes a tangible interface for controlling a granular sound engine through the manipulation and exploration of physical materials with granular properties. By physical materials, we refer to elements that, when touched, are perceived as multiple similar particles (e.g., stones, grains, sand) or objects that have protrusions in their structure, creating a tactile sensation resembling separate particles within the texture.

The design of this Tangible Granular Device was primarily, though not exclusively, guided by the design principles of musical instruments with an enactive approach proposed by Essl and O'Modhrain [6].

This paper begins by providing a brief overview of tangible user interfaces and the development of musical instruments with an enactive approach (20 years after the Pebblebox presented by O'Modhrain and Essl). It then introduces the Tangible Granular Device, a tangible exploration table for granular synthesis inspired by these concepts. The underlying idea of this prototype is to manipulate sound grains through physical grains, as proposed in PebbleBox, and to explore and investigate the various relationships between physical gestures and sonic outcomes to discover new forms of performative expressiveness with granular techniques.

To achieve this, an exploration of physical materials with granular properties was conducted, followed by the implementation of an apparatus capable of capturing and recognizing interactions with these materials. Subsequently, the Tangible Granular Device was designed and implemented to facilitate interaction with these materials, according to the guidelines of tangible interfaces and enactivism in musical instruments. Finally, the paper discusses the outcomes of the process, reflects on the current state of enactive design, and proposes improvements for future versions of this instrument.

2. BACKGROUND

In 1997, the Tangible Media group at the MIT MediaLab, led by Hiroshi Ishii, proposed "Tangible Bits", outlining a vision for Tangible User Interfaces (TUIs) [9]. TUIs represent a type of interface that engages physically with users through their senses, primarily touch, aiming to enhance human interactions with the digital world by leveraging multimodal senses and skills developed throughout a lifetime of real-world interactions. The concept involved transitioning from Graphical User Interfaces to Tangible User Interfaces,

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designed and constructed with a focus on senses and abilities that graphical interfaces and traditional peripherals may not effectively utilize.

The goal of TUIs is to give physical form to digital information, allowing manipulation with hands and perceptibility through senses. This shift is intended to address the limitations of graphical interfaces and traditional peripherals, offering a more immersive and intuitive interaction with digital content.

In this context, tangibility is defined as any physical form that represents information and, therefore, exists outside of any virtual medium. While a traditional instrument, such as a violin, is inherently tangible, it does not correspond to a representation since it is the object itself that produces sound due to its physical characteristics. Thus, it is crucial to emphasize the quality of being a representation of an idea. In most cases, this involves a manipulable object or surface that can alter information within it or even be altered by the information.

In 2005, the reacTable* was developed, representing an iconic example of tangible user interfaces. It was created at the Music Technology Group of the Universitat Pompeu Fabra and underscores the value of modularity, asserting that modular synthesis "Modular synthesis has largely proved its unlimited sound potential" [11, p. 2].

For this research, we mainly draw inspiration from the work proposed in 2004 by Sile O'Modhrain and Georg Essl: *PebbleBox* and *CrumbleBag*, two musical instruments in which "the manipulation of physical grains of an arbitrary material becomes the basis for interacting with granular sound synthesis models" [15, p. 74]. The development of these instruments was later termed by the authors as an enactive approach to the design of new tangible musical instruments [6]. The paper on PebbleBox and CrumbleBag has been recognized by the NIME community (and akin communities) with over 100 citations, as well as being included in "A NIME Reader: Fifteen Years of New Interfaces for Musical Expression" [10].

The enactive approach to digital instruments focuses on generating sound synthesis from events where the tactile sensation of the object and the sound they produce are loosely related. The mechanism to enhance these weak relationships between the haptic and sonic aspects involves leveraging interactions that have an acoustic component. This acoustic information is captured and processed to obtain relevant parameters of the event, which are used to control sound synthesis models. The fact that the physical properties of the interface provide the element linking tactile sensation and sound ensures that the interaction dynamics are appropriately preserved, even though these can be obtained with other types of sensors, such as light, force or motion sensors. Moreover, this approach is connected to the tangibility concepts proposed by Hiroshi Ishii in Tangible Bits [8].

Both the proposals by O'Modhrain and Essl and the concept of Tangible User Interfaces contribute to the theoretical foundation of this paper. This places the search for new connections between granular synthesis techniques and tangible interface design at the core of this work, aiming to explore novel expressive forms of interaction with granular synthesis.

