Hybrid Drum: Iterative Development Toward Standalone Operation and Physical Feedback

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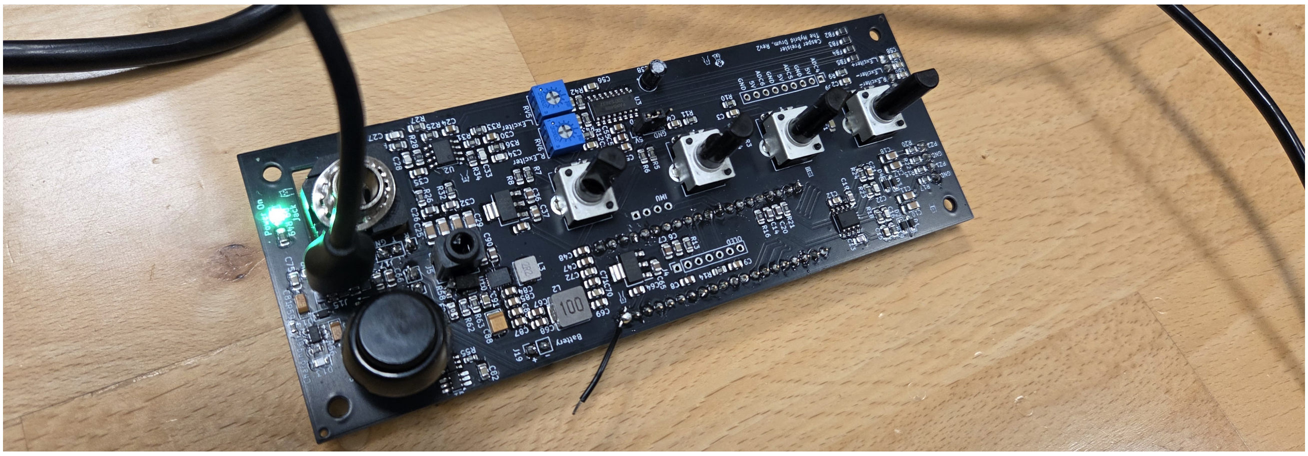

Figure 1: Iteration 2: fabricated and populated PCB for the Hybrid Drum

Abstract

This paper presents the iterative development of a self-contained hybrid percussion instrument combining acoustic excitation with digital signal processing. Building on a prior frame-drum prototype (Iteration 0 [5]) that demonstrated low-latency hybrid augmentation but required an external computer and power supply, this work documents two subsequent design iterations toward a compact, battery-powered, standalone instrument.

Iteration 1 introduces a cajón form factor, Daisy Seed microcontroller, Karplus-Strong synthesis, and a first custom PCB, establishing the core interaction model and eliminating host-computer dependency. **Iteration 2** adds full battery-powered standalone operation, a redesigned PCB with dual audio outputs, and an internal actuator that reintroduces digitally processed vibrations into the drum body as a physically grounded feedback loop. Three guiding principles emerge across iterations: standalone operation as a non-negotiable condition for performative viability; simplicity in the control interface; and hardware as a platform for future software exploration. The actuation path is functional but under active development to address feedback control challenges; hardware is further prepared for gyroscope-based sensing.

Exploratory encounters with a professional drummer, a creative technologist, and a child revealed the instrument's capacity to invite interaction beyond conventional techniques and informed the design decisions shaping Iteration 2. This research contributes to hybrid instrument design at the boundary of physical resonance and electronic transformation, documenting both progress made and challenges that remain.

Keywords

Augmented Drums, Digital Musical Instruments, Electronic Percussion, Music Technology, Sound & Music Computing, Active Acoustics, Hybrid Instruments, Actuated Musical Instruments

1 Introduction

1.1 Motivation and Background

A hybrid drum (one that preserves the organic resonance of an acoustic instrument while augmenting it with real-time digital processing) occupies a compelling design space. The expressive potential lies not only in the sound produced but in the dynamic relationship between the performer's physical gesture, the instrument's acoustic body, and the digital system that mediates bidirectionally. In prior work (hereafter **Iteration 0**) [5], the authors explored this relationship through a piezoelectric-augmented frame drum running on a Bela platform with Pure Data, demonstrating that hybrid augmentation could achieve sub-10 ms latency while preserving the organic qualities of hand percussion. That initial design, however, revealed a tension common to many research prototypes of digital musical instruments: the more expressive and responsive the system becomes, the more it tends to depend on external infrastructure (power cables, computers, and complex setup) that conflicts with the very portability and spontaneity that make hand percussion appealing in the first place.

