

From Control Structure to Haptic Strategy: A Design Heuristic for IoMusT and Smart Instruments

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Abstract—As Digital Musical Instruments (DMIs) increasingly join networked and Internet of Musical Things (IoMusT) ecosystems, designers face a growing need to know not just whether to add vibrotactile feedback to a connected instrument, but what kind. This paper investigates whether a DMI’s physical control structure is associated with which feedback strategy (Inherent or Augmented) performers find most appropriate, offering a design-time heuristic for haptically augmenting smart musical instruments before deployment. Building on our prior study of the wireless, gesture-driven T-Stick [8], we conducted facilitated design sessions with nine expert musicians across three structurally diverse instruments: a discrete keyboard (AKAI MPK Mini), a multidimensional touch surface (Linnstrument), and the T-Stick. Using Card et al.’s morphological analysis of input devices and Jacob et al.’s integral/separable interaction framework, we find that separable, layout-composed control structures favor Inherent feedback to enhance embodiment, while integral or sensor-fused structures favor Augmented feedback for navigation and state awareness. These exploratory findings, drawn from new AKAI and Linnstrument data analyzed alongside our previously reported T-Stick results, offer an initial framework for anticipating haptic feedback requirements as IoMusT devices are designed and networked.

Index Terms—Haptics, Vibrotactile Feedback, Digital Musical Instruments, Internet of Musical Things, Smart Musical Instruments, Interaction Design

I. INTRODUCTION

The Internet of Musical Things (IoMusT) extends networked, sensor-driven instruments into an ecosystem where devices sense, process, and communicate with performers, other musicians, and audiences alike [1]. As Smart Musical Instruments (SMIs), DMIs characterized by embedded intelligence, actuation, and wireless connectivity, become a more common target for designers in this space [2], a practical question follows close behind the technical one: once an instrument can be connected, should it also be made to vibrate, and if so, how?

Acoustic instruments give performers a continuous, coupled stream of vibrotactile information that guides timing, intonation, and expressive control [3]. Digital Musical Instruments, including networked and IoMusT devices, typically lack this channel entirely, leaving a haptic gap that has been cited as a barrier to the expressiveness acoustic instruments take for granted [4], [5]. Vibrotactile actuation is a natural way to close this gap, but existing implementations are largely

ad hoc: a designer adding haptic feedback to a new smart instrument has little guidance on what kind of feedback best suits their device: feedback that reinforces the felt sensation of playing (Inherent), versus feedback that conveys system state or control information (Augmented) [7]. Beyond the performer, recent work has extended haptic augmentation to audience members in live IoMusT performance contexts [6], underscoring the breadth of the haptic gap across the ecosystem.

In prior work, we explored this question for a single gestural IoMusT controller, the T-Stick, finding that performers consistently favored Augmented strategies for sensor-state and patch-state awareness [8]. That result raised a broader question this paper addresses directly: is this preference a property of the T-Stick specifically, or of a more general class of instrument? We extend our exploratory design-session methodology to two structurally distinct, non-gestural controllers: a discrete keyboard (AKAI MPK Mini) and a multidimensional touch surface (Linnstrument), and analyze all three instruments together through Card et al.’s morphological analysis of input device structure [9] and Jacob et al.’s integral/separable interaction framework [10]. Our results suggest that an instrument’s control structure itself may shape which haptic strategy performers gravitate toward: a heuristic with direct implications for designers adding vibrotactile feedback to the next generation of smart and networked instruments.

II. BACKGROUND

A. Vibrotactile Feedback in DMIs

Acoustic instruments couple performer and instrument through a continuous exchange of mechanical energy [11]: a guitarist feels the string’s vibration through their fingertip as they play it. DMIs, including networked IoMusT devices, typically decouple gesture from sound production, eliminating this channel. Restoring it through vibrotactile actuation has shown measurable value; Chafe [12] found that tactile feedback corresponding to lip tension improved control of a physical-model brass instrument, and Papetti et al. [13] showed that vibrotactile feedback consistent with a device’s audio output improved both playing experience and perceived interface quality. Marshall and Wanderley [14] also found that

feedback can trade engagement for perceived control, a finding echoed in performer-led haptic practice [15].

