Kuturani: a low-cost device to augment acoustic string instruments

Kuturani: um dispositivo de baixo custo para aumentar instrumentos de corda acústicos

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Abstract: The concept of hyperinstruments emerged around forty years ago with various approaches to instrumental augmentation, such as Tod Machover's Hypercello (Machover; Chung, 1989) and Andrew McPherson's magnetic resonator piano (McPherson; Kim, 2010). These instruments are typically designed by experts utilizing advanced technologies that are often expensive, with unique designs tailored to each instrument. Aiming to democratize the field of augmented instrument design, we developed Kuturani, a cost-effective system for instrument augmentation. The aim is to support communities with limited resources by emphasizing the use of locally crafted musical instruments. Our concept is to develop a device that can be adapted to work on any string instrument and to keep its design open-source, allowing users to modify or replicate it. To achieve this goal, we have designed multiple versions of the device, each one offering different options that can be tailored to the user's needs. During the development of Kuturani, we encountered several challenges, including maintaining all the design characteristics while integrating various technical approaches and components. In this paper, we report the progress of our project and the strengths and weaknesses of working with four different microcontrollers to produce our device, as well as our approach to dealing with data acquisition, feedback and signal ,processing, all while trying to keep the cost of the variations of the device as low as possible.

Keywords: hyperinstrument. augmented instrument. low-cost instrumental augmentation. digital lutherie. DMI.

Resumo: O conceito de hiperinstrumentos surgiu há cerca de quarenta anos com várias abordagens para aumento instrumental, como o Hypercello de Tod Machover (Machover; Chung, 1989) e o piano ressonador magnético de Andrew McPherson (McPherson; Kim, 2010). Esses instrumentos são normalmente projetados por especialistas que utilizam tecnologias avançadas e muitas vezes caras, com designs exclusivos adaptados a cada instrumento. Visando democratizar o campo do design de instrumentos aumentados, desenvolvemos o Kuturani, um sistema de aumento de instrumentos com boa relação custo-benefício. Nosso objetivo é dar suporte a comunidades com recursos limitados, enfatizando o uso de instrumentos musicais produzidos localmente. Nosso conceito é desenvolver um dispositivo que possa ser adaptado para funcionar em qualquer instrumento de cordas e manter seu design em código aberto para que possa ser modificado ou replicado pelos usuários. Para atingir esse objetivo, projetamos várias versões do dispositivo, cada uma oferecendo diferentes opções que podem ser adaptadas às necessidades do usuário. No processo de desenvolvimento do Kuturani, enfrentamos vários problemas, como a dificuldade de manter todas as características do nosso design enquanto trabalhamos com diferentes abordagens técnicas e componentes. Neste artigo, relatamos o progresso do nosso projeto e os pontos fortes e fracos de trabalhar com quatro microcontroladores diferentes para produzir nosso dispositivo, bem como nossa abordagem lidando com aquisição de dados, feedback e processamento de sinal, tudo isso enquanto tentamos manter o custo das variações do dispositivo o mais baixo possível.

Palavras-chave: hiperinstrumento. instrumento aumentado. aumento instrumental de baixo custo. luteria digital. DMI.

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1. Introduction: something for everyone

Advancements in music software and the augmentation of acoustic instruments through the addition of electronic components offer new possibilities for musical expression. However, in the Mexican state of Michoacán, where we are working on this project, and in most parts of the country, these advancements are rarely explored, despite the rich local musical traditions and resourcefulness of local musicians and sonic artists. Many factors are at play; while Morelia, the capital city, is an essential reference in the modern musical life of Mexico — hosting some of the country's most important music festivals[1] and the Mexican Center for Music and Sonic Arts (CMMAS), as well as being close to the *zona lacustre* (zone around the Pátzcuaro lake) where rich musical heritage and lutherie have been fostered since colonial times, in this part of the country, the lack of access and equity are significant issues that need to be addressed, particularly for artistic education (Duarte-García; Sigal-Sefchovich, 2019). In addition, socioeconomic factors make it more difficult for people in Latin America to enter the field of music interface development due to a lack of access to resources — for instance, some electronic components can be challenging to find locally, and high shipping costs discourage the growth of interfaces (Martínez Ávila *et al.*, 2022).

In light of the factors mentioned above, we believe it is essential to find ways to improve access to the interface and the field of augmented instrument development for our community. To address this, we have created a low-cost instrumental augmentation system called Kuturani. *Kuturani* is a word in P'urhépecha[2] that means 'to add' or 'to join.' This word summarizes our project, which combines electronic components and acoustic instruments. Another critical aspect of the project was to create pedagogical materials — including instructional videos and PDF guides — to teach the skills necessary for building similar devices. We aim to

1 The list of Morelia's music festivals includes Festival Internacional de Órgano de Morelia Alfonso Vega Núñez, Festival de Música de Morelia Miguel Bernal Jiménez, Festival Internacional de Guitarra de Morelia, and the Jazztival de Michoacán, as well as one of the few mexican music festivals dedicated to academic electronic music, Visiones Sonoras.

2 A pre-hispanic language, from the Michoacan State area in Mexico, that is still in use.

provide an educational resource that enables our local community to participate in developing NIMEs using readily available and accessible resources. We hope to initiate a local musical interface builder movement by sharing these educational resources and the design of our device and software as an example. The design of Kuturani and its variations, as well as the building process and software, can be found at **www.kuturani.com.mx** and are freely distributed and licensed under Creative Commons. We aim to impact a group of people who may not have a scientific or technical background, as well as those with limited resources.

The concept of hyperinstruments inspires our project; however, the Kuturani is intended to be an instrumental augmentation system concept, rather than a defined and final product. We have designed multiple versions of the device to achieve this goal, each offering different options tailored to the user's needs while keeping costs low and making it easy for non-experts to build. Our designs incorporate modularity, enabling users to add sensors and connect to other devices, allowing them to rethink and redesign their instruments to explore new interactive possibilities and sonic results.

Currently, our device consists of a system that uses a microcontroller, custom PCBs, a few onboard sensors, and connection ports to connect a variety of extra sensors, a microphone, and a transducer. We have considered the most essential features of a hyperinstrument, such as monitoring performance to capture the physicality of interaction between the performer and instrument, and collecting data that is processed to either produce synthesis, process audio, trigger audio, or feed a variety of systems. We have also considered the possibility of capturing audio and processing it directly on the device without the use of a secondary device, such as a computer and software. This is, with some limitations, possible in some versions of the Kuturani. Lastly, following the example of recent developments in augmented instruments, we have included a transducer installed on the body of the acoustic instrument, which helps output an audio signal while leveraging the instrument's acoustic chamber and natural amplification system. We have documented our design and construction process and will continue to do so as we make new developments.

2. State of the art in technologically augmented instruments

Traditional musical instruments have historically been made by experts using the latest technologies along with conventional construction techniques and material preparation. While this traditional approach is still employed, non-experts, such as composers and researchers, are becoming involved in modifying, designing, and building instruments. This trend is accelerating the creation of new instruments, the development of existing ones, and the expansion of a global community of individuals interested in musical interface development — such as the NIME movement (Fasciani; Goode, 2021).

Access to technology has transformed the way we engage in music creation. New technologies have become valuable assets, enabling the rapid advancement of musical innovation and allowing composers to explore and manipulate sound in ways that were previously inconceivable. For example, Iannis Xenakis' UPIC changed the way in which technology helped us visualise and structure music, requiring utterly new techniques for performance at the same time as allowing composers to explore pitch and time with a novel approach to build sounds, timbre, and microstructures (Marino *et al.*, 1993); On the other hand, Tod Machover looked back and focused on traditional instruments — "perfected" by luthiers — augmenting them by mounting electronic devices on their bodies, giving them new sounding capabilities and turning them into what he called hyperinstruments. As well as enabling the development of new musical instruments, technology has also helped us change the way in which we think about music; Will Mason affirms that the French spectralist music "is fundamentally mediated by technologies of sound synthesis and analysis [...] the tools of the recording studio revealed aspects of sound (especially timbre) which became metaphorical and structural resources for their compositions (whether acoustic or electroacoustic)" (Mason, 2019, p. 5).

We believe that some streams of modern music are only able to exist due to the mediation of new technologies, and have proposed in the past that the media (by which we mean specific technologies created to realise particular works, such a technological system for installations, a Max patch, supercollider code, personalised interface, etc) should be considered as part of the musical work (Ramos Flores, 2021, 2022). This belief holds in the case of augmented instruments. They allow for unique compositions in which interaction and performance exploration are core elements, as is the physicality of interacting with the musical instrument and its acoustic characteristics. Several instrumental developments, such as Leon Theremin's Fingerboard Theremin (also known as the Theremin Cello) or Max Matthews' electric violin, laid the groundwork for the research and development of augmented instruments, also referred to as hyperinstruments. Well-known examples of the latter include Todd Machover's hyperinstruments, NIMEs produced and documented in the last twenty-five years, as well as the exploration of acoustic-electronic systems research, such as the IMAREV project, which are discussed in the following sections.

2.1 Hyperinstruments

A hyperinstrument is a single system that combines sensors and computer processing with traditional instruments to augment expressive capabilities. In Machover's words, hyperinstruments are systems based on "the combination of machine-augmented instrumental technique, knowledge-based performance monitoring, and intelligent music structure generation" (Machover, 1992, p. 3). They combine traditional instruments and electronic components to provide composers and performers with new expressive possibilities.

> [...] the basic idea of a hyperinstrument is where the technology is built right into the instrument so that the instrument knows how it's being played literally, what the expression is, what the meaning is, what the direction of the music is. If a performer pushed to a downbeat, or relaxed on a phrase, or brought out a particular F sharp, those things would be recognized and valued by the instrument (Machover, 2008).

Traditional instruments produce sound through the mechanical interaction of their parts; for example, blowing a column of air into a clarinet while vibrating the reed. These conventional instruments have intrinsic physical limitations when producing sounds due to their acoustic properties. However, synthetic sounds don't have the same constraints. In theory, through synthesis, any sound can be created. Machover recognised this potential and aimed to enhance these instruments through new technology. He introduced computer systems with sensors that collect data from the performer's interaction with the instrument and the resulting sounds, such as the use of sensors to detect the force that fingers apply to the violoncello fingerboard while playing a specific note on a string.

> Therefore, the computer employs various techniques, some mathematically based on the analysis of the spectrum at a given moment, some based on physical monitoring of a player's movement ... or some artificial-intelligence techniques (Machover, 1986, p. 592).

The Kuturani was designed following Machover's paradigm, monitoring the performance, processing data, generating audio, and outputting audio signals directly into the instrument's body to maintain a sense of embodied sound. However, unlike previous hyperinstruments, our system is not designed exclusively for one instrument but is intended to be flexible enough to be used on multiple string instruments. This means that the collected data and performative aspects will differ from one instrument to another. For this reason, processing the collected data and matching a physical action with a sounding result must always remain open in our system. We have preprogrammed a set of audio features that are commonly used (such as reverb, distortion, granulation, and others), but left the code open so that these features can be activated, tweaked, and controlled according to the different modes of interaction corresponding to the instrument on which the Kuturani has been installed. The system also allows users to code synthesis processes, remaining open to interact with third-party commercial software using Serial, MIDI, and OSC protocols.