This paper picks up directly from that tension. Rather than treating portability and hybrid expressivity as competing constraints, we investigated how successive design iterations can work toward resolving them together. Three guiding principles

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emerge and are discussed further in Sec. 6 The path from a tethered research prototype to a self-contained instrument requires rethinking the platform, the form factor, the power architecture, and ultimately the physical relationship between the digital system and the acoustic body of the drum. The introduction of an internal actuator, a transducer mounted inside the drum body that reintroduces digitally processed sound as mechanical vibration, represents the most significant conceptual ambition in this trajectory. It moves the digital processing from an external augmentation layered on top of the acoustic instrument toward becoming an active participant within its physical resonant structure, turning it into an actuated musical instrument [3]. This paper documents where that ambition currently stands: the hardware is in place, the actuation path is functional, and the feedback control challenges that come with closing that physical loop are actively being addressed.

1.2 Objectives of the Study

The work described showcases iterative development of a self-contained hybrid percussion instrument across two major design iterations. Rather than presenting a single finalized design, this work traces the evolution from an initial proof-of-concept through successive refinements that address fundamental challenges in portability, power efficiency, and physical feedback integration.

The overarching goal is to create a hybrid drum that operates independently (i.e. requiring no external computer, plugged-in power supply, or complex setup) while working toward a physically grounded feedback loop where digitally processed sound is reintroduced into the acoustic instrument body via mechanical actuation. Each iteration builds upon lessons learned from the previous one, incorporating performer feedback and addressing technical limitations. This paper contributes both a detailed technical account of the design decisions at each stage and reflections on how exploratory evaluation with diverse users informed the iterative process.

1.3 Scope and Applications

The instrument aims for true portability, from studio experimentation to outdoor and stage performances to informal exploratory sessions, in contexts where setup complexity and power requirements are real constraints. By prioritizing standalone operation and maintaining the familiar form factor of a drum, the design aims to lower barriers to entry for percussionists while opening new possibilities for extended technique through embedded actuation and sensing.

2 Related Work

2.1 Hybrid Instruments in percussion

The *aFrame* by ATV uses a mesh batter head combined with piezoelectric sensors, an FSR (force sensing resistor), and on-board DSP. It takes audio signals directly from the piezoelectric sensors for real-time audio processing, giving it a more organic, hybrid character. The *Sunhouse Sensory Percussion* attaches sensors to an existing drum set, processed through a dedicated audio interface. The exact sensing method is not publicly disclosed but likely combines magnetic field sensing, piezoelectric and/or photoelectric sensors. A pickup element attached to the batter head acts as a reflective surface or magnetic field source; the system detects up to 10 hit zones per drum along with velocity, enabling nuanced sample triggering. All within a retrofit approach that preserves the existing acoustic instrument.

The *Mandala V3* features multiple hit zones combining piezoelectric and capacitive sensors, making it versatile enough to trigger different samples depending on strike position, with velocity sensitivity and compatibility with both hands and drumsticks. The *Korg Wavedrum* offers two striking zones (head and rim), detecting hits with a combination of piezoelectric and pressure sensors for velocity sensitivity. It incorporates advanced synthesis and sampling capabilities, resulting in a versatile and expressive sounding instrument.

The *Digitally Active Drum (DAD)* [8] is of particular relevance to Iteration 2 of this work. It is an enhanced snare drum with an in-built speaker, a sound transducer, and near-field photoelectric sensors for position detecting above the drumhead. The DAD routes digitally generated sound back into the drum body via an internal transducer, creating coupling between the acoustic and digital domains, the same principle pursued here through the internal actuator. Where the DAD uses photoelectric proximity sensing to enable contactless gestural control, this work relies on piezoelectric impact sensing, prioritizing percussive excitation and retaining the physical act of striking as the primary interface. The DAD also uses a full speaker cone within a snare body, whereas the Hybrid Drum integrates a compact exciter actuator within a cajón form factor box, raising distinct challenges around physical coupling, resonance modes, and feedback control.