We adopt Birnbaum and Wanderley’s [7] performer-centered topology, which distinguishes two functions of vibrotactile feedback. **Inherent** feedback is task-intrinsic: it reinforces a cognitive model the performer already holds from acoustic instruments, such as a haptic click that fires in lockstep with a key press, making the digital action feel physically consequential. **Augmented** feedback instead conveys information not present in the task itself: for example, a vibration that intensifies as a continuous sensor value approaches a threshold the performer cannot otherwise perceive. The distinguishing test we apply throughout this paper is not the vibrotactile signal’s complexity but its referent: does the sensation correspond to something the performer’s body is already doing (Inherent), or does it report something the performer could not otherwise know (Augmented)?

B. Structural Frameworks for Input Devices

To explain why performers favor one strategy over the other for a given instrument, we turn to two HCI frameworks for input device structure. Card et al. [9] model input devices as compositions of primitive sensing transducers combined in one of three ways: *layout* (independent controls sharing physical proximity, e.g., a row of keys), *merge* (multiple sensing dimensions fused into a single control point, e.g., a pressure-sensitive XY pad), and *connect* (the output of one sensing stage mapped onto the input of a higher-level interpretation stage, e.g., raw IMU data mapped onto a recognized gesture).

Jacob et al. [10] complement this with a perceptual framework, classifying multi-dimensional controls as **separable** (where a user perceives and adjusts each control dimension independently) or **integral** (where dimensions are perceived and manipulated as a fused whole). This aligns with Hunt and Kirk’s [16] distinction between analytical interaction (sequential, parameter-by-parameter) and holistic interaction (simultaneous, perceived as a unified gesture). Together, these frameworks let us characterize an instrument not just by what sensors it has, but by how a performer is likely to perceive controlling it, which, as our results suggest, is associated with the haptic strategy they reach for.

III. METHOD

A. Instrument Selection

Three DMIs were selected to span a deliberate range of control structures, following Card et al.’s morphological composition types [9]: the AKAI MPK Mini (discrete keys, pads, and knobs: *layout* composition), the Linnstrument (pressure-sensitive XY pads fusing position and force into a single point: *merge* composition), and the T-Stick (distributed IMU/FSR/capacitive sensors interpreted via gesture recognition: *layout* combined with *connect* composition) (Table I). All three were retrofitted with an identical 52mm Tectonic TEAX25C05-4 voice coil actuator to control for actuator-driven variation in feedback intensity across instruments.

TABLE I: DMI Control Structure Comparison

	AKAI	Linnstrument	T-Stick
Composition	Layout	Merge	Layout + Connect
Dynamics	Separable	Integral	Integral (emergent)
Gestural Range	Low	High	Very High
Protocol	MIDI	MIDI/MPE	OSC

B. Toolkit and Procedure

In each session, the participants designed vibrotactile effects and mapped them to their DMI’s control data using the Sonic Touch Toolkit¹, a Max/MSP-based environment for rapid haptic prototyping introduced in [17] and previously applied to T-Stick haptic design in [8]. Nine expert musicians (≥ 4 years instrumental experience; eight with prior DMI design experience) took part in individual, facilitated 60-minute design sessions, each working one-on-one with the first author and their assigned DMI, rather than in a group workshop setting. Participants were matched to the DMI they had the most prior experience with, to minimize time spent on basic familiarization. The facilitator operated the toolkit on request and answered technical questions, but the design goals and mappings were created by the participants. Each session was preceded by a background questionnaire and followed by a semi-structured interview and a post-session questionnaire of five 1–5 agreement statements (expressiveness, engagement, satisfaction with the design, design-process enjoyability, toolkit ease of use), plus the same tactile-importance item asked in the background questionnaire.

C. Participants and Data Provenance

Three participants per DMI took part: P5, P6, P8 (AKAI), P2, P3, P4 (Linnstrument), and P1, P7, P9 (T-Stick).² The T-Stick sessions were previously reported in [8]; here, they are reanalyzed alongside new AKAI and Linnstrument data to evaluate whether the Inherent/Augmented strategies observed for a single gestural IoMusT controller generalize across structurally distinct instrument classes.

All nine participants had at least four years of instrumental experience and prior experience programming audio or haptic feedback; eight of nine had previously designed or modified a DMI. Haptic familiarity ranged from slight to high; P1, P4 and P9 had prior musical vibrotactile experience.