2.2 Physical interaction and new interfaces

Physical interaction between performers and their instruments, as well as various techniques to monitor these interactions, collect data, and use that data to produce synthesis, has been explored for a long time. Research on musical performance sensing has brought new techniques and ideas. For example, Dan Trueman's Rbow (consisting of an acoustic violin bow) and Perry Cook's Squeezevox Lisa and Squeezevox Bart (modified accordions), as well as other controllers developed by both, monitor performance and group different motion sets to generate sound synthesis (Cook; Lieder, 2000; Cook, 2001, 2004; Curtis; Dan, 2001). This paradigm has been extensively explored in the past twenty-five years, resulting in the development of multiple interfaces that range from modifications to objects not intended to be musical instruments (Crevoisier; Polotti, 2005; Monache *et al.*, 2008; Bowers; Haas, 2014), modified instruments (such as Machover's hyperinstruments and others discussed in the following pages), and new instruments which draw inspiration from traditional acoustic instruments, such as Rafaele Andrade's Knurl.

A recent development in the history of new musical interfaces, Andrade's Knurl was designed based on the size, feel, and performability of a violoncello. The Knurl, however, consists of four sets of four strings over a rotating body, allowing access to each set of strings as though it were a set of four violoncellos. The design affords the performer the possibility of accessing multiple tuning configurations for the strings, thereby varying the instrument's range, while also providing new tactile sensors for each string (Andrade, 2022; Mantel, 2022). This configuration, along with the multiple possible ways of processing the data obtained via the strings, offers the composer and performer a large number of potential sonic results. To define and limit the sounding and interactive possibilities, as is the case with any musical interface, a careful mapping system must be designed.

The connection between the physical action and the resulting sound, known as mapping, is fundamental in designing any hyperinstrument. While it is true that the mapping can be reprogrammed with ease, the interactive aspect requires consideration. For example, a flute can be easily lifted and tilted, and with the appropriate sensors, this action could result in pitch shifting. However, the same sounding effect could not be easily mapped to the same action while playing an augmented double bass, as the instrument's size and weight would make it difficult or impossible. Therefore, a different strategy would be necessary. This highlights the importance of considering the physical interaction with the acoustic instrument when developing a hyperinstrument. The sounding result is always the priority, and the configuration of sensors and software is often changing in search of a "new sound."

Cléo Palacio-Quintin developed a hyperflute that features magnetic field sensors on two flute keys, allowing the system to detect when the keys are pressed (Palacio-Quintin, 2008). Sébastien Schiesser's SABRe, on the other hand, features magnets clamped to the key axes to measure the key positions (Schiesser & Schacher, 2012). These are two similar approaches to monitoring two different instruments using the same type of interaction. Nonetheless, the musical results are very different thanks to the re-mapping that is done. Other approaches to monitoring the keys of wind instruments use very different techniques; Sarah Reid's MIGSI uses force-sensing resistors (FSR) to monitor the trumpet's valves (Reid *et al.*, 2016), while Cristohper Ramos' HypeSax integrates capacitive touch sensors on top of the D, E, and F keys (Ramos Flores, 2021). These techniques have the same goal: to monitor the interaction with the instrument's keys.

Nevertheless, the data obtained is very different: Palacio-Quintin and Schiesser's approach continuously tracks the motion of the keys, independently of whether the keys are fully closed. Reid's sensors will only take continuous data after the keys have been closed, measuring the force pressing the valves. This parameter has no effect on the acoustic sound. Finally, the sensors on the HypeSax are not designed to monitor whether the keys are moving or to measure pressure. Instead, they function as triggers activated only when the performer touches the sensor terminals positioned on the keys, often while closing the key for a specific fingering.

The examples discussed above demonstrate that, even when the mode of interaction is the same, the musical goals will always be the decisive factor. It is essential to strike a balance between musical goals, interaction, and performance gestures, especially when dealing with acoustic instruments, as these instruments have their own performance techniques, and performers have established relationships and modes of interaction with them. However, in the case of the Kuturani, since the device can be installed on many different instruments, we approached our design differently. The Kuturani features expansion ports that can connect to additional digital or analog sensors, depending on the performer's needs. This means there is no set "action to specific expected data" correspondence. Our system collects data, but the performer must define the corresponding result according to the chosen instrument and sensors.

The system's openness is not the only difference from traditional hyperinstruments. We also implemented an audio signal output system, aiming to transform the instruments' timbre in the near future through the active control of the instrument bodies' vibrations, as some researchers have already achieved (as described in the following section). This closed audio loop also opens an avenue for interacting with audio feedback as a creative resource.

2.3 Actuated instruments

New instrumental augmentation techniques utilize transducers to output audio signals directly through the body of acoustic instruments. These are known as actuated or active instruments. In 2011, Overholt, Berdahl, and Hamilton defined actuated musical instruments as "those which produce sound via vibrating element(s) that are co-manipulated by humans and electromechanical systems" (Overholt, Berdahl, Hamilton, 2011).

Three design approaches can be found in actuated instruments:

• **A non-traditional instrument is actuated.** Dan Overholt, for instance, designed an instrument that resembled a violin but lacked a resonant chamber. This setup minimised the strings' amplification. Instead, the augmentation system would output audio through a transducer, whose sound was amplified using a carbon fibre structure placed in the back of the instrument (Overholt, 2011). Also, decoupling the mechanisms that help instruments to project their sound, Laurel S. Pardue designed an instrument that isolates each component of a violin, avoiding vibration transmission between strings and body, and reconfigures a system that provides a natural performance experience but allows for the control of synthetic sound with an output enriched by the acoustic qualities of a violin (Pardue *et al.*, 2019).

• **A traditional instrument is actuated to produce a conventional sound, such** as Andrew McPherson's electromechanical system that induces vibration into the piano strings. The resulting sound has the spectra of the piano but with a very different form, as the envelopes, especially the attack, change drastically (McPherson; Kim, 2010). Similarly, Cameron Brit experimented with electromagnetic coils to actuate the bars of a vibraphone (Britt, Snyder, & McPherson, 2012), and David Rector converted a bass drum into a large speaker by installing large coils inside the instrument (Rector & Topel, 2014).

• **A traditional instrument is actuated to produce acoustic, synthetic, or hybrid sound.** Juan Arroyo's hybrid string quartet, for instance, makes use of microphones and transducers installed directly on the quartet's instruments' bodies. The audio is captured and then processed to finally be output through the quartet's instruments again, creating a hybrid sound (Houlès, 2017). Similarly, Otso Lähdeoja experimented with transducers on guitars (Lähdeoja, 2016), and David Rector/Spencer Topel on drums (Rector & Topel, 2014).

The Kuturani can be included in the last of these categories, as it is intended to incorporate a transducer mounted on the instrument to output audio directly through the acoustic system of the instrument's body. Nevertheless, this approach can produce unwanted feedback, which has been one of the most significant problems during the development of the Kuturani. Considering that the device is designed to be attached to various instruments, the placement of the transducer and microphone/pickup may vary. These variations in the setup make it challenging to adjust algorithms and have a fixed configuration to prevent feedback. As explained later in this article, we have used an LMS algorithm to manage unwanted feedback. We've been maintaining the same settings across all instruments, controlling input by adjusting the gain of the transducer and the microphone/pickup. Hardware feedback control has yet to be implemented and will be incorporated into future design changes. We are also considering controlling feedback via hardware and software as a sound feature, but more sophisticated controls still need to be implemented.

In actuated instruments, feedback can also be utilized as an expressive resource; Matthew Burtner's Metasax, although not an active instrument, explored feedback as a meaningful element of its sound (Burns; Burtner, 2004; Burtner, 2002). Neal Farwell's augmented trombone was one of the first examples, where feedback was undesired but was an integral part of the instrument's sound (Farwell, 2006). Similarly, The Feral Cello (Davis, 2017), Halldór Úlfarsson's cello (Eldridge *et al.*, 2021; Eldridge; Kiefer, 2017), and Adam Pultz's and Thanos Polymeneas' basses feature feedback as an expressive element (Melbye, 2021; Melbye; Ulfarsson, 2020; Melbye; Úlfarsson; Lab, 2020; Polymeneas Liontiris *et al.*, 2018).

Feedback is often unwelcome, and many efforts have been made to avoid it in the context of active instruments and hyperinstruments. Some systems do not allow input to take over by implementing complex algorithms and electronic components (Benacchio, 2014; Benacchio *et al.*, 2012; Berdahl, 2009; Berdahl, Smith; Niemeyer, 2012; Mamou-Mani, 2014; Ménage; Mamou-Mani; Puvilland, 2022; Overholt; Berdahl; Hamilton, 2011). Among the most impressive achievements in feedback control is the HyVibe, developed by Adrien Mamou-Mani, former director of the research group investigating active and innovative instruments (HyVibe Guitar – The world's first Smart Guitar, 2024; IRCAM, 2014, 2015). His instrument can output clean, amplified audio, including effects such as reverb, free of feedback, even when the pickup (input) and transducers (output) are only a few centimeters away.

Being able to control feedback not only solves an issue but also opens up the possibility of creating the illusion of timbral transformation by mechanically mixing acoustic and synthetic audio, causing the instrument body to vibrate with both the string vibrations and synthetic audio signals.

2.4 Hybrid sound

A technical goal of our project is to set up a system that can analyse audio and create a synthesis based on the analysis. Then, using an onboard audio system with output directly integrated into the acoustic body of the instrument, create a hybrid sound. Some of these approaches to hyperinstrument design research have demonstrated that a cohesive integration of acoustic and synthesised sound can be achieved with varying levels of success.

Paul Clift designed a process that aims to leverage the virtual capabilities of actuated instruments while harnessing the acoustic qualities of instruments. This process, the Acoustic-Aggregate-Synthesis (AAS), consists of four steps: 1) An analysis of the spectrum of a given timbre obtains data on the power of 64 prominent sinusoidal components. Then, this data is stored for later use. 2) A similar analysis is done in real-time using an acoustic instrument; 3) Then, the data is compared to find the intensity difference of each timbre's matching sinusoidal components. 4) Finally, synthesis introduces more gain on specific components to create the illusion of sound morphosis (Clift, 2012).

When applied to instruments with resonating bodies, actuation poses multiple challenges, and various solutions are necessary. Simon Benacchio did thorough research in active control applied to resonating bodies, specifically to string instruments, using mathematical models later demonstrated with experimental tests (Benacchio *et al.*, 2012, 2016). Seminal experimentation was done by Benacchio's IMAREV team, particularly on the guitar and violoncello. However, these experiments aimed to experiment with the acoustic effects of actuation but without particular musical outcomes (Benacchio, 2014). One of the most important outcomes of this research was the discovery that, while a mathematical model for active control may exist, it becomes very difficult to have a standardised approach due to the many possible variations. Additionally, Benacchio's study demonstrated that the placement of actuators not only depends on the sounding goals but also varies from instrument to instrument and from pitch to pitch as certain structures favour specific frequencies.