2.2 Sensor Technology in Music

The instruments discussed above rely primarily on piezoelectric sensors, which are also the core sensing element in this project. Piezoelectric sensors, typically of a ceramic material or crystal, generate an electric charge when put under mechanical stress, such as deformation, which can be pressure, impact, vibration or bending [6]. In stringed instruments, they act as pickups converting vibrations into an electrical signal. In percussive instruments, they usually serve as triggers in electronic drums and are integrated in hybrid drum setups (e.g. *aFrame* and *Hybrid Percussion* [1]), capturing vibrations and impacts for a more natural feel. Piezoelectric sensors are effective at detecting timing and sound; a single sensor cannot determine position, though this can be achieved by using four sensors in a square layout [4, 7].

3 Iterative Development Overview

Table 1 summarises the three iterations at a glance; Sections 4 and 5 provide detailed accounts of design rationale, implementation, and reflections for Iterations 1 and 2 respectively.

4 Iteration 1: Cajón Prototype with Daisy Seed

4.1 Design Rationale and Modifications

Following initial experiments with the frame drum design (Iteration 0 using Bela/BeagleBone with Pure Data), Iteration 1 introduced several fundamental changes: shifting to a travel cajón body, transitioning to Daisy Seed with C++ programming, and designing a first custom PCB. These changes were motivated by converging design goals around simplification and moving toward stable and standalone operation.

Form factor changes:

- **Acoustic stability**: The cajón's rigid box construction provided more consistent acoustic properties compared to the tensioned membrane of a frame drum

Table 1: Key characteristics across iterations of the Hybrid Drum.

	Iteration 0 [5]	**Iteration 1**	**Iteration 2**
Form	Frame drum	Travel cajón	Travel cajón
Platform	Bela + Pd	Daisy Seed (C++)	Daisy Seed (C++)
Sensing	2 piezos + FSR	2 piezos	2 piezos
Power	External (mains)	External USB	Li-ion battery
PCB	None	Custom v1	Custom v2
Audio out	Single mini-jack	Single mini-jack	Dual (6.35 mm + 3.5 mm)
Actuation	None	None	Internal transducer
Expansion	–	–	OLED + gyroscope headers

Figure 2: Iteration 1 with PCB mounted on the outside, 3D printed and lasercut case and knobs.

- **Sensor mounting**: Internal mounting surfaces simplified piezo placement without affecting drumhead tension
- **Portability**: Travel cajón dimensions (approx. dimensions 29 x 22 x 10 cm) maintained portability while offering more internal volume for electronics

Platform transition to Daisy Seed:

- **Size**: Smaller in size made an easier fit
- **Power efficiency**: Lower power consumption made future battery operation more feasible
- **Cost**: Lower cost per unit supported iteration and experimentation
- **Programming paradigm**: Shift from Pure Data to C++ for more direct hardware control and optimization

The FSR was removed entirely, simplifying the sensor array to two piezoelectric elements positioned to capture impact variations across the playing surface. This reduction emerged from observations in iteration 0 that the FSR's pressure-sensing capabilities did not have as big impact as expected when playing the drum, adding complexity without proportional expressive benefit.

A demo of Iteration 1, showing percussive interaction, synthesis response, and exploratory use contexts, is available online.[1]

[1]https://youtu.be/IDYSpnn1Yy0

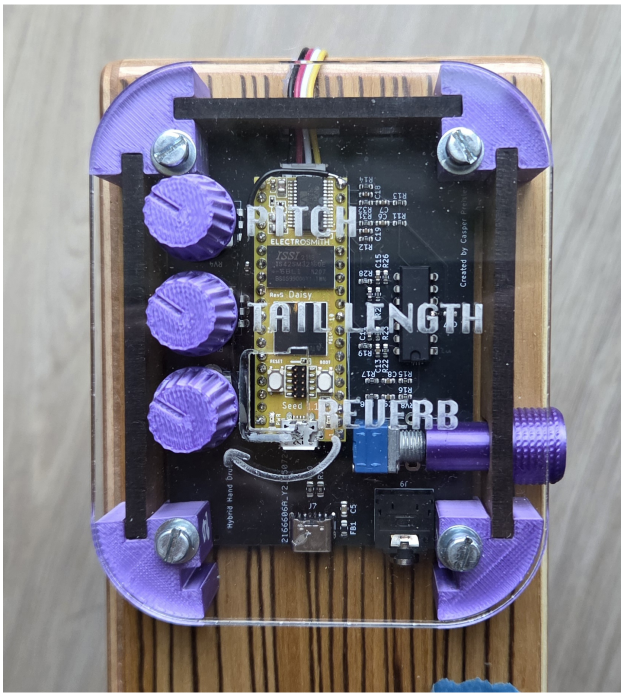

Figure 3: Iteration 1: user interface layout. Hole cut for mounting an ST-Link on the 10-pin header for flashing the Daisy Seed.