D. Analysis

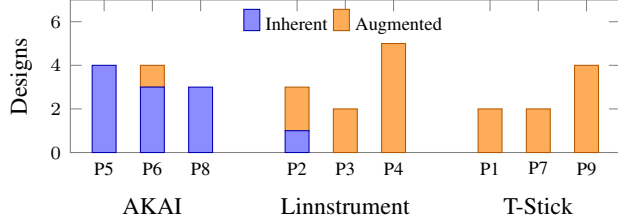
Design sessions and post-session interviews were transcribed and analyzed using critical incident technique [18]. Each vibrotactile design was classified as Inherent or Augmented based on the participant’s stated design goal and an analysis of the design’s mapping to DMI input. Classification was performed by the first author; given the small sample,

¹Available at <https://github.com/IDMIL/Haptic-Toolkit>

²For continuity with [8], where the same three T-Stick participants were numbered P1–P3: P1 $\leftrightarrow$ P1, P7 $\leftrightarrow$ P2, P9 $\leftrightarrow$ P3.

TABLE II: Post-Session Ratings by DMI (1–5 scale)

	AKAI	Linnstrument	T-Stick
Expressiveness	5.0	3.7	4.0
Engagement	5.0	5.0	4.0
Toolkit Ease of Use	3.3	3.7	4.7
Design Satisfaction	4.3	4.3	5.0
Process Enjoyability	4.7	4.3	4.7

Fig. 1: Inherent vs. Augmented vibrotactile designs per participant, grouped by DMI ($n = 29$ designs from nine participants).

we report classifications as supported directly by participant-vocalized intent (quoted throughout Section IV) rather than as independently validated through multi-coder agreement.

IV. RESULTS

A. Quantitative Overview

Post-session ratings (1–5 scale) were favorable across all three DMIs (Table II), with direct engagement rated highest overall ($M = 4.7$) and toolkit ease of use lowest ($M = 3.9$). These are post-session ratings only; no pre-session expressiveness or engagement baseline was collected, and because participants were rating feedback they had designed themselves, the ratings may be inflated by self-evaluation bias. Perceived importance of tactile feedback in DMI design (1–5 scale, asked in both the background and post-session questionnaires) rose from $M = 3.11$ to $M = 4.11$ (P1 4→4, P2 4→5, P3 2→3, P4 3→4, P5 2→4, P6 4→5, P7 2→3, P8 4→4, P9 3→5; Wilcoxon signed-rank, $W = 0$, $p = .016$). Given the small sample ($n = 9$), we report this as a descriptive trend, indicating participants left the session with a more favorable view of haptic feedback, not that the effect is generalizable at this sample size.

Of 29 vibrotactile designs across all sessions, AKAI participants produced overwhelmingly Inherent strategies (10 of 11), while Linnstrument (9 of 10) and T-Stick (8 of 8) participants produced almost exclusively Augmented strategies (Fig. 1). Because each participant produced several designs, these are not independent observations. However at the participant level, each AKAI participant produced majority-Inherent designs, and each Linnstrument and T-Stick participant majority-Augmented designs.

B. AKAI MPK Mini: Separable Control, Inherent Feedback

AKAI participants consistently designed feedback that reinforced the physical act of playing rather than conveying new information. P6 mapped a filter-sweep knob to continuous

amplitude scaling that mirrored the audible sweep. P8 mapped pad pressure directly to vibration amplitude, describing the appeal in terms of effort-reward congruence: “*I had to press harder to make more [feedback]; it’s like I had to put more energy in to get more energy out.*” P5 went further, tying haptic event timing to the tempo of an arpeggiator driven by the same key presses: “*My approach, it’s basically based on the audio effects, mostly.*”

This pull toward audio-haptic congruence was explicit and shared: P6 stated “*the mappings inherently need to be tied to the sound,*” and P8 described the resulting sense of agency directly: “*It feels like I’m actually doing something, as opposed to just like triggering digital events.*” Across this group, the dominant goal was not information transfer but embodiment: making a separable, layout-composed control surface feel physically substantial to press.

The group’s single Augmented design was P6’s: discrete “detent” pulses triggered at fixed points across a knob’s range, increasing in amplitude toward the end of the range. We classified it as Augmented because it indicates knob position, which the MPK Mini’s endless encoders do not convey physically: “*It lets me know the range of the parameter without seeing it, which is really useful on these kind of continuous encoders that can spin in any direction.*” P6’s filter-sweep design by contrast mirrors the audible sweep and thus was classified Inherent.

