Augmenting IoMusT Devices with Haptic Feedback: Design Tools and Strategies from Expert T-Stick Performers

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***Abstract*—Internet of Musical Things (IoMusT) devices, such as wireless musical interfaces, often lack the haptic feedback inherent to acoustic instruments, which creates challenges for accurately controlling musical output and engaging in embodied interaction. This limitation is particularly pronounced in IoMusT contexts, where complex sensor fusion and networked collaboration require enhanced state awareness. We present a systematic investigation of vibrotactile feedback design for the T-Stick, a wireless musical interface that has been in use for nearly two decades. Through exploratory design workshops with three experienced T-Stick performers using the Sonic Touch Toolkit, we examined how musicians conceptualize and implement haptic feedback for gestural control. Our findings reveal three distinct haptic feedback strategies: (1) sensor state indication, (2) patch state communication, and (3) inter-musician communication. Our work offers design strategies for integrating vibrotactile feedback into other smart digital instruments, demonstrating the potential for haptically enhanced gestural controllers for networked performers, state synchronization, and pedagogical tools for technique development.**

***Index Terms*—vibrotactile feedback, haptic interaction, digital musical instruments, performer sensing, two-way musical interfaces, T-Stick**

I. Introduction

The trajectory of Digital Musical Instrument (DMI) design reveals an evolution from unidirectional controllers to bidirectional interactive systems. Early augmented instruments focused on *sensor-based augmentation* to capture nuanced performance gestures for controlling external sound processes [1]–[3]. A shift came with *actuator-based augmentation*, with one approach focusing on repairing the lost haptic channel on digital instruments that are inherent to acoustic instruments [4]. This established a two-way interaction, where the instrument not only sensed the performer's input but also 'responded' in a way that fit the performer's mental model [5]. Our work investigates a different approach to using actuation not for sonic modification, but as a dedicated channel for conveying abstract information, a key capability of what Turchet et al. [6] define as Smart Musical Instruments.

This paper presents three distinct strategies for vibrotactile augmentation to aid the design of IoMusT devices. Whilst the literature has largely focused on the technical implementation and quantitative impact of vibrotactile feedback, we believe there is a gap in understanding how expert performers would choose to design and implement it for their own DMIs and practice. Through a set of exploratory workshops, we present a set of performer-derived haptic feedback strategies that support the notion that integrated haptic feedback can serve as a non-visual channel for cognitive support and networked collaboration.

The following is organized as follows: Section II reviews related work on haptically augmented DMIs and introduces the T-Stick instrument. Section III describes the Sonic Touch Toolkit and the mapping modules developed for this study. Section IV details our validation study methodology, including the workshop design and analysis approach. Section V presents our findings, organized around three distinct haptic feedback strategies identified through the workshops. Section VI discusses the implications of these strategies for gestural control and haptic feedback design in IoMusT contexts. Section VII outlines limitations and future research directions, and Section VIII presents our conclusions.

II. Background

A. Haptically Augmented DMIs

The advancement of DMIs has revolutionized the sonic landscape, offering a near limitless palette of synthesis and mapping combinations. Digital instruments are no longer bound by the physical limitations of acoustic sound production, however this physical decoupling has come at a cost of this coupled haptic system. The vibration of string and the resonance of the body of an acoustic instrument provide a constant stream of tactile information that musicians use to guide and refine their performance [7]. In DMIs, this haptic gap between performer's action and its sonic result can pose challenges for expressivity and control [8].

Research into restoring or creating new forms of haptic feedback in DMIs has evolved along two primary branches, distinguished by the function of the actuation.

The first, Sonically-Focused Actuation, uses actuators to directly generate or modify the haptic feedback based on the instruments output. This type of feedback can be perceived as task-intrinsic, i.e. it naturally arises from the task itself such as plucking the string on a guitar and feeling the corresponding vibrations through the body of the instrument. Some examples include the Daïs [9], a hand controlled physical bowed string model, allowing users to feel the audio output directly through a voice coil attached to the underside of the pressure plate. The Viblotar [10] DMI was built to examine the effects of vibrotactile feedback on the feel of a digital instrument. It featured two speakers embedded in the body of the instrument, facing outwards to prioritize sound projection.

A second branch, Information-Focused Actuation, which uses the haptic channel to convey abstract information to the performer. This type of feedback provides additional information beyond, or not intrinsic to, the musical task itself. Young et al. provided a functional analysis categorizing haptic feedback's role in motor guidance, state awareness, and error feedback [11]. For example, the GestoLumina DMI [12] featured haptic rings worn on the fingers, through which the performer could feel rhythmic patterns sent by accompanying musicians wearing the same rings.

Our research builds upon this second branch. While these studies provide valuable insight into technical implementation details and quantitative value of haptic feedback, a gap remains in understanding the haptic design process from the performer's perspective in collaboration within their own complex performance systems.

B. The T-Stick DMI

The T-Stick is a gestural musical interface that has been in continuous development since its creation in 2007 [13].The T-Stick has progressively integrated all five core SMI capabilities defined by Turchet's [14] framework through continuous development, culminating in the 5th generation T-Stick 5GW with its custom ESP32-S3 board for enhanced IoT connectivity and reliability.

The T-Stick exemplifies what Card et al. [15] describe as a connect composition structure, where distributed sensors (inertial measurement unit (IMU), force-sensitive resistor (FSR), capacitive touch-sense) are computationally fusing data from these distinct sensors to interpret holistic gestures rather than discrete control actions. While some mappings might be direct (e.g., raw FSR pressure to volume), most gestures on the T-Stick, such as 'jab', 'brush', 'rub', are achieved by mapping the output domain of the physical sensor (the raw data streams from the IMU or the capacitive strip) onto the input domain of the gesture recognition algorithm. The *connect* composition structure results in an instrument where the control signals are often not tied to one specific sensor's direct output, but are emergent from the user's complex gestural interact to control the sound. This complexity presents