3. The development of the Kuturani

From the project's outset, we considered the possibility of building four different hyperinstruments, one for each of the wind, brass, string, and percussion instrumental families. However, considering the potential impact on a broader cross-section of our community, we focused on a flexible concept rather than a design specifically tailored for each instrument within a family. This meant that, although we were working with a device for string instruments, the design we developed could be modified to suit many instruments as long as it featured these characteristics:

- Cheap with alternative lower-cost configurations — some components might be swapped, and software is being developed considering this possibility.
- Monitors performance data through a base set of sensors.
- Extra modules can be attached through the use of expansion ports.
- Features audio input for analysis and, when possible, audio processing.
- Features audio output using the instrument's resonant body.
- It can be installed without modifying the host instrument.
- Communicates with other devices.

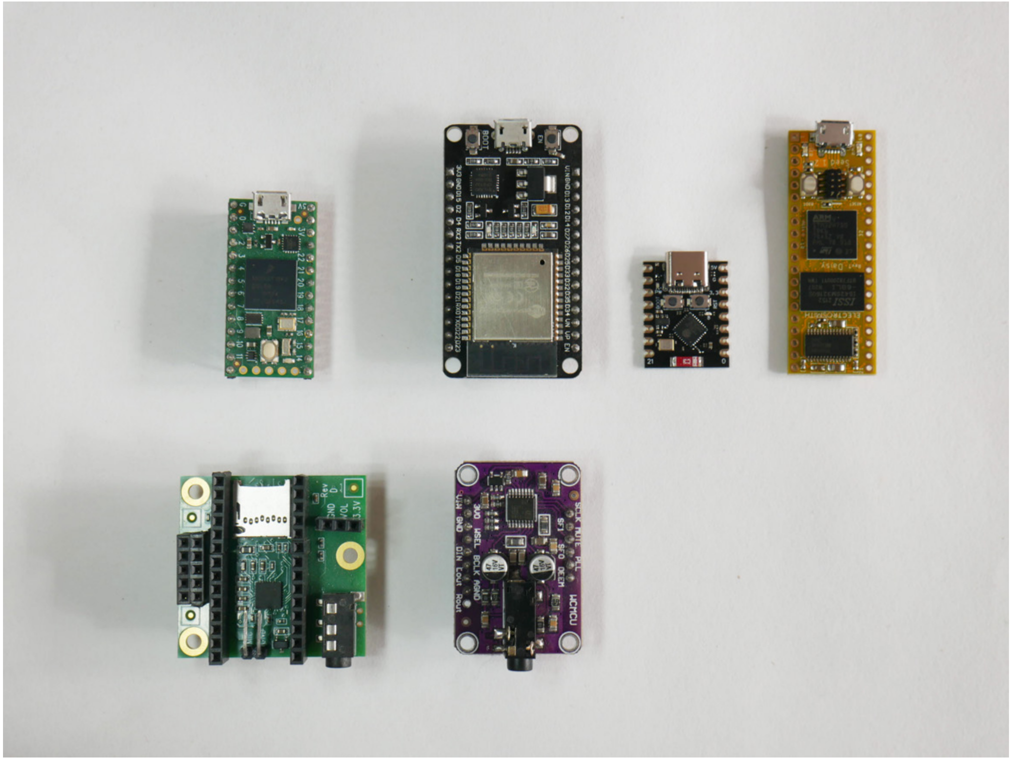
The device's basic setup includes: the microcontroller, audio controller (if needed), microphone/pickup, a transducer (to be mounted directly on the instrument), and a set of basic sensors to control the most essential functions, as well as expansion ports to connect external sensors to expand data-capturing possibilities.

3.1 Low-cost construction and alternative lower-cost configurations

We considered the possible sonic output and how to achieve it. Keeping in mind the idea of eventually involving community members in the project or learning from it, we considered the musical needs of the community. With this project, we aim to reach musicians, composers, media, and digital artists who are not experts in the use of electronics in music, as well as more experienced users interested in learning, exploring, and developing electronic music devices. For this reason, we started from a standard "comfort zone" that would make the project more accessible, focusing on the development of a system that could produce some of the most common sound effects found in commercial software and audio effect devices (units, processor, pedals) such as reverb, delays, distortion, or flange, planning that we, as well as users, could build up from there.

We selected four low-cost microcontrollers as the core configurations that were formulated to offer different price options for the Kuturani. Although they differ significantly in hardware and software, they all adhere to the same paradigm and provide the same fundamental features. These setups feature Teensy, Daisy Seed, and ESP32 microcontrollers. These boards offer the possibility of capturing performance data and audio processing. The ESP32 is, out of the three, the most limited in terms of DSP capabilities. However, its communication capabilities facilitate interfacing with third-party devices to process audio. There are two versions of the Kuturani, both utilizing the ESP32 chip; one uses the ESP32 WROOM 32 module, which can handle some DSP processes. The second version utilizes the Mini ESP32 C3 module, which is used to send data to cell phones for audio processing.

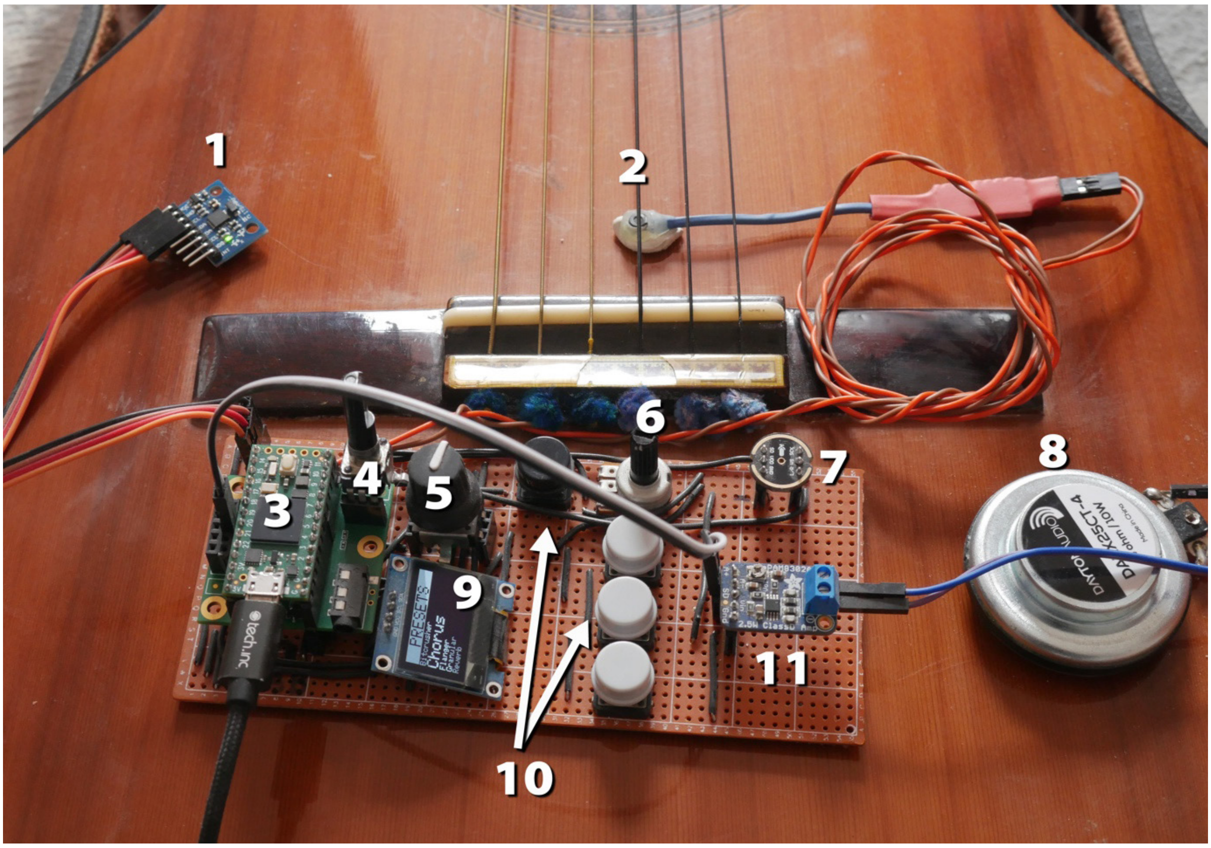
Figure 1: Microcontrollers used in the different versions of the Kuturani and their respective audio decoders



Source: Cristohper Ramos Flores
Image description: From left to right: Teensy 4.0 and Adapter Audio Board; ESP32-WROOM32 and UDA1334A, ESP32-C32 (no audio), and Daisy Seed (integrated audio decoder).

Four custom PCBs, dedicated to the use of each of the microcontrollers mentioned above, were created featuring a basic setup with the following components: A gyroscope/accelerometer helps monitor the overall motion of the instrument; two potentiometers are used to either control input and output gain or control a parameter in real-time; an LED display; a rotary encoder and buttons to activate functions, edit presets and setup communication with third-party software; and, audio input and output ports (one version of the Kuturani uses a cellphone for this) interfaced with a D-class amplifier paired with a transducer. We also included expansion-programmable ports for two analogue sensors, two digital sensors, and two I²C-based sensors to be added to the system. The PCB designs can be found at https://www.kuturani.com.mx/recursos.

Figure 2: Prototype of Kuturani – Teensy version.



Source: Cristohper Ramos Flores
Image description: A prototype of the Kuturani featuring: 1) Gyroscope/accelerometer, 2) miniature electret microphone, 3) Teensy 4.0 mounted on Audio Adaptor Board, 4) potentiometer to control output gain, 5) rotary encoder, 6) potentiometer to control input gain, 7) INMP441 microphone, 8) transducer, 9) OLED display, 10) push buttons, and 11) class D audio amplifier.

3.1.1 Kuturani - Teensy

One of the Kuturani versions uses a Teensy 4.0 board, as it is not only powerful but also programmable in the Arduino language. It is advantageous to learn to program in the Arduino IDE due to its closeness to C++, which can open the door to future endeavours in programming. On the other hand, a commercial plug-and-play Audio Adaptor Board is available,[3] along with an Audio Library