Even two decades after the introduction of PebbleBox, it remains crucial to question why a well-defined research trajectory on this subject has not emerged. This is not to diminish the substantial research and the development of novel tangible interfaces in recent years [21, 18, 20, 5, 12], which have even included brief explorations into enactive-focused musical instrument design [1, 16]. However, as of the current date, there are no notable new frameworks that emphasize enaction in the design of innovative instruments. We believe that, especially in a digital environment that is increasingly driven by virtual immersion, it is worth resurfacing enactive approaches.

3. METHODS

3.1 Material Exploration

As part of the development process of the Tangible Granular Device, a tactile-sonic exploration of specific granular materials was conducted to identify potential candidates for use in the device's design.

For this process, a practice-based research method was employed, as the first author designed and executed a series of experiments focusing on exploring his own tactile perception with hands concerning various materials (see Fig. 1). These materials were placed in different bins or containers and on surfaces with varied shapes and materials. The objective was to investigate suggestive interactions in each combination of granular material and bin.

This exploration constituted an enactive practice in itself, wherein knowledge was acquired through action, specifically by manipulating the materials mentioned. Moreover, this process was conducted with the awareness that acoustic and tactile events are closely intertwined, and it aimed to decouple these events to devise novel approaches for substituting the acoustic component with other sounds that remain pertinent to the tactile event within the overall interaction.

Figure 1: Samples of granular materials utilized during the exploration phase: a) rolled pebbles b) small seashells c) glass pebbles d) medium-size seashells e) crushed stones.

Additionally, experimentation extended beyond materials resembling grains to include objects that imparted a granular sensation, such as the bristles of a brush, objects with protrusions, or textured sponges.

From this personal and systematic process of experimentation, reflections emerged—informed and inspired by the previously described background section. These reflections would later guide decision-making regarding the design of the Tangible Granular Device prototype.

Each of these experiments was documented in videos. Subsequently, this material was edited and shared on a blog, where comments, ideas, and reflections on each experiment were articulated.[1]

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[1] The blog (in Spanish) is accessible through the following link: `https://tangiblegranulardevice.wordpress.com`

The exploration results were classified according to the type of interaction gestures with the grains. The most common gestures involved **stirring** inside the container and **tossing** grains from outside the container to the inside. The nuances of these interactions varied based on the material, shape, and size of the grains, the quantity of grains, as well as the size and shape of the container in which the interaction took place. Conclusions regarding the grains and the aforementioned variables are as follows:

- When the grains cover a small surface area (regardless of grain size), it is more comfortable to interact with them on a small surface. If the surface is larger than the size of a hand, then the entire surface is optimally utilized when the grains cover the entire space.
- For larger grains, it is intriguing to explore gestures involving collisions between each of the grains. In contrast, for smaller grains, it is more interesting to investigate how they behave as a cloud or mass of grains within the container.

Furthermore, experimentation included certain granular objects that, while not grains per se, imparted a tactile sensation similar to grains. Although these objects were not utilized in the final prototype, gestures produced with brush bristles were closely aligned with Essl and O'Modhrain's instrument design, as can be appreciatted in the corresponding video[2]. In subsequent iterations, it would be worthwhile to delve deeper into these gestures.

4. CAPTURE AND CLASSIFICATION OF GESTURES

Following the exploration of granular materials, an apparatus dedicated gesture capture and classification was implemented, specifically for grains within containers as described in the previous section. The aim was to capture and parameterize granular gestures so that they could be mapped to the parameters of a granulator. For this purpose, an electroacoustic and digital processing chain was developed, primarily incorporating tools for Audio Content Analysis and Machine Learning (see Fig. 2).

The apparatus encompasses the entire electroacoustic and digital processing chain. The electroacoustic chain comprises a piezoelectric sensor, a preamplifier for an electroacoustic guitar capsule, and a Focusrite Scarlett 8i6 audio interface. The equalization controls of the preamplifier were not utilized, only the gain control to receive a signal within an acceptable dynamic range.

Furthermore, before sending the signal to the feature extractors, signal filtering and dynamic gate processing was applied. These processes were implemented in Max software.