C. Linnstrument: Integral Control, Augmented Feedback

Linnstrument participants moved in the opposite direction, designing feedback to help navigate, not just feel, the instrument’s fused pressure/position control surface. P3 combined a continuous amplitude ramp with a discrete pulse to mark approach and crossing of a pad pitch boundary: “*Just anything that would let you play the instrument more easily without looking at it... that kind of helps me know where I am in relation to the other notes.*” P2 proposed using pressure-mapped feedback to support precise single-dimension control within the merged pad: “*You could actually use that to say you wanted to precisely set a parameter, but only with pressure.*”

P4’s design process is the clearest illustration of the integral-control problem: addressing a known difficulty controlling “raw, exposed pitch bend data,” P4 iterated through V-shaped envelope mappings that increased haptic intensity as a finger rolled away from a note’s pitch center. Notably, P4 also voiced a preference for Inherent feedback in the post-session interview: “*I would much rather have just the audio going through the voice coil.*” This underscores that the Augmented strategies observed here were a response to the instrument’s control complexity, not a stated aesthetic preference.

D. T-Stick: Connect Composition, Augmented Feedback

T-Stick performers unanimously designed Augmented feedback (8 of 8 designs), using vibrotactile cues for two purposes: sensor-state indication (proximity to FSR pressure thresholds, gyroscope orientation relative to vertical) and synthesis patch-state communication (distinguishing presets in multi-channel patches). Full transcripts, designs, and quotes for this dataset

TABLE III: Vibrotactile Design Parameters by Classification

Parameter	Inherent (n=11)	Augmented (n=18)
Waveform	Sine (8), Triangle (3)	Sine (17), Triangle (1)
Frequency	80–180 Hz (Mdn 122) ^a	100–300 Hz (Mdn 185)
Duration	50–100 ms	50–250 ms
Envelope	Exp. decay (3), ADSR (2), ASR (1)	Exp. decay (8)
Signal Type	Discrete (6), Continuous (5)	Continuous (10), Discrete (8)

are reported in [8]; here we note only that the unanimity of the Augmented preference, stronger than either the AKAI or Linnstrument groups, aligns with the T-Stick’s *connect* composition (Section II-B), where control signals emerge from fused, computationally interpreted gestures rather than direct single-sensor mappings.

E. Vibrotactile Parameterization

Beyond strategy classification, the specific vibrotactile parameters participants chose differ systematically between Inherent and Augmented designs (Table III), offering descriptive support for the structural account developed in Section V.

Inherent designs clustered at lower frequencies (80–180 Hz among fixed-frequency designs, median 122 Hz, $n = 10$), consistent with mimicking the resonance of an acoustic instrument body under the fingers. One further Inherent design (P8) continuously swept frequency between 50–200 Hz in direct proportion to knob position, an even tighter form of audio-haptic coupling than a fixed pitch. Augmented designs instead clustered at higher frequencies (100–300 Hz, median 185 Hz), closer to the approximately 250 Hz peak of human cutaneous sensitivity [19], and, where an envelope was applied, relied almost exclusively on exponential-decay envelopes to produce sharp, unambiguous cues. Sine waves dominated both classifications (25 of 29 designs); the limited use of more complex waveforms appeared driven less by Inherent/Augmented intent than by their audibility through the actuator, which several participants noted as a distraction.

V. DISCUSSION

A. Why Structure May Shape Strategy

The pattern across all three instruments can be explained by reading Card et al.’s composition types alongside Jacob et al.’s interaction dynamics, rather than either framework alone. The AKAI’s *layout* composition keeps control dimensions physically and perceptually separable: a knob and a key can be reasoned about and acted on independently, so a performer already has all the information needed to control the instrument before any haptic feedback is added. In this setting, feedback that conveys additional information is redundant; feedback that reinforces the felt connection between gesture and sound is not. P6’s and P8’s convergence on tying haptic and audio mappings into a single congruent signal reflects exactly this.