4.2 Technical Implementation

Figure 3 shows the user interface layout of the first iteration, where control elements are positioned to allow real-time parameter adjustments while playing. A cross-sectional view of the instrument is shown in Figure 4, detailing the internal placement of electronic components in relation to the resonating body.

Platform: Daisy Seed microcontroller, programmed in C++, powered via USB C from external power bank or wall adapter

Custom PCB (iteration 1): First custom PCB design:

- Input buffers for two piezoelectric sensors
- Daisy Seed mounting and power distribution
- Three potentiometer inputs for parameter control
- Analog output volume control (potentiometer in output stage)
- Mini-jack audio output

Sensors: Two piezoelectric disc sensors (ø27mm) mounted internally against the cajón's playing surface, connected through PCB input buffers.

Control interface: Three potentiometers for real-time parameter adjustment.

DSP: Karplus-Strong string synthesis implementation in C++, where piezo impact directly excites the synthesis with the actual audio. The algorithm creates a plucked-string effect through a delay line with feedback, mapping naturally to percussive strike interaction.

Limitations: While the custom PCB represented a significant step toward integration, the system still required external USB power. The single output configuration meant no dedicated path for future actuator implementation. PCB schematics and layout was functional but not optimized for component spacing or optimized circuitry.

4.3 Exploratory Evaluation: Iteration 1

Iteration 1 of the Hybrid Drum was explored through two unstructured and non-formal exploratory encounters. Both evaluations are presented as situated design reflections rather than as comparative or validation studies.

4.3.1 Professional Drummer Session. Iteration 1 was explored through an informal session with a professional drummer in a small concert space equipped with a live sound system. The performer interacted freely with the instrument for approximately ten minutes, exploring dynamic range, timbral variation, and the relationship between physical strike and synthesized response.

Key observations:

- The Karplus-Strong synthesis mapped intuitively to percussive playing, physical impacts naturally activates the "pluck" and the synthesis responds dynamically to strike velocity
- Dynamic response across the playing surface was perceived as consistent. However, the two-piezo configuration did not produce noticeably timbral variation between edge and center strikes, suggesting that a single piezo may be sufficient for the current synthesis mapping. Two sensors are nonetheless retained in Iteration 2 for redundancy and to preserve the option of position-dependent mappings in future iterations.
- Parameter ranges supported musical utility and expressive variation. The internally implemented plate-reverb was not utilized, as an external reverb effect from the mixing console was preferred.
- The analog output volume control enabled effective real-time gain adjustment during performance
- Airborne acoustic feedback, which had been problematic in an earlier prototype (iteration 0) was not observed, likely due to the more rigid playing surface of a cajón.
- The Daisy Seed platform performed well with low perceptible latency and stable real-time performance

Design implications: The session validated the core synthesis approach and platform choice, while also highlighting areas for further refinement:

- The addition of a non-slip surface on the underside of the instrument to prevent movement when played on the lap
- Reduced emphasis on internal effects processing, as external effects units are commonly preferred in performance contexts
- Interest in the implementation of a movement sensor (gyroscope) to support embodied control beyond percussive excitation.

4.3.2 Diverse User Encounters. The same iteration was explored informally in a home environment by a creative technologist and a three-year-old child.

The child engaged with the instrument intuitively as a playable percussion object, while the technologist explored it more deliberately. Notably, both users initially played on the opposite side from where the piezo sensor was mounted, revealing that the instrument did not clearly communicate its intended orientation. Key observations from this encounter are consolidated in the Observations and Design Insights section below.

4.3.3 Observations and Design Insights. Both encounters emphasized different aspects of the instrument's behavior:

- **Physical responsiveness**: The instrument invited immediate percussive engagement across user backgrounds, from professional drummer to three-year old child, suggesting the tactile response was intuitively legible as a playable surface.
- **Timbral character**: The Karplus-Strong synthesis produced sounds distinct from conventional drums while remaining connected to percussive gesture. The technologist noted its potential for foley applications in film and media production, highlighting the instrument's capacity for unconventional timbral material beyond music performance contexts.
- **Accessibility and orientation**: The child's immediate engagement demonstrated that the core interaction required no specialized knowledge. However, both users initially played on the wrong side of the instrument, revealing a critical orientation ambiguity. The technologist suggested this could be resolved through visual indicators (symbols or text on the playing surface) or physical affordances such as rubber feet or a handle on the base side. Clearer physical design cues are essential for guiding first-time users toward intended interaction patterns.