4.1 Feature Extraction

Real-time audio feature extraction was performed using the ZSA Descriptors library [13] available in Max. Thirteen MFCC coefficients were extracted, along with the calculation of the first and second derivatives. The decision to compute MFCCs was based on prior literature where this feature is employed as a parameter for similar recognition tasks in other audio signals, such as spoken voice [7]. Regarding MFCCs and their derivatives, these characteristics enable robust and consistent classifications, although they exhibit some error in transitions between gestures. This error was not investigated in detail, but studies confirm that MFCCs are susceptible to noise [2]. For the particular case of Dynamic Time Warping, the signal envelope was added to the feature extraction process.

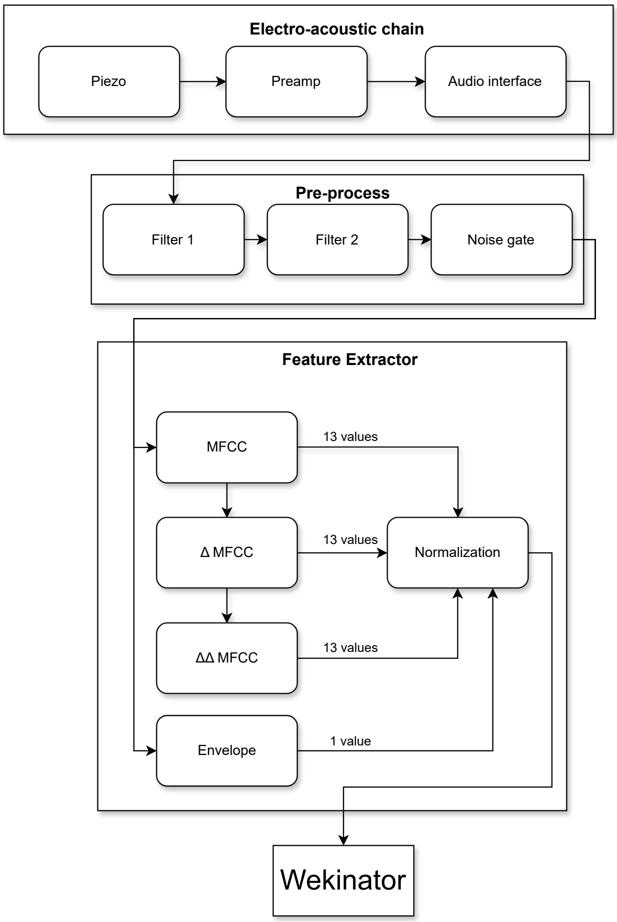

Figure 2: Flow diagram of apparatus utilized in the Tangible Granular Device, depicting the electroacoustic chain and the features extracted from the signal that feed Wekinator.

Normalization of the signal features was necessary before sending it to classification models to enhance performance and prevent the preponderance of certain features over others, particularly for models like k-Nearest Neighbors (kNN) and temporal analysis models such as Dynamic Time Warping (DTW).

4.2 Machine Learning Pipeline

For the Machine Learning stage, Wekinator[3] software was utilized. The algorithms employed were k-Nearest Neighbors (kNN), AdaBoost, Decision Tree, Support Vector Machine (SVM), and Naive Bayes, aiming to evaluate which algorithm performs best for the project. The input data included the previously mentioned MFCCs and their derivatives, along with the envelope, resulting in a total of 40 inputs for each training example. These data was sent to Wekinator via OSC. Subsequently, during the prediction phase, Wekinator's output messages were received in the same Max patch via OSC.

4.3 Validation of the Processing Chain

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[2] `https://tangiblegranulardevice.wordpress.com/4-2/`

[3] `http://www.wekinator.org`

To assess the effectiveness of the processing chain, a series of experimental configurations were designed to test the developed apparatus. The aim was to determine which physical and sonic properties could be recorded and classified by the system. Additionally, unrelated sound sources were added to ensure that the system could recognize gestures based on their sonic characteristics and not by chance. These experiments can be reviewed in detail and accompanied by audiovisual material at the corresponding blog section[4].

The experiments confirmed that it is possible to automate the recognition of **stirring** and **tossing** grain gestures. The nuances in the gestures are not detectable, but the degree of prediction is acceptable for the purposes of this project. For all datasets from each experiment, 10-fold cross-validation was performed using the tool available in Wekinator, and in most cases, values exceeding 95% were achieved (see Table 1). Therefore, the classifications are quite robust and consistent, having minor issues when switching from one gesture to another. This transition error is mitigated in later stages of development through signal processing. For the final prototype, the prediction model based on Support Vector Machine was utilized.