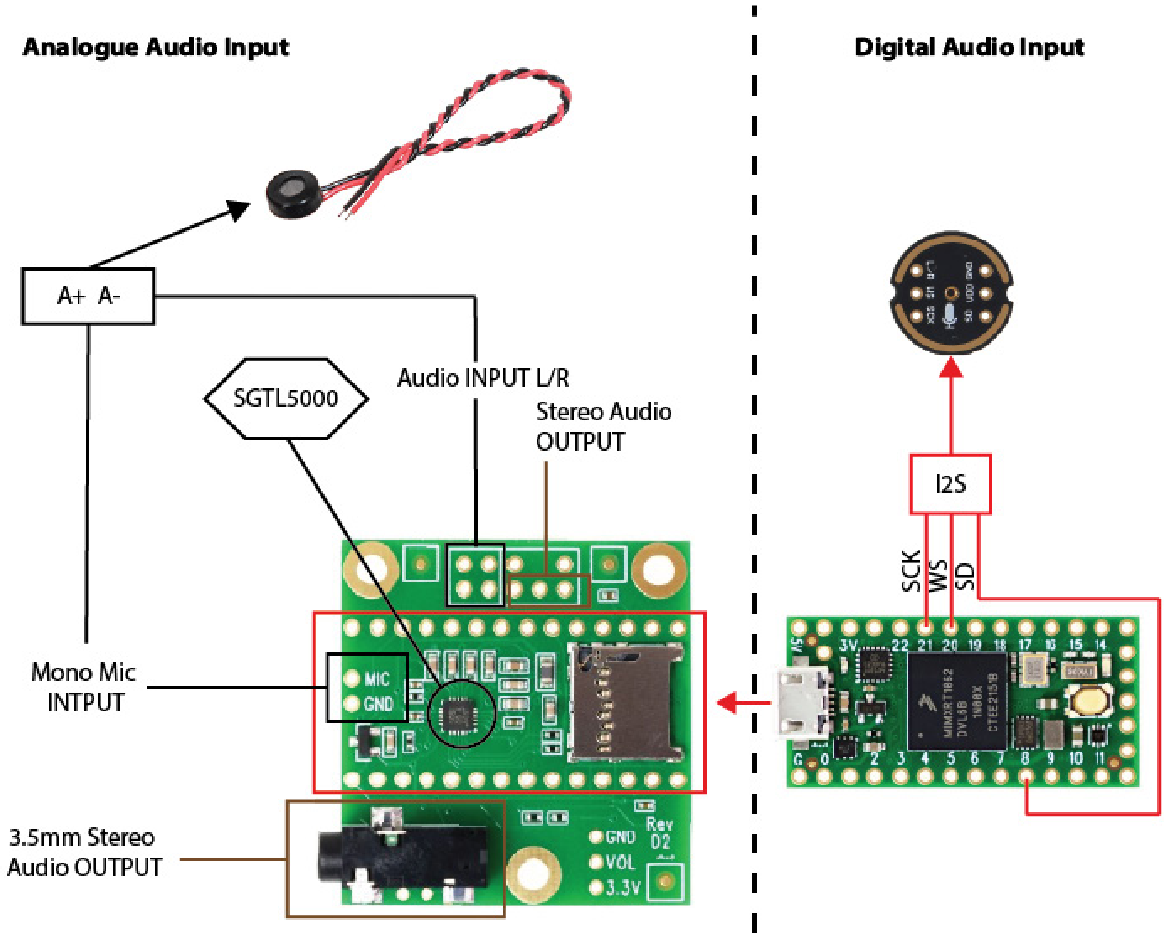
3 https://www.pjrc.com/store/teensy3_audio.html Accessed on: 3 Mar. 2025

and Audio System Design Tool that includes audio effects and the possibility of creating customisable synthesizers.[4]

To capture audio, we tried a few microphones compatible with the Teensy or the Teensy Audio Adaptor Board. Better-quality microphones were not considered due to the constraints we had set to keep the cost as low as possible. We decided to implement the possibility of using two of these microphones in the software and custom PCB. The two microphones we chose are the INMP441 and a miniature condenser microphone. The INMP441 is I^2S compatible, while the electret mic can utilize the SGTL5000 chip in the Teensy Audio Board, also through I^2S. Ports to connect them were included in the custom PCB. The decision of which one to use depends on the instrument, as the form factor of each microphone makes one or the other more convenient in different situations. For instance, the INMP441 — of which a PCB module version is preferred due to its ease of use — does not fit well below the guitar strings, between the bridge and the soundhole, which is what we found to be the best location for capturing audio. On the other hand, it cannot be placed inside the soundhole, as it becomes too challenging to control feedback once a transducer is mounted and in operation on the instrument. In that case, the miniature electret is a better choice.

4 https://www.pjrc.com/teensy/gui/index.html Accessed on: 3 Mar. 2025

Figure 3: Available setups for analogue and digital audio with the Teensy 4.0 setup.



Source: Cristohper Ramos Flores
Image description: LEFT: Teensy Audio Board and audio connections, including analogue audio input, made possible through the SGTL5000 chip. RIGHT: Teensy 4.0 and I²S ports for digital audio input.

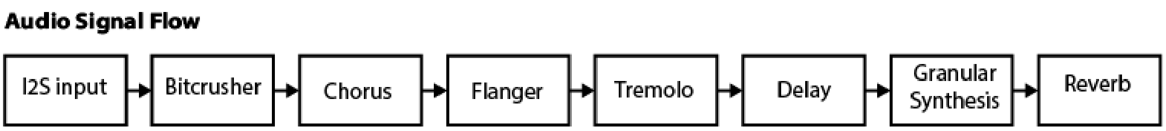
We also considered piezoelectric microphones. However, we identified some potential issues, such as difficulty calibrating the setup to minimize feedback, as the microphone and transducer were to be mounted on the top plate of the instrument. It is possible to avoid feedback, but considering that we are trying to share this project with non-experts, we thought that the potential frustration of troubleshooting this issue might be a reason why users would not want to continue working with our device. Nevertheless, piezoelectric microphones can be used in place of the miniature electret mic in applications where feedback is not expected to occur.

A PAM8302A 2.5W Class D amplifier, in combination with the Teensy Audio Adaptor Board, which features the SGTL5000 chip, delivers enough power to the transducer mounted on the instrument's body. The transducer paired with this system is a 10W, 4Ω impedance Dayton Audio DAEX25CT-4.

To interact with the program, we have included an SD1306 OLED display and a rotary encoder to scroll through the different audio effects and their parameters. This, together with a set of buttons, allows for easy personalisation and running of presets as needed.

The audio library, developed for the Teensy Audio Adaptor, offers numerous DSP possibilities, including ready-to-use audio effects that utilize circular buffers and FIFO logic, which are ideal for real-time audio applications. Using this library, we coded a program that allows for a chain of sound effects in a fashion similar to a guitar pedal rack signal chain. It includes the following audio effects: bitcrusher, chorus, flanger, tremolo, delay, granular synthesis, and reverb. Each effect can be activated separately, and its parameters can be saved as presets. Additionally, twenty-five more presets can be saved to allow for the activation and combination of these effects. Demonstration videos of the system are available at www.kuturani.com.mx/videos.

Figure 4: Audio signal flow.



Source: Cristohper Ramos Flores
Image description: Audio signal flow, including all available effects. Any of them can be bypassed.

The effects and presets can be activated as a permanent audio feature, similar to a guitar pedal, or in response to the sensors that can trigger presets or control various parameters. For instance, by mapping the gyroscope's readings to a trigger, granular synthesis can be activated when the instrument is tilted over 90º on the

X-axis and deactivated when the instrument returns to 89º or less. Another example would be to use the pressure (force-resistive) sensor, attached to one of the expansion ports, to adjust the reverb's decay.

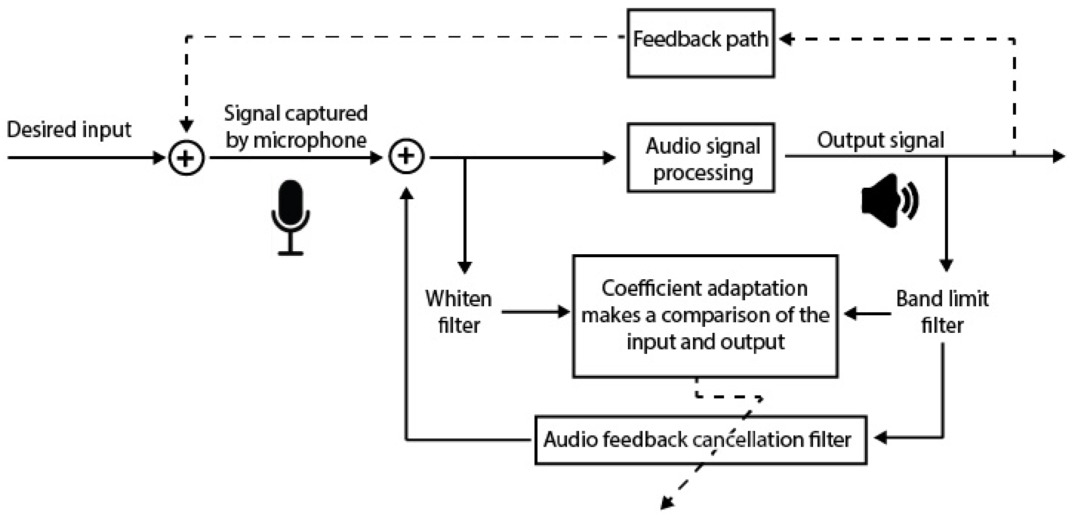
The Teensy Audio Library includes a robust set of analysis, synths, and filter objects that are easy to implement. Programming synths for the Kuturani is relatively easy and will be implemented in the program in future updates. Future work will also focus on using the libraries' objects to attempt timbral morphosis similar to Clift's Acoustic Aggregate Synthesis (see Section 2.4).

One of the most critical aspects of approximating timbral morphosis, and currently more important, is being able to use the effects already coded into the Kuturani to output audio directly through the instrument's body using the mounted transducer. The biggest issue we have encountered is controlling unwanted feedback. To address this issue in the Teensy version, we implemented a Least Mean Square (LMS) algorithm based on the Adaptive Feedback Cancellation algorithm developed at Boys Town National Research Hospital. It is available via their CHAPRO library of hearing aid algorithms.[5] Chip Audette developed the version of the algorithm used in our code for the Tympan Library,[6] necessary for his Tympan hearing aid device.[7]

The typical Adaptive Feedback Cancellation algorithm considers the following: The desired input, the signal captured by the microphone, the output signal, and the feedback path feeding the system in a loop. The algorithm seeks to estimate and subtract the feedback signal from the microphone signal. This is achieved by placing a finite impulse response (FIR) filter in parallel with the audio processing. The filter coefficients are continuously updated to emulate the impulse response of the feedback path.

5 https://github.com/BoysTownOrg/chapro Accessed on: 7 Jun. 2024
6 https://github.com/Tympan Accessed on: 15 Jan. 2024
7 https://shop.tympan.org Accessed on: 3 Jan. 2025

Figure 5: Framework for adaptive feedback cancellation.



Source: Cristohper Ramos Flores
Image description: The diagram shows the signal flow inside the adaptive feedback algorithm. This version is a variant of the algorithm known as normalized LMS (NLMS), which helps mitigate some instability problems by reducing the sensitivity of the coefficients to the input signal level.