The Linnstrument’s *merge* composition collapses position, pressure, and release velocity into a single sensing point, producing, per Jacob et al., integral interaction dynamics: a performer cannot easily isolate “how hard am I pressing” from “where am I pressing” through proprioception alone. P4’s pitch-bend struggle and P2’s pressure-isolation strategy both describe this disambiguation problem directly, and Augmented feedback is the response to it. The T-Stick’s *connect* composition produces a more acute version of the same problem: because gestures like “jab” are computed from fused IMU and FSR streams rather than read off a single sensor, performers have no proprioceptive access to the instrument’s interpreted state at all, only to their own raw motion, hence the unanimous Augmented preference reaffirmed from [8]. This acuteness is reflected descriptively as well: T-Stick Augmented designs used a higher median frequency (200 Hz) than the Linnstrument’s (150 Hz), consistent with a steeper need for perceptual salience as proprioceptive access to control state diminishes further.

This suggests a structural hypothesis rather than a per-instrument rule of thumb: the more a control surface’s composition obscures a legible mapping between what a performer’s body is doing and what the instrument registers, the more its haptic design should lean Augmented; the more that mapping stays legible, the more it should lean Inherent.

B. Implications for Smart and Networked Instrument Design

This hypothesis is most useful at exactly the moment IoMusT and SMI designers face it: before an instrument is built [1], [2]. Adding wireless connectivity or networked control typically increases an instrument’s effective dimensionality (additional sensor streams, remote parameters, multi-performer state), pushing many SMIs toward integral or connect-composed control regardless of their original form factor. Our framework suggests this structural shift should itself be read as a cue to favor Augmented strategies, surfacing connection status, latency, or remote-performer state through touch rather than a screen a performer cannot consult mid-performance. Conversely, designers retrofitting haptics onto already-separable, layout-composed smart instruments (e.g., a networked MIDI controller) may gain less from informational feedback and could benefit from the audio-congruent, embodiment-enhancing approach our AKAI participants converged on unprompted.

C. A Design Heuristic for IoMusT Practitioners

Synthesizing the structural account in Section V-A with the parameterization patterns in Section IV-E, Table IV offers a practical starting point for designers adding vibrotactile feedback to a new IoMusT or SMI device: identify the instrument’s dominant composition type using Card et al.’s framework, then select a strategy and parameter range accordingly. We emphasize this as a starting point for iterative design rather than a substitute for it, as P4’s Linnstrument data show (Section IV-C), an individual performer’s mental model can shift

TABLE IV: Design Heuristic for IoMusT Haptic Feedback

Composition (Card et al.)	Interaction Dynamics (Jacob et al.)	Suggested Strategy	Suggested Parameters
Layout	Separable	Inherent	Low frequency (80–180 Hz, Mdn 122 Hz); short duration; audio-congruent envelope (e.g., ADSR matched to sound)
Merge	Integral	Augmented	Mid frequency (100–270 Hz, Mdn 150 Hz); continuous or threshold-triggered; exponential decay
Layout + Connect	Integral (emergent)	Augmented	Higher frequency (100–300 Hz, Mdn 200 Hz); combine discrete event cues with continuous state cues

a structurally integral instrument toward a more separable, Inherent-favoring experience in practice.

VI. LIMITATIONS AND CONCLUSION

This study’s findings are primarily exploratory: three participants per instrument is sufficient to surface a consistent directional pattern but not to establish it statistically, and the first author’s dual role as toolkit designer and session facilitator may have shaped which designs participants felt able to pursue. Furthermore, because participants worked only with their familiar DMIs, instrument type and user background are confounded, a limitation a within-subjects design, with each participant working on multiple instruments, would resolve. The Sonic Touch Toolkit’s own architecture, built around assembling new signals rather than passing audio through directly, may also bias participants toward more elaborate designs than they would otherwise choose, as P4’s comment in Section IV-C suggests. Finally, because the heuristic was derived from the same designs it summarizes, it has yet to be tested independently. Future work should validate the structural hypothesis proposed here with larger, independently-coded samples across a wider range of SMIs. In particular, researchers should assess whether performers presented an unfamiliar instrument’s control structure, without a design session, anticipate needing the strategy our framework assigns to it.

We find that a DMI’s control structure, characterized through Card et al.’s composition types and Jacob et al.’s separable/integral interaction dynamics, was associated with whether performers favor Inherent or Augmented vibrotactile feedback. Discrete, layout-composed controls favor Inherent feedback that reinforces embodiment; integral or connect-composed controls favor Augmented feedback that supports navigation and state awareness. Extending our prior single-instrument findings on the T-Stick [8] to two structurally distinct controllers suggests this may be a structural pattern rather than an instrument-specific one, offering IoMusT and SMI designers a structural heuristic for haptic design decisions that currently have no principled guidance.

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