5. TANGIBLE GRANULAR DEVICE

Having conducted granular material explorations and designed an apparatus and processing chain to capture gestures, the following design principles were established for the development of the Tangible Granular Device:

- **Enactive**: It is crucial that the user experience is informed by the user's prior knowledge. We possess a basic understanding of the laws of physics on an experiential level, meaning we can anticipate certain sonic, visual, or tactile outcomes based on our actions. Following the enactive instrument design premise, the Tangible Granular Device explores the correlation between tactile and sonic sensations.

- **Modular**: The interface should provide extensive interconnection possibilities among its modules, thereby generating unlimited sonic behaviors and outcomes. This allows variability in the user experience.

- **Versatile**: The interface should have a degree of flexibility, allowing users to adapt it to their personal experience and develop their own style, both at the software and hardware levels.

The Tangible Granular Device consists of an exploration table with a series of containers containing grains with which the user can interact and modify freely. Interactions within each of these containers are captured through a piezoelectric sensor connected to an audio interface, which is then processed by the software developed in Max and Wekinator (see Fig. 3).

Inspired by the proposal of the Digital Musical Instrument (DMI) described by Wanderley and Depalle in their article "Gestural Control of Sound Synthesis" [23], the Tangible Granular Device consists of three main parts: (1) control surface, (2) granular mapper, and (3) granular sound engine. Direct and indirect gestures are captured by the control surface, processed by the granular mapper, and then lead to changes in the parameters of the granular sound engine (see Fig. 4).

Figure 3: General view of the Tangible Granular Device.

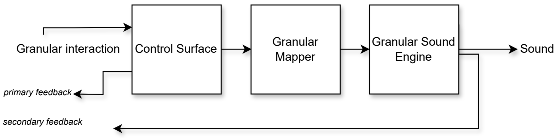

Figure 4: General flow diagram of the Tangible Granular Device, following the proposal of Wanderley and Depalle [23].

5.1 Control Surface

The control surface is the physical space where users can interact with the grains through granular gestures within the grain bins. The gestures are captured through the piezoelectric sensors placed underneath each container, and the signal is pre-processed before being sent to the granular mapper (see Fig. 5).

The control surface provides primary tactile and auditory feedback, informing the user initially about the development of granular interactions. This feedback is complemented by secondary feedback produced by the Granular Sound Engine.

5.2 Granular Mapper

Once the granular interactions are captured, the granular mapper processes and assigns them to input parameters of the granular synthesizer. The granular mapper is composed of control modules, which are signal processing algorithms that convert audio signals into control signals for the granular sound engine. Each module is designed to control a specific part of the granular sound engine, whether it be the audio buffer, playback parameters, or grain manager. These modules adscribe to the design principles previously mentioned and are the result of reflections on theoretical and artistic references combined with practical experimentation (see Fig. 6).

Event Detection

Inspired by the operation of PebbleBox and CrumbleBag by O'Modhrain and Essl, this module is responsible for detecting the timing granular interactions occurring on the granular control surface. The resulting granular events are converted into triggers that the grain manager receives, re-

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[4] `https://tangiblegranulardevice.wordpress.com/3-2/`

Table 1: Cross-Validation using Wekinator k-fold tool. k = 10.

Experiment/Model	kNN	AdaBoost	Decision Tree	SVM	Naive Bayes
Experiment 1	99.64%	99.93%	99.67%	98.97%	98.68%
Experiment 2	99.02%	98.63%	98.63%	98.73%	98.86%
Experiment 3	86.51%	90.39%	88.12%	92.46%	85.20%