The placement of the microphone and transducer is a crucial factor in feedback control and audio output quality. Empirical research was performed to learn more about the effects of the placement location of the transducer. The study consisted of the following:

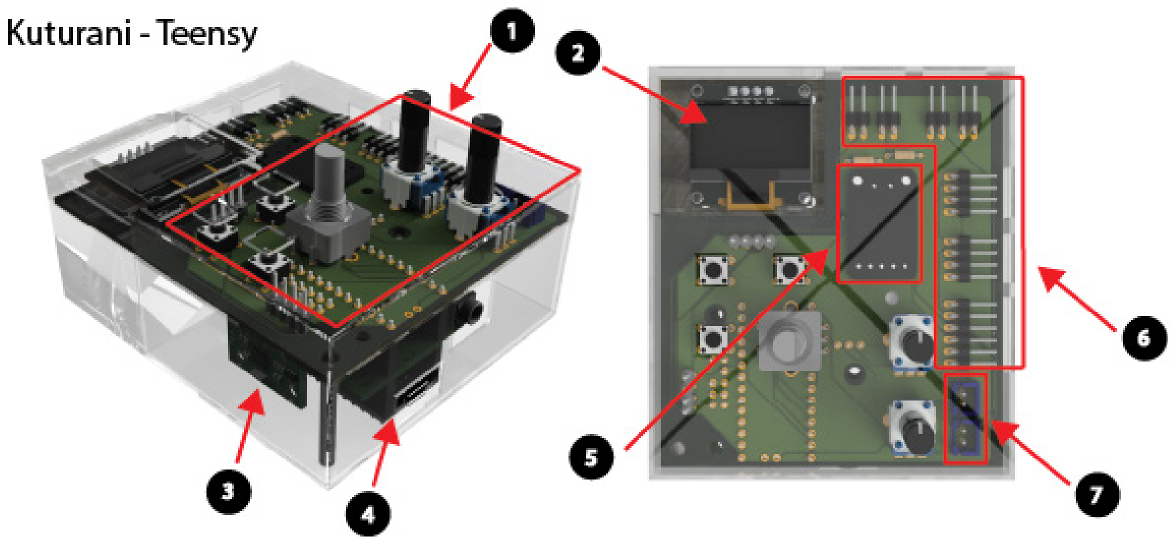
- We recorded audio from three instruments (guitar, violoncello, and violin) and used the recorded audio to output a signal through transducers mounted on the instruments. Then, we analysed and compared the original audio with the audio coming out of the transducer — which was placed in different locations on the top plate of the instruments — to find the location that produced the best sound

• The second stage involved analyzing the spectra to determine the frequency response curves (FRC) of the instruments, aiming to better understand the prominent components of the spectra that were amplified by the instrument's body.

• We obtained and observed Chladni patterns on the top plates of the instruments.

• Finally, the information was compared, and an optimal location for the transducer was revealed. This location not only enables the best audio quality by utilizing the transducer on the body of the instrument, but also establishes a reference for the vibration modes of the top plate, ensuring stability throughout the instrument's range. This stability also contributes to the stability of feedback cancellation.

Figure 6: Kuturani – Teensy and its components

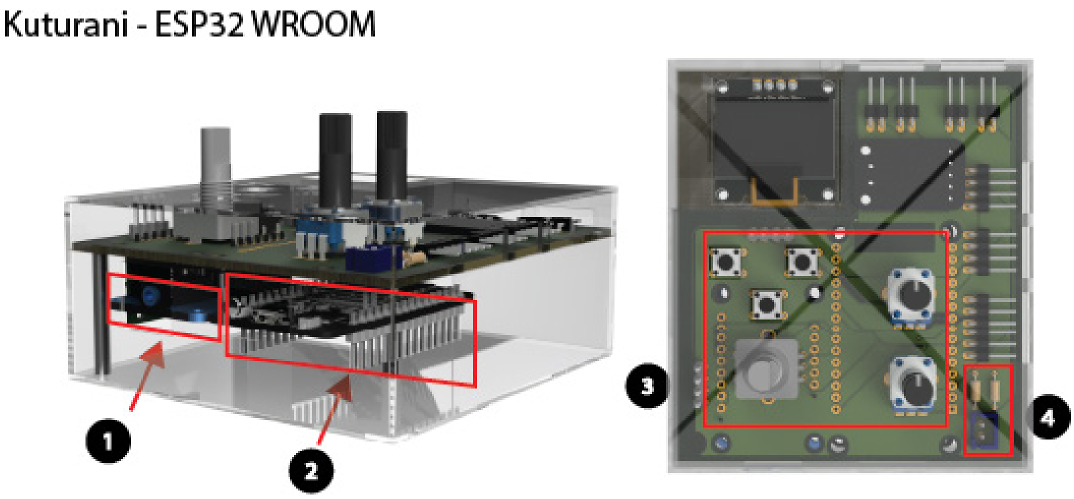


Source: Cristohper Ramos Flores
Image description: Kuturani – Teensy and costume PCB: 1) basic sensors, 2) OLED display, 3) gyroscope, 4) Teensy 4.0 mounted under the Adapter Audio Board, 5) PAM8302A audio amp, 6) extension ports, and 7) audio input and output ports.

3.1.2 Kuturani – ESP32 WROOM 32

A second version of the Kuturani features the ESP32, which has a limited audio library and is currently unable to run the Teensy Audio Library. However, this board's capabilities hold promise for DSP. Additionally, multiple audio libraries are being developed for this microcontroller. In particular, the Arduino Audio Tools by Phil Schatzmann,[8] compatible with ESP32, already offers a large set of possibilities for DSP.

Figure 7: Kuturani – ESP32 WROOM



Source: Cristohper Ramos Flores
Image description: Kuturani – ESP32 WROOM features a similar design as the Teensy version with the following differences: 1) UDA1334A audio decoder, 2) ESP32 WROOM DevKit1 microcontroller, 3) different layout and one missing button, and 4) no analogue audio input.

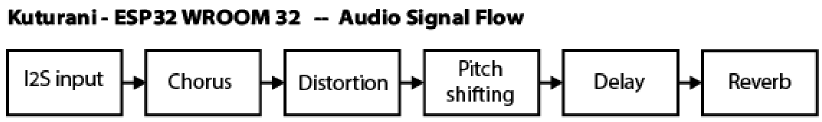
This Kuturani version requires a dedicated audio board. We are using the INMP441 microphone as the input and the UDA1334A I²S Stereo DAC breakout, paired with the PAM8302A amplifier, to output the signal.

In this version, the system works similarly to the Teensy version. However, we have implemented only a few audio effects, including delay, distortion, pitch shifting, chorus, and reverb. The

8 https://github.com/pschatzmann/arduino-audio-tools

option to combine the sound effects remains on the list for future developments. Editing and saving presets is also possible, and activating them via sensor data triggers works as in the Teensy version.

Figure 8: Current audio signal flow.



Source: Cristohper Ramos Flores
Image description: Signal flow used with the ESP32 WROOM 32 microcontroller.

Managing real-time audio processing is more complex with this board, as factors such as latency and unwanted feedback (the NLMS still needs to be implemented) can hinder achieving the desired results. Nevertheless, latency helps prevent feedback. In future versions, a hardware-based feedback cancellation system will be implemented.

This board, utilising Schatzmann's library, is capable of FFT analysis, which is a promising lead towards achieving timbral morphosis in the near future, as multiple synthesis and signal processing capabilities are already available. This opens up the possibility of designing sounds paired with acoustic sounds, following the pitch changes in real time. We have already conducted a few tests that demonstrate this is possible, although the system remains very unstable and is not yet usable in a real musical context.

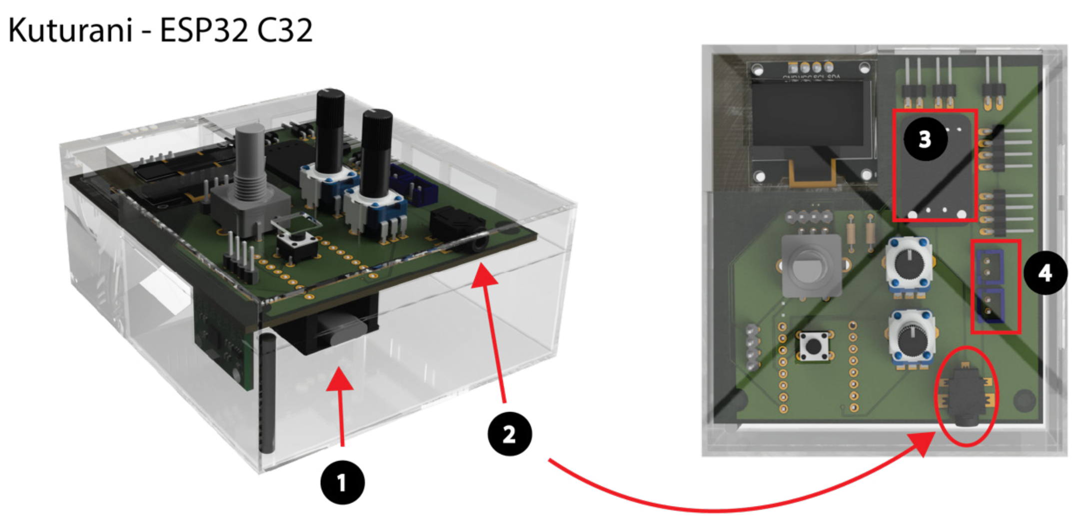
Overall, the Kuturani-ESP32 has the potential to become one of the best versions of the Kuturani, thanks to the board's power and its competitive price. On the other hand, this board features

WiFi, Bluetooth, BLE, and ESP-NOW. These communication abilities set the ESP32 apart as it provides the option to wirelessly interface with other devices to either process audio, trigger audio events, or interface with mechatronic devices.

3.1.3 Kuturani – ESP32-C3

The ESP32-C3, also known as SuperMini, is the cheapest version of the ESP32 boards. It does not feature two cores but has similar memory specifications and the same connectivity characteristics. The device only collects performance data via sensors, but no audio inputs or outputs are included on the board. Some components are absent in this version of the Kuturani because a cellphone is used to capture and process audio.

Figure 9: Kuturani - ESP32 C32



Source: Cristohper Ramos Flores
Image description: This Kuturani version features: 1) the smallest ESP32, 2) a 3.5mm audio jack to interface audio with a phone, 3) PAM8302A amp, and 4) audio input and output ports for microphone and transducer.

The only components included for audio output are a PAM8302A amplifier and audio input and output ports. An analogue microphone can be connected to the input port. The signal is sent to a cellphone using the 4-pin 3.2mm audio jack. Once the audio has been processed, it comes back via the same audio cable. The signal is routed through the amplifier and then output using the output port to a transducer. The amplifier takes power from the ESP-32.

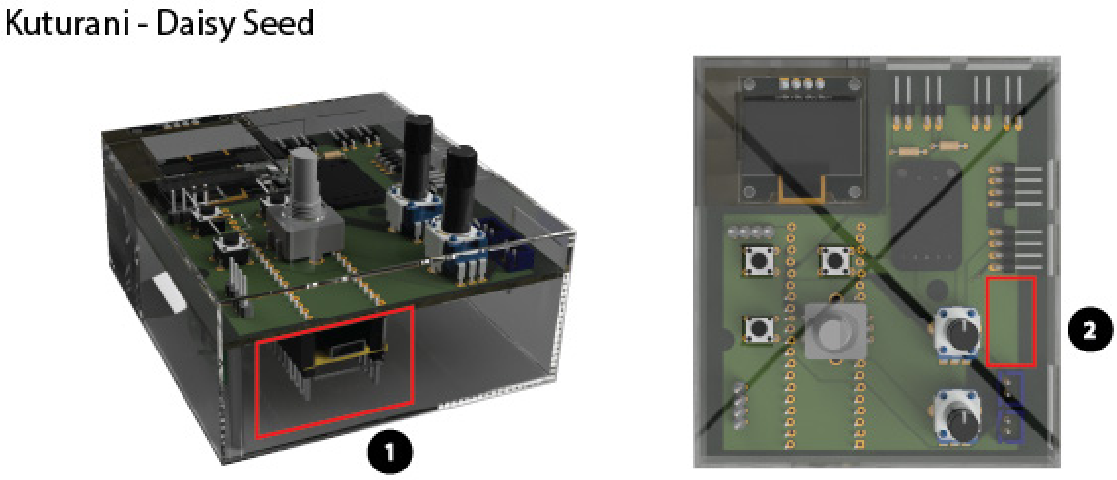
It features input and output audio gain controls, as well as a rotary encoder and screen for setting up OSC connections and visualizing other data. A basic interface is available for Android and iOS. The ESP32-C3 cannot handle DSP, so we developed a system that uses the OSC protocol to stream the data collected via sensors to a cellphone. We are using MobMuPlat,[9] a software developed by Daniel Iglesia, to run Pure Data patches. MobMuPlat receives data that controls the parameters of the objects embedded in the PD patches and also leverages the device's capabilities to take audio, process, and output audio signals. In this case, due to the nature of the setup, the Kuturani software is straightforward, as it only captures and sends data. The audio processes depend entirely on the PD patches. Some generic patches with sound effects have been developed; however, a new patch is expected to be created for each composition. A version of the NLMS algorithm, developed by Marcus Noisternig and Thomas Musil at the Institute of Electronic Music and Acoustics of the University of Music and Performing Arts Graz,[10] has been tested on a Pd patch running in MobMuPlat. The results indicate that it is possible to utilize the library, but further development is necessary.