These encounters serve as situated design reflections rather than evidence of musical effectiveness or usability.

4.4 Design Modifications Identified

Based on the evaluation session, subsequent use, and reflection on the PCB design process, several key improvements were identified for Iteration 2:

- **Integrate battery and power management**: Eliminate external USB dependency through onboard battery, charging circuitry, and voltage regulation
- **Improve signal path**: Clearer signals in input buffer, output path, and potentiometer circuits to reduce audio noise
- **Improve PCB layout**: Better component spacing, clearer visual signal flow, Daisy Seed mounting on backside to reduce profile
- **Add visual indicators**: LED indicators for power and battery charging status
- **Clarify playing surface**: Add visual or tactile cues to distinguish playing surface from base
- **Implement internal actuation**: Add loudspeaker/actuator inside drum body with dedicated amplifier and independent gain control for haptic feedback and acoustic excitation

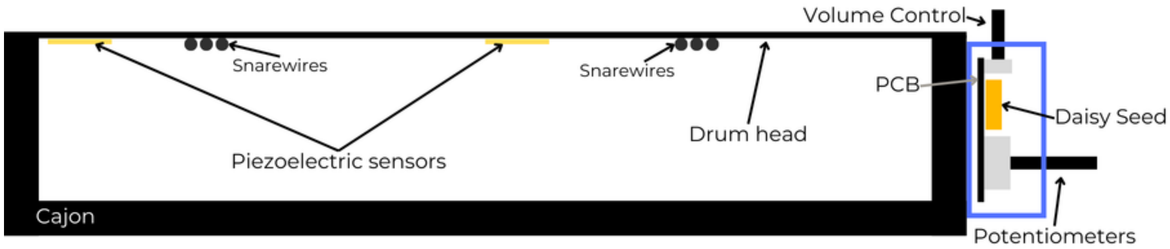

Figure 4: Iteration 1: cross section of the drum, showing the placement of PCB, potentiometers and piezo.

- **Shift volume control to digital**: Move output gain from analog potentiometer to digital control for better precision and future preset capability
- **Prepare for expansion**: Integrate headers for OLED display and gyroscope sensing
- **Add power switch**: Dedicated on/off button for battery operation

5 Iteration 2: Self-Contained System with Improved PCB

5.1 Design Rationale and Core Changes

Iteration 2 represents a hardware evolution focused on achieving true standalone operation and adding physical feedback. Maintaining the Daisy Seed platform from Iteration 1, this iteration addressed the identified limitations through comprehensive PCB redesign and feature expansion:

- **Battery integration**: Eliminate external USB power dependency for field deployment and performance flexibility
- **Internal actuation**: Introduce physical feedback loop. Routing audio back into drum body creates haptic response and acoustic excitation
- **Improved PCB layout**: Refined component placement for better ergonomics, visual clarity, and technical performance
- **Expansion readiness**: Prepared hardware infrastructure for future sensing and display capabilities without requiring redesign

The design philosophy shifted from “functional prototype” (Iteration 1) to “deployable instrument”, prioritizing power autonomy, robustness, and extensibility while maintaining the established interaction paradigm.

A supplementary video shows the current state of Iteration 2. This video illustrates ongoing development rather than evaluated performance.[2]

5.2 Technical Implementation

Figure 5 shows a cross-sectional view of the second iteration of the instrument, illustrating the placement of sensing elements, actuation mechanism, and embedded electronics within the drum.