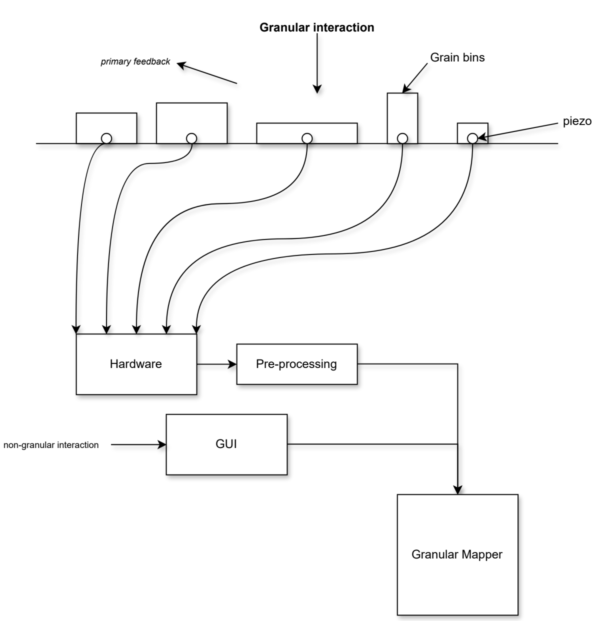

Figure 5: Flow diagram of the Control Surface that feeds the Granular Mapper of the Tangible Granular Device.

sulting in the playback of one or multiple grains, depending on the density of the granular interactions.

For this implementation, the algorithm proposed by Malt [14] based on the spectral standard deviation of the signal was used. According to the authors, this algorithm has proven to be very useful for detecting noisy events in complex musical situations where many types of sounds are mixed.

Exploration of this implementation confirmed that the response between an event and the playback of grains is perceived as instantaneous. Therefore, the haptic and sonic sensations are strongly synchronized, thus fulfilling the hypothesis of weak sensorimotor integration described in the design of enactively focused musical instruments by Essl and O'Modhrain [6].

Gesture Recognition

This module can recognize the gestures of stirring and tossing grains, triggering one or several events based on these gestures. It has been decided to use only these gestures due to the satisfactory recognition results provided by the developed classification chain. For this module, only the Support Vector Machine model is used, as it experimentally yielded the best results. An additional class of silence has been added to prevent misclassifications when transitioning from one gesture to another. The processing chain can be seen in section 4. Subsequently, this data is processed with a moving average filter and rounded to the nearest integer. Upon recognizing a gesture, the corresponding granular sound is activated, while the other is muted.

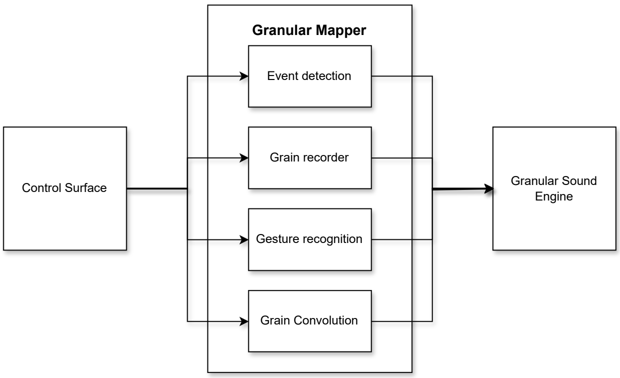

Figure 6: Different modules of the Granular Mapper that link the information received from the Control Surface with the Granular Sound Engine.

Grain Recorder

This module does not transform the audio signal into a control signal; instead, it dynamically feeds the granular sound engine with new sonic material. Specifically, it allows recording the sound captured by the piezoelectric sensor and then immediately loading this recording into the audio buffer of the granular sound engine.

The interesting aspect of this module is that once the granular interaction is recorded, we have the ability to manipulate timbral characteristics such as pitch or grain duration. This allows the grain to remain recognizable but possess a sonority that would not otherwise be achievable, reinforcing the central idea of the design of instruments with an enactively focused approach.

Grain Convolution

This module involves a convolution process between the output signal of the granular sound engine and the audio signal from the piezoelectric sensor. Two algorithms have been implemented. Due to the quality of the piezoelectric transducer, the multiplication of phase and amplitude in the frequency domain is less sonically interesting. Therefore, the second proposed algorithm (similar to AM synthesis) was preferred, where one of the signals acts as the carrier, and the other as the modulator. By assigning the output of the granular sound engine to the carrier signal and the grain bins to the modulator, it can be perceived as if the gestures made with the grains were the envelope of the granular sound. The sound quality is perceived as 'low-fi'; however, by exciting certain frequencies, it is possible to obtain a sound closer to the original granular sound. These differences can be seen in the corresponding video[5].

5.3 Granular Sound Engine

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[5] `https://tangiblegranulardevice.wordpress.com/5-2/`

The sound engine is responsible for generating sound based on parameter changes received from the granular mapper. The audio buffer, playback parameters, and grain manager can be modified by the granular mapper, and then the grain generator is responsible for reproducing the sound based on these parameters.