3.1.4 Kuturani – Daisy Seed

The last iteration of the Kuturani is based on a Daisy Seed 64MB board. This board features high-quality audio inputs and outputs, which help set up a system very similar to the one implemented with the Teensy version. The system is almost identical to the Kuturani - Teensy. Nevertheless, the software for this version was developed on PD, as this board includes a utility called pd2dsy, which translates Vanilla Pure Data to firmware that can be run on the board. The same NLSM algorithm used on the ESP32-C32 PD patches was used on this version.

9 https://www.danieliglesia.com/mobmuplat/ Accessed on 3 Mar. 2025
10 https://old.iem.at/Members/noisternig/science/iem_adaptfilt/ Accessed on 20 Feb. 2025.

Figure 10: Kuturani – Daisy Seed



Source: Cristohper Ramos Flores
Image description: The Kuturani – Daisy Seed is almost identical to the Teensy version with the following changes: 1) uses the Daisy Seed microcontroller — which includes audio input and output ports — and 2) does not feature a digital audio input.

The Daisy Seed has been designed for audio, and it features characteristics that make it perfect for our project, including a lower price than the Teensy (considering the additional cost of the Audio Adaptor Board). Additionally, this board can be programmed using Arduino language, C++, Max/Gen~ and PD. However, we have not achieved the same sound quality, possibly due to our lack of experience in programming code for this board.

We look forward to exploring more of what this board offers, as the inclusion of different programming languages may help us achieve our goal of impacting a larger number of members within our community.

3.2 Data monitoring and action mapping

The Kuturani, despite its different variations, aims to hybridise an acoustic instrument and an electronic controller. As the acoustic instrument responds to performance by producing sound, the electronic controller must also exhibit specific relationships between performative actions and sonic outcomes. We have programmed a few of these possible relationships. Still, we hope that users develop new mapping strategies and design new sonic results with a logic that somehow expands the correspondence between the performative action and the acoustic sound. In this section, we present a few examples of the framework we have developed to facilitate this. We also discuss some features that, while available in the Kuturani, do not define our instrument.

3.2.1 Sensors

We have chosen to include just a few sensors in our basic setup, described in Section 3.1. In the current version of the software, most of these sensors have a defined main function and alternative functions that can be employed according to the user's needs, as described in Table 1.

Every parameter of the preprogrammed sound effects can be edited directly on the device using the OLED display (except the ESP32-C3 version, for which a phone app needs to be developed to enable this feature), as well as using the rotary encoder, edit button, and rotary button. In the edit menu of each effect, there is a 'Trigger' function, which allows the user to define a value — from the sensor incoming data — to activate or deactivate a sound effect. For instance, the reverb could be activated using a simple button press or using the microphone gain level; when the gain levels go over a defined threshold, the reverb is activated, but once the level goes under the threshold, the gain of the reverb goes down on a timer, and eventually the effect is deactivated.

In addition to the previously listed sensors, we have included expansion ports for both analogue and digital sensors. These ports are deactivated by default but can be activated by selecting the Sensors option and then choosing Dig1, Dig2, An1, or An2 options. This shows a new screen that shows the readings obtained by the sensor (if connected). The scales available for these sensors are 0-1 (digital) and 0-1023 (analog). Once these sensors are activated, their values can be used like those of the installed basic sensors. A third option is to use the I^{2}C-based port; however, the user will need to code how these readings are utilized due to the variability of sensors that use this protocol. Future versions of the software will include pre-coded functionalities for multiple I^{2}C-based sensors.

Table 1. Basic sensors and their functions

SENSOR	MAIN FUNCTION	ALTERNATIVE FUNCTION	NOTES
Microphone/pickup	Capture audio.	Signal level can be used as a trigger.	This sensor is not available in the ESP32-C3, except via the paired phone.
Gyroscope/ Accelerometer	Detect and measure the angular motion of the instrument. The values obtained are used to control the parameters of the audio effects.	It can work as a trigger by specifying an axis (X, Y, or Z) value.	'Home' values of the X, Y, and Z axes of the sensor have to be calibrated on start-up according to the mounting location on the instrument.
3 Buttons + Rotary encoder's button	1-Edit 2-Trigger 1 3-Trigger 2 Rotary button-activates/deactivates selected sound effect.	All programmable	In ESP32-C3, these buttons are only triggers.
Rotary encoder	Navigate the main menu.	In the edit menu, navigate the menu and scroll the presets' values	
Potentiometers	1-Input gain 2-Output gain	---	These potentiometers can be reprogrammed via IDE.

Source: Cristohper Ramos Flores
Image description: Basic sensor setup and its functions

3.2.2 Action to sound

Multiple issues arise when mapping a specific interaction with a controller to a sonic result, such as performativity, instrumentality, or embodiment. Mapping strategies can help mitigate some of these issues, but several key aspects must be considered.

A clunky design and poor choice of sensors can hinder aspects of performativity. Likewise, the actions to be mapped should not be too different from the usual performance. For instance, if we decided to map inclination over the X-axis of the instrument to control a bouncing delay effect, this mapping might be acceptable on a guitar but not on a violoncello. There is a difference in the playing position of the left-hand between the two instruments: on the guitar, while the instrument tilts, the entire left arm moves together with the instrument, allowing for a comfortable position in which the performer can still play the instrument; on the violoncello, only the forearm would move with the instrument, causing the wrist to bend and hindering mobility of the hand and fingers over the fingerboard and strings, making performance more difficult.

In the same example, it would also be questionable to map a bouncing delay effect with the inclination of an instrument, but it would depend on how it is done. For instance, if the sound that had just been played on the instrument is to be repeated a few times as it fades away, would these repetitions depend on the instrument's angle of inclination? Or would it be a better strategy to tilt the instrument and shake it simultaneously, creating a closer relationship between action and sound? John Croft believes that the designed interactions of a controller should meet a few conditions for instrumentality; for instance, the sonic response generated by the computer should be proportionate to the performer's action and share energetic and morphological characteristics (Croft, 2007).

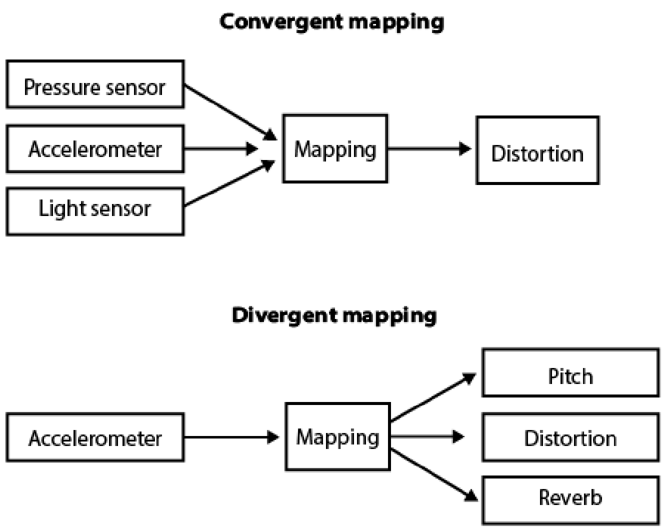
Aspects of instrumentality are essential for any hyperinstrument, as this helps create a relationship between the performer and the instrument, allowing for the opportunity to 'learn' and improve how to make music with the devices, which in turn affords the possibility of expression.

Regarding embodiment, there are many perspectives through which this issue can be understood and addressed. For instance, the relationship between the performer's body and the instrument, gestures, perception, entrainment, and more. While these are fascinating topics for discussion, they fall outside the scope of this paper. However, embodiment is still essential in mapping the actions and sonic result, especially considering that the sound emanates directly from the instrument's body. If the Kuturani is mounted on a violin, it would cause some issues if the synthesis were to produce a very low pitch; it would be even more of a problem if this sound were triggered by simply pressing a button. It would be more logical if a pitch track were set to identify pitches below the regular range of the instrument to trigger such sound. In this way, the performer could produce subharmonics, which would be detected by the system, triggering an even lower pitch. This way, the mapping between the action and sonic result follows the logic of how the body of the instrument works.

The standard mapping strategy is based on one action resulting in one sonic change; for instance, rotating a knob changes the pitch. This relationship is usually not found in mechanical acoustic systems. However, Andy Hunt and Ross Kirk identify two different parameter mapping strategies that follow the logic of acoustic instruments. To change the pitch of a saxophone, for instance, the performer not only changes the fingering but also requires a specific change in air pressure to tune the instrument correctly. In other words, multiple actions control one parameter, a strategy known as *convergent mapping.*

On the other hand, sometimes, one action controls various parameters. For example, adjusting the air pressure on the saxophone alters the loudness, but this action can also affect the timbre and pitch. This is known as *divergent mapping (Hunt and Kirk, 2000)*. These strategies have also been explored using the Kuturani (see Figure 11).

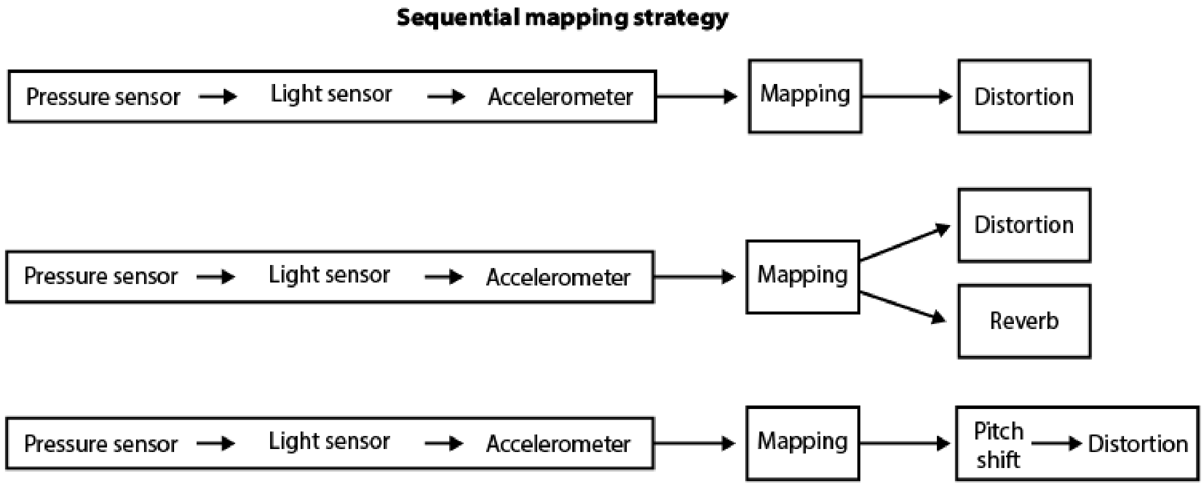
Figure 11: Example of mapping strategies tested with the Kuturani.