Platform: Daisy Seed microcontroller (continued from Iteration 1), programmed in C++

Custom PCB (iteration 2) - Key improvements:

Power system:

- Rechargeable lithium-ion battery with integrated battery management system (charging circuit, protection)
- Buck-boost converter providing stable 5V rail regardless of battery charge state (input range 3.0-4.2V)
- On/off button for power control and battery conservation
- LED indicators for power (on/off) and charging status

Audio architecture:

- Audio input buffering for two piezoelectric sensors (optimized circuit from Iteration 1)
- Dual audio outputs: 6.35mm jack and 3.5mm minijack for flexible connection options
- Dedicated digital amplifier stage for internal actuator drive with independent gain control
- Volume control for audio output via potentiometer → ADC → code (replacing Iteration 1's analog output volume control)

Internal actuation:

- Actuator mounted inside cajón body
- Driven by dedicated amplifier with own gain control
- Functions as both acoustic excitation source (exciting drum body resonances) and haptic feedback element
- Creates physical feedback loop: piezo senses strike → DSP processes → actuator excites body → performer feels and hears response

PCB layout improvements:

- Daisy Seed mounted on backside of PCB, reducing profile and protecting pins
- Improved potentiometer spacing for better adjustment while playing
- Optimized circuits for reduced noise in audio signal, better and more stable performance

Expansion preparation:

- OLED display header (prepared but not yet utilized, for future parameter visualization and preset indication)
- Gyroscope integration header (hardware ready, awaiting software implementation for gestural sensing)
- Three additional ADC inputs available for possible future sensor or control expansion

Control interface: Four potentiometers implemented. Three for DSP parameters, one controlling audio volume output.

DSP: Karplus-Strong string synthesis (maintained from Iteration 1), with actuation feedback creating a physical analog to the algorithm's delay-line structure

5.3 Implementation Status and Development Process

At the time of writing, Iteration 2 hardware is fully assembled and operational. The PCB has been fabricated and populated, battery

[2] https://www.youtube.com/shorts/aaEJ9srHpWs

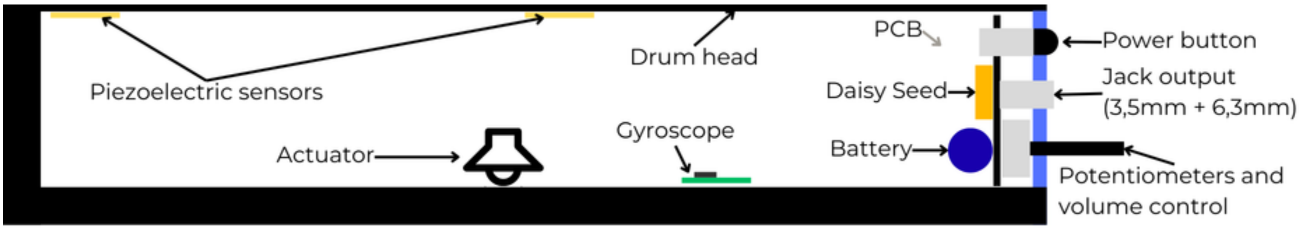

Figure 5: Iteration 2: cross-section view of the drum, showing the revised placements of PCB, potentiometers, and piezos, and the added actuator, gyroscope, and battery.

integration is complete, and basic audio I/O and actuation are functional. Software development is ongoing:

Implemented:

- Audio input/output routing for both external outputs (jack and minijack)
- Basic piezo signal processing
- Digital potentiometer reading for all four controls
- Actuator output with dedicated amplifier and gain control
- Battery operation and power management

In development:

- Gyroscope sensor integration (hardware prepared, software implementation and gesture algorithms pending)
- Anti-feedback strategies, addressing structural coupling where actuator vibrations mechanically re-trigger piezo sensors, creating runaway feedback. Strategies under exploration include adaptive gain limiting, high-pass filtering, and utilizing a secondary reference piezo to characterize and subtract mechanical output from the primary signal.
- DSP algorithm refinement and parameter range optimization based on evaluation feedback.
- OLED display implementation for parameter feedback and visual status indication.
- Power consumption characterization and runtime optimization (estimated typical use runtime of approximately 2-4 hours; precise characterization is ongoing).

6 Cross-Iteration Reflections

6.1 Design Principles Emerging from Iterations

Across both iterations, several design principles emerged that shaped decision-making:

1. Standalone operation as non-negotiable: Both evaluations emphasized that external dependencies (power, computer) fundamentally limited the instrument's utility. This drove the hardware consolidation in Iteration 2

2. Simplicity in control interface: The four-potentiometer approach proved adequate for real-time expression while avoiding menu-diving complexity. Future expansion (presets, OLED display) should augment rather than replace this directness

3. Hardware as platform for evolution: Iteration 2's prepared gyroscope and ADC expansion reflect a design philosophy where hardware readiness enables future software exploration without requiring new builds

6.2 Technical Lessons Learned

Platform selection trade-offs: The Bela's ultra-low latency and powerful I/O helped initial prototyping, but its power draw and size made it unsuitable for standalone operation. The Daisy Seeds constraints required software adaptation but matched the core goal of portability.