It is important to mention that the grain manager can be controlled internally through a variable clock with parameters of randomness, or it can be externally controlled from the granular mapper through the event detection module described earlier.

5.4 Prototype Demonstration

Demonstrations of the Granular Tangible Device can be seen in the corresponding videos[6][7]. In these demonstrations, the Gesture Recognition and Event Detection modules are the most used as they are directly related to the playback of the granular sound engine. The Grain Recorder module is only used when seeking to change the overall timbre of the sound texture. Ultimately, the grain convolution module is the least used as it requires additional effort by having to use both hands in different containers to play the granular sound engine while convolving, while the sonic result is not as interesting.

6. DISCUSSION

One of the main contributions of this paper lies in the material exploration process, where reflections were made based on physical perception, which in turn informed the decision-making in the design of the tangible interface. This practice-based research approach differs from other traditional methods, yet it is still informed by a theoretical framework that supports the use of these materials for designing interfaces and instruments that leverage other senses and abilities of individuals. We believe that this form of practice-based research is equally valuable and allows the integration of the cultural experience of the artist, turning the process itself into an object of study.

The physicality provided by the Granular Tangible Device is an interesting aspect that can be further explored. It is not only the sound outcome that is important, but the whole experience: both listening and touch are present when interacting with the Granular Tangible Device. Additionally, the device is accompanied by a graphical interface that allows to modify the behaviour of each of the control modules.

The novelty of this device lies in the granular mapper, where several mapping modules are proposed. These modules receive the information captured by the control surface and changes parameters of the granular sound engine or trigger its playback.

Despite this, the Tangible Granular Device is still in the prototype stage: Max knowledge is needed in order to modify the default behavior of the device. Therefore, the assistance of one of the authors is required at all times to interact with it, as there is also no documentation available.

It would be interesting to move beyond the personal experience space to enrich this enactive process with other experiences. The tangible and enactive interaction forms that have been designed can serve as input for other instrument creation processes or for artistic creation, acting as a tool that enables alternative forms of expressiveness.

The theoretical background of this work relies largely on bibliography predating 2010, including the concepts proposed by O'Modhrain and Essl regarding enactive design. This raises the question of whether an enactive approach in the design of DMIs is still relevant to the NIME community.

Despite the continued appearance of the enactive concept in recent publications [4] [16], they do not necessarily derive from the PebbleBox article; instead, they reference the original definition by Varela, Rosch and Thompson [22], contextualizing it to other areas. In the context of the mentioned publications, enactive design aims to integrate the body—primarily touch, vision, and hearing—into interaction to varying degrees, with the goal of creating immersive experiences. Within this framework, it can be suggested that the NIME community is more inclined towards embracing the vision of enactivism within performance-related practices rather than exclusively adopting an "enactive way" of designing.

Conversely, the technical requirements for enactive interfaces can be quite specific, rendering them less versatile and more challenging to implement. In contrast, within industry standards, immersion has been approached differently, particularly in virtual or mixed reality contexts, where visual effects are commonly utilized to immerse users in the experience, often neglecting the tactile component.

7. CONCLUSSIONS AND FUTURE WORK

We have presented a prototype of a tangible interface for expressive and gestural interaction with a granular sound engine. The prototype was designed based on the principles of enaction, modularity, and versatility, under the premise that the physical manipulation of the grains signifies the manipulation of the sound produced by the granulator. In terms of the design process, it was primarily guided by reflections stemming from the personal tactile and gestural exploration of materials by the first author. These explorations were informed by theories of tangible user interfaces and enaction. This process seeks to explain a specific phenomenon within the DMI community through personal experience: the challenge of finding new ways to explore expressivity in novel musical instruments.

Future work includes exploring tactile granular sensations more broadly (i.e. granular surfaces), and extending interactions and gestures to other artistic dimensions such as live performances and interactive installations. In these contexts, the goal is to establish a connection not only between the physical and the sonic but also with the generation of other tangible and intangible stimuli that contribute to the performative or installative experience.

8. ETHICAL STANDARDS

This project was undertaken within the standards of the NIME ethical code of conduct. No studies involving external participants were conducted in this research, so no ethical issues relating to study subjects were encountered. However, the authors acknowledge that this work does make use of laser cutting technologies to construct MDF parts, which can contribute to environmental damage.

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