Source: Cristohper Ramos Flores
Image description: This image presents two examples of mapping strategies using various sensors to obtain specific sonic results with the Kuturani.

Besides *convergent* and *divergent* mapping strategies, a sequential mapping strategy can be beneficial for developing musical gestures or shaping the sound. The Kuturani, with the previously described basic sensor setup and the software's current state of development, offers numerous possibilities for shaping sound; however, these must be carefully programmed and learned. Currently, a small set of sound effects is available. Nonetheless, their parameters can be controlled continuously, which offers the possibility to chain a sequence of effects with evolving characteristics. These can be controlled with basic sensors, and to achieve a specific sound, it is necessary to learn a sequence of actions: for instance, tilt the instrument 45 degrees to activate distortion, then tap on the instrument to trigger granular synthesis, and finally press button 2. All of these actions, performed in the described order, trigger noise.

Figure 12: Examples of a sequential mapping strategy



Source: Cristohper Ramos Flores
Image description: Three examples of sequential mapping strategies that have a different sonic result, showing that a sequential mapping strategy can map multiple events to one sounding result. It can also map the events to numerous consecutive or concurrent audio results.

Complex interactions with the instrument using the Kuturani are possible through the use of the expansion ports, which afford the possibility of using more adequate sensors for the performer's instruments, or for specific compositions or performative practices. As stated before, the Kuturani is not a device specific to one instrument but rather a system that allows for exploration and personalisation of the interaction with an instrument the performer chooses to play. Regarding mapping strategies that utilize other sensors through the expansion ports, we leave the possibilities open but encourage users to consider the aspects of performativity, instrumentality, and embodiment.

4. Conclusions and future work

The development of the Kuturani has afforded multiple avenues for shared exploration. It has allowed us to investigate different approaches to developing a conceptual device and presented numerous challenges with contrasting paths. While many of the challenges still need to be addressed, the current state of the four versions of the device demonstrates that designing a conceptual instrument, rather than a specific and fixed design, is a promising direction in musical interface design. This approach mirrors the design of acoustic instruments, in which an instrumental archetype, such as a guitar, does not need to be redesigned entirely each time a luthier builds one. Similarly, the design of a concept, such as the Kuturani, can be the basis for future variations and improvements made by multiple users. Maintaining a low cost, combined with the Creative Commons licensing strategy, supplements and strengthens this possibility.

We see the Kuturani as a strong first step towards establishing a development path in which, while components may vary, the core way in which they work as a unit, as well as the supporting onboard software, remains consistent and becomes more robust with each iteration and personalisation made by the users. The Kuturani provides a solid stepping stone upon which beginner interface developers can learn, practice, and improve their skills. At the same time, the most advanced users can find in it a framework for rapid prototyping. Using our developments, users can quickly explore different modes of interaction between the performers and their instruments, which can be helpful when planning to develop a new interface, analysing performance, or for pedagogical use.

At the time of the development of the four versions listed here, the price of building the devices ranged between approximately $30 and $70 US dollars, as shown in Table 2 and Table 3. The prices listed are based on the cost of the components from the different vendors from whom we purchased them for the development of the iterations. The vendors included international companies such as DigiKey, AliExpress, and Amazon, as well as local electronics stores. The prices include shipping costs to central Mexico. Selecting other brands for some of the components could also help reduce the cost; for instance, by choosing to work with a generic, unbranded transducer of similar characteristics at an approximate price of $7 US dollars from AliExpress. Considering these prices, we believe our development offers a cost-effective option that helps to democratise access to the field of augmented instrument development.

Table 2. List and price of components in Kuturani based on Teensy 4.0

Iteration 1: Based on Teensy 4.0, using the onboard audio processing capabilities, outputting through the DaytonAudio DAEX25CT-4. It features 4 digital sensors (push buttons), 2 analogue ones (potentiometers), and a rotary encoder to access and setup configuration through a mini display.	
Teensy 4.0	$24.00
Teensy Audio Adaptor Board	$15.60
PAM8302A Class D Amp	$3.33
DaytonAudio DAEX25CT-4 Transducer	$13.00
INMP441 MEMS Microphone	$1.70
GY-521 MPU-6050 Gyroscope/Accelerometer	$1.80
SSD1306 OLED Display	$1.56
Rotary encoder	$1.20
4 X 6mm Push buttons	$0.50
2 X 10KOhm Potentiometers	$2.20
Miscellaneous (cables, PCB or Veroboard, pin headers, etc.)	~ $5.00
TOTAL	**$69.89**

Source: Cristohper Ramos Flores
Image description: List and prices of components

Table 3. List and price of components in Kuturani based on ESP32-C3

Iteration 4: Based on ESP32 ESP32–C3r mini), processing audio using PureData/MobMuPlat on a cell-phone, outputting audio through the DaytonAudio DAEX25CT-4. It features 1 push button, 2 analogue sensors (potentiometers), and a rotary encoder to access and setup configuration through a mini display.	
ESP32 - C32 (Super Mini)	$3.20
PAM8302A Class D Amp	$3.33
DaytonAudio DAEX25CT-4 Transducer	$13.00
INMP441 MEMS Microphone	$1.70
GY-521 MPU-6050 Gyroscope/Accelerometer	$1.80
SSD1306 OLED Display	$1.56
Rotary encoder	$1.20
1 X 6mm Push buttons	$0.50
2 X 10KOhm Potentiometers	$2.20
Miscellaneous (cables, PCB or Veroboard, pin headers, etc.)	~ $5.00
TOTAL	**$33.49**

Source: Cristohper Ramos Flores
Image description: List and prices of components

The Kuturani has been tested on acoustic guitar, violin, violoncello, and ukulele, yielding similar results, demonstrating that it is possible to develop a single device that can be used on various string instruments. However, while the same design can be used on all of these instruments, some caveats need to be considered, i.e., the size of the transducer may make installation difficult on violins and ukuleles, for which a more miniature transducer might offer better results. Additionally, different transducer sizes would have an impact on features such as power efficiency, loudness, or frequency response. Similarly, external sensors connected to the expansion ports may require different cable lengths to be placed in similar locations as other instruments, i.e., a force-resistive sensor located on the first fret of the guitar versus the first fret of the ukulele.

On the other hand, our experience developing the different versions of the Kuturani also demonstrates that it is impossible to offer the same characteristics on every version of the device, as hardware and processing power pose apparent limitations. Nevertheless, we view these limitations as inherent features of each iteration rather than problems, and believe that they can also be overcome through the use of third-party devices, such as computers and commercial software.

Future developments include simplifying the current software code so that it can be understood and manipulated easily. We also aim to include a series of code lines, as classes, to receive data from different sensors that could be used with the expansion ports. Android and iOS apps will also be developed to control the Kuturani – ESP32-C32 version, providing the same basic effects available in the other device versions. In terms of hardware, a power management system needs to be developed, as the device currently runs on power banks connected to the microcontroller's USB ports. Additionally, the miniaturization of components and PCBs will be implemented to reduce costs and enable more specialized Kuturani versions. Finally, a hardware-based audio feedback control system needs to be developed and integrated, along with a system to introduce and control feedback when desired as a sound feature.

One of the most critical aspects of the project's future is the development of pedagogical materials that facilitate community involvement, as it is a key goal of our venture. We have already prepared some instructional videos and written guides, which can be found at www.kuturani.com.mx/recursos. However, there is still much to cover, and with further developments, we plan to continue releasing pedagogical resources. We hope that, through these materials, we can introduce people, particularly musicians in our community, to computer science and electronics development, and guide them in completing the development of their own devices.

References

ANDRADE, R. A case study of instrument design. **KC Research Portal**, [*s. l.*], no. 1, 2022. Available at: https://www.researchcatalogue.net/view/1518982/1518983. Accessed at: 1 Sept. 2025.

BENACCHIO, S. *et al.* Active control applied to string instruments. *In*: ACOUSTICS 2012 CONFERENCE, 2012, Nantes, France. **Proceedings of the Acoustics 2012 Nantes Conference**. Nantes, France: [*s. n.*], 2012. p. 367–372.

BENACCHIO, S. **Contrôle actif modal appliqué aux instruments de musique à cordes**. 2014. Doctoral Dissertation - Université Pierre et Marie Curie - Paris VI, Paris, France, 2014. Available at: HAL Theses. https://theses.hal.science/tel-01134711.

BENACCHIO, S. *et al.* Modal proportional and derivative state active control applied to a simplified string instrument. **Journal of Vibration and Control**, [*s. l.*], vol. 22, no. 18, p. 3877–3888, 2016.

BERDAHL, E. **APPLICATIONS OF FEEDBACK CONTROL TO MUSICAL INSTRUMENT DESIGN**. 2009. Doctoral Dissertation - Stanford University, Stanford, CA, 2009.

BERDAHL, E.; SMITH, J.; NIEMEYER, G. Feedback control of acoustic musical instruments: Collocated control using physical analogs. **The Journal of the Acoustical Society of America**, [*s. l.*], vol. 131, p. 963–973, 2012.

BOWERS, J.; HAAS, A. Hybrid Resonant Assemblages: Rethinking Instruments, Touch and Performance in New Interfaces for Musical Expression. *In*: 2014, London, United Kingdom. **Proceedings of**

the International Conference on New Interfaces for Musical Expression. London, United Kingdom: Goldsmiths, University of London, 2014. p. 7–12. Available at: http://www.nime.org/proceedings/2014/nime2014_438.pdf.

BRITT, N. C.; SNYDER, J.; MCPHERSON, A. The EMvibe: An Electromagnetically Actuated Vibraphone. *In*: NIME 2012, 2012, Ann Arbor, Michigan. **Proceedings of New Interfaces for Musical Expression**. Ann Arbor, Michigan: [*s. n.*], 2012.

BURNS, C.; BURTNER, M. Recursive Audio Systems: Acoustic Feedback in Composition. **Leonardo Music Journal Electronic Almanac**, [*s. l.*], 2004.

BURTNER, M. Noisegate 67 for Metasaxophone: Composition and Performance Considerations of a New Computer Music Controller. *In*: , 2002, Dublin, Ireland. **Proceedings of the International Conference on New Interfaces for Musical Expression**. Dublin, Ireland: [*s. n.*], 2002. p. 24–29.

CLIFT, P. Acoustic-Aggregate-Synthesis. *In*: ICMC 2012, 2012, Ljubljana. **Proceedings of ICMC 2012, Non-cochlear sound**. Ljubljana: [*s. n.*], 2012. p. 120–123.