PCB integration benefits: Consolidating components onto a custom PCB dramatically improved reliability, reduced setup time, and proved essential for a deployable instrument.

Power management complexity: Battery integration introduced significant complexity (charging circuitry and protection, voltage regulation) that was underestimated in initial planning.

6.3 Future Improvements

Based on the development process and evaluations, several directions for future work have been identified:

Software integration priorities:

- Gyroscope implementation enabling interaction through rotational movement of the drum
- Development of anti-feedback strategies to prevent unstable behavior arising from physical coupling between actuator and piezo sensors
- OLED display for visual parameter feedback
- Preset system for quick sound exploration and performance flexibility
- Refined DSP algorithms optimized for Daisy Seed architecture

Hardware refinements:

- Power consumption characterization and optimization for extended runtime
- Feedback mitigation strategies (signal processing, sensor shielding)
- Alternative drumhead materials exploration (e.g., perforated surfaces to reduce airborne pickup)
- Refinement of the drum construction to improve acoustic qualities
- Exploration of textured side surfaces for additional expressive interaction (e.g., grooves or roughened materials for sliding gestures)
- Cable management and enclosure design for field robustness

Evaluation and study:

- Structured usability assessment (e.g., System Usability Scale [2])
- Longitudinal study with diverse performers to understand learning curves and performance practices
- Comparison of actuation strategies (different actuator types, placements, control schemes)

7 Conclusions

The introduction to this paper identified a tension that surfaces repeatedly in the design of expressive digital musical instruments: the more responsive and sonically rich a hybrid system becomes, the more it tends to depend on external infrastructure that undermines the very spontaneity and portability that motivate the work. The two iterations documented here represent a sustained attempt to work toward resolving that tension without sacrificing either side of it.

Iteration 1 established the core interaction model. Piezoelectric sensing mapped to Karplus-Strong synthesis on a compact, low-power platform, and demonstrated through exploratory evaluation that the synthesis approach is intuitively legible to performers ranging from professionals to young children. The transition from Bela to Daisy Seed, and from a frame drum to a cajón form factor, were not merely engineering convenience. They were steps in a design trajectory whose destination was standalone operation.

Iteration 2 takes that direction seriously at the hardware level. The battery integration, dual outputs, and redesigned PCB address the practical constraints identified in Iteration 1. The internal actuator represents the more ambitious step: routing the synthesised signal back into the drum body as mechanical vibration, with the intention of closing a feedback loop that is both literal and experiential. At the time of writing, the actuation path is functional and the same Karplus-Strong synthesis runs through it, but structural and airborne coupling between the actuator and the piezo sensor creates a feedback instability that requires dedicated control strategies. Adaptive gain limiting and signal filtering are actively being explored. The gyroscope, for which the hardware header is prepared, has not yet been implemented in software. These are not presented as failures but as the current frontier of the work.

Across these iterations, three guiding principles emerged: standalone operation as a necessity for performative viability, simplicity in the control interface, and hardware designed as an extensible platform. The informal evaluations from Iteration 1 provided reflective insights that shaped subsequent priorities. By prioritizing a robust, self-contained architecture, this work positions the Hybrid Drum to explore the potential for commercial viability as a reliable tool for the professional percussion community. Internalizing all necessary infrastructure allows the authors to lower entry barriers for musicians of all backgrounds, establishing a blueprint for standalone, actuated instruments that match the portability and intuition of their acoustic counterparts.

8 Ethical Standards

This project was developed with the aim of making hybrid instruments accessible to musicians of all backgrounds.The Hybrid Drum is designed to make it low entry for percussionists. No data was collected from individuals outside the creators of the project, and the participants in the evaluation gave informed consent, with the option to withdraw at any time. Feedback was anonymized to ensure privacy.

While the authors strove for an inclusive and versatile instrument, some limitations remain. Those with limited or no hand mobility may find it challenging to play and use the drum. Additionally, musicians with visual impairments may face difficulties adjusting parameters without additional accessible features. Future iterations may accommodate these challenges, and find ways to improve usability for a broader range of performers.

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