COOK, P. R. Principles for Designing Computer Music Controllers. *In*: , 2001, Seattle. **Proceedings of the CHI'01 Workshop on the New Interfaces for Musical Expression**. Seattle: [*s. n.*], 2001. p. 3–6.

COOK, P. R. Remutualizing the Musical Instrument: Co-Design of Synthesis Algorithms and Controllers. **Journal of New Music Research**, [*s. l.*], vol. 33, no. 3, p. 315–320, 2004.

COOK, P.; LIEDER, C. SqueezeVox: A New Controller for Vocal Synthesis Models. *In*: INTERNATIONAL CONFERENCE ON MATHEMATICS AND COMPUTING, 2000, San Diego, CA USA. **Proceedings of ICMC 2000**. San Diego, CA USA: [*s. n.*], 2000.

CREVOISIER, A.; POLOTTI, P. Tangible Acoustic Interfaces and their Applications for the Design of New Musical Instruments. [*s. l.*], p. 4, 2005.

CROFT, J. Theses on liveness. **Organised Sound**, [*s. l.*], vol. 12, no. 01, p. 59–66, 2007.

CURTIS, B.; DAN, T. Interface. Electronic Chamber Ensemble. *In*: , 2001, Seattle. **Proceedings of the CHI'01 Workshop on the New Interfaces for Musical Expression**. Seattle: [*s. n.*], 2001. p. 19–23.

DAVIS, T. The Feral Cello: A Philosophically Informed Approach to an Actuated Instrument. *In*: NIME 2017, 2017, Copenhagen, Denmark. **Proceedings of New Interfaces for Musical Expression**. Copenhagen, Denmark: [*s. n.*], 2017.

DUARTE-GARCÍA, M. A.; SIGAL-SEFCHOVICH, J. R. Working with Electroacoustic Music in Rural Communities: The use of an interactive music system in the creative process in primary and secondary school education. **Organised Sound**, [*s. l.*], vol. 24, no. 3, p. 228–239, 2019.

ELDRIDGE, A. *et al.* Self-resonating Vibrotactile Feedback Instruments ||: Making, Playing, Conceptualising :||. *In*: NIME 2021, 2021, Shanghai, China. **NIME 2021**. Shanghai, China: PubPub, 2021. Available at: https://nime.pubpub.org/pub/6mhrjiqt. Accessed at: 5 May 2024.

ELDRIDGE, A.; KIEFER, C. The Self-resonating Feedback Cello: Interfacing gestural and generative processes in improvised performance. [*s. l.*], 2017.

FARWELL, N. Adapting the Trombone: a Suite of Electroacoustic Interventions for the Piece. *In*: , 2006, Paris, France. **Proceedings of the International Conference on New Interfaces for Musical Expression**. Paris, France: [*s. n.*], 2006. p. 358–363.

FASCIANI, S.; GOODE, J. 20 NIMEs: Twenty Years of New Interfaces for Musical Expression. *In*: NIME 2021, 2021, Shanghai, China. **NIME 2021**. Shanghai, China: PubPub, 2021. Available at: https://nime.pubpub.org/pub/20nimes. Accessed at: 25 July 2022.

HOULÈS, F. **Le premier quatuor à cordes hybride, l'example de Smaqra de Juan Arroyo**. L'Harmattaned. Paris: [*s. n.*], 2017.

HUNT, A.; KIRK, R. Mapping Strategies for Musical Performance. [*s. l.*], 2000.

HYVIBE GUITAR – THE WORLD'S FIRST SMART GUITAR. [*S. l.*], 2024. Available at: https://www.hyvibeguitar.com/. Accessed at: 28 Apr. 2024.

IRCAM. **IMAREV | Acoustique Instrumentale**. [*S. l.*], 2014. Available at: http://instrum.ircam.fr/imarev/. Accessed at: 15 Jan. 2019.

IRCAM. SmartInstruments | Acoustique Instrumentale. *In*: ACOUSTIQUE INSTRUMENTALE. MODÈLES, SYNTHÈSE, CONTRÔLE, AIDE À LA FACTURE INSTRUMENTALE. 2015. Available at: http://instrum.ircam.fr/smartinstruments/. Accessed at: 15 Jan. 2019.

LÄHDEOJA, O. Active Acoustic Instruments for Electronic Chamber Music. *In*: NIME 2016, 2016, Brisbane, Australia. **Proceedings of New Interfaces for Musical Expression**. Brisbane, Australia: [*s. n.*], 2016.

MACHOVER, T. **A Composer At The Edge Of Sound**. Liana Hansen. [*S. l.: s. n.*], 16 Nov. 2008. Available at: https://www.npr.org/2008/11/16/96999557/a-composer-at-the-edge-of-sound. Accessed at: 12 Oct. 2023.

MACHOVER, T. **Hyperinstruments. A progress Report 1987-1991**. Cambridge, Mass: MIT, 1992.

MACHOVER, T. The Extended Orchestra. *In*: PEYSER, J. (ed.). **The Orchestra: A Collection of 23 Essays on Its Origins and Transformations.** New York, NY: Billboard Books, 1986. p. 583–600. Available at: Accessed at: 19 Oct. 2017.

MACHOVER, T.; CHUNG, J. T. Hyperinstruments: Musically Intelligent and Interactive Performance and Creativity Systems. *In*: ICMC89, 1989, San Francisco. **Proceedings of the 1989 International Computer Music Conference**. San Francisco: [*s. n.*], 1989.

MAMOU-MANI, A. Adjusting the soundboard's modal parameters without mechanical change: A modal active control approach. **The Journal of the Acoustical Society of America**, [*s. l.*], vol. 136, p. 2132–2132, 2014.

MANTEL, M. R. M. **Curating Music: Understanding Material Relationality in Music Performance**. 2022. Masters Thesis - Utrecht University, Utrecht, Netherlands, 2022.

MARINO, Gérard *et al.* The UPIC System: Origins and Innovations. **Perspectives of New Music**, [*s. l.*], vol. 31, no. 1, p. 258–269, 1993.

MARTÍNEZ ÁVILA, J. P. *et al.* Being (A)part of NIME: Embracing Latin American Perspectives. *In*: NIME 2022, 2022, Auckland, NZ. **Proceedings of New Interfaces for Musical Expression, 2022, Auckland**. Auckland, NZ: [*s. n.*], 2022. p. 33.

MASON, W. **Feeling Machines: Immersion, Expression, and Technological Embodiment in Electroacoustic Music of the French Spectral School**. 2019. - Columbia University, New York, NY, 2019.

MCPHERSON, A.; KIM, Y. Augmenting the Acoustic Piano with Electromagnetic String Actuation and Continuous Key Position Sensing. *In*: NIME 2010, 2010, Sydney, Australia. **Proceedings of the International Conference on New Interfaces for Musical Expression**. Sydney, Australia: [*s. n.*], 2010. p. 217–222.

MELBYE, A. P. Resistance, Mastery, Agency: Improvising with the feedback-actuated augmented bass. **Organised Sound**, [*s. l.*], vol. 26, no. 1, p. 19–30, 2021.

MELBYE, A. P.; ULFARSSON, H. A. Sculpting the behaviour of the Feedback-Actuated Augmented Bass: Design strategies for subtle manipulations of string feedback using simple adaptive algorithms. [*s. l.*], 2020. Available at: https://zenodo.org/record/4813328. Accessed at: 6 June 2024.

MELBYE, A. P.; ÚLFARSSON, H.; LAB, E. The FAAB (Feedback-Augmented Double Bass). *In*: NIME 2020, 2020, Birmingham, UK. **Music Proceedings of the International Conference on New Interfaces for Musical Expression**. Birmingham, UK: [*s. n.*], 2020.

MÉNAGE, F.; MAMOU-MANI, A.; PUVILLAND, S. Contrôle actif de vibration par un capteur/actionneur électrodynamique. [*s. l.*], 2022.

MONACHE, S. D. *et al.* Sonically Augmented Found Objects. *In*: NIME 2008, 2008, Genova, Italy. **Proceedings of the International Conference of New Interfaces for Musical Expression**. Genova, Italy: [*s. n.*], 2008.

OVERHOLT, D. The Overtone Fiddle: an Actuated Acoustic Instrument. *In*: NIME 2011, 2011. **Proceedings of the International Conference on New Interfaces for Musical Expression**. [*S. l.: s. n.*], 2011.

OVERHOLT, D.; BERDAHL, E.; HAMILTON, R. Advancements in Actuated Musical Instruments. **Organised Sound**, [*s. l.*], vol. 16, no. 02, p. 154–165, 2011.

PALACIO-QUINTIN, C. Eight Years of Practice on the Hyper-Flute: Technological and Musical Perspectives. *In*: NIME 2008, 2008, Genova, Italy. **Proceedings of the International Conference of New Interfaces for Musical Expression**. Genova, Italy: [*s. n.*], 2008. p. 293–298.

PARDUE, L. S. *et al.* Separating sound from source: sonic transformation of the violin through electrodynamic pickups and acoustic actuation. *In*: NIME 2019, 2019, Porto Alegre, Brazil. **Proceedings of the International Conference on New Interfaces for Musical Expression**. Porto Alegre, Brazil: [*s. n.*], 2019. p. 272–277.

POLYMENEAS LIONTIRIS, T. *et al.* The Ensemble as Expanded Interface. Sympoetic Performance in the Brain Dead Ensemble. *In*: ICLI 2018, 2018, Porto, Portugal. **ICLI 2018 4th International Conference on Live Interfaces: Inspiration, Performance, Emancipation**. Porto, Portugal: Universidade do Porto, 2018. p. 117–125. Available at: https://live-interfaces.github.io/2018/pdf/ICLI2018-Liontiris.pdf. Accessed at: 6 June 2024.

RAMOS FLORES, C. **Integrating Score, Performance, and Medium in the work-concept: The HypeSax as a Case Study**. 2021. Doctoral Dissertation - Victoria University of Wellington, Wellington, New Zealand, 2021. Available at: https://openaccess.wgtn.ac.nz/articles/thesis/Integrating_Score_Performance_and_Medium_in_the_work-concept_The_HypeSax_as_a_Case_Study/14837754.

RAMOS FLORES, C. The bodyless sound and the re-embodied sound: An expansion of the sonic body of the instrument. **Ricercare**, [*s. l.*], p. 30–58, 2022.

RECTOR, D.; TOPEL, S. EMdrum: An Electromagnetically Actuated Drum. *In*: NIME 2014, 2014, London, UK. **Proceedings of the International Conference on New Interfaces for Musical Expression**. London, UK: [*s. n.*], 2014. p. 395–398.

REID, S. *et al.* Minimally Invasive Gesture Sensing Interface (MIGSI) for Trumpet. *In*: , 2016, Brisbane, Australia. **Proceedings of the International Conference on New Interfaces for Musical Expression**. Brisbane, Australia: Queensland Conservatorium Griffith University, 2016. p. 419–424.

SCHIESSER, S.; SCHACHER, J. C. SABRe: The Augmented Bass Clarinet. *In*: NIME 2012, 2012, Ann Arbor, Michigan. **Proceedings of the International Conference of New Interfaces for Musical Expression**. Ann Arbor, Michigan: [*s. n.*], 2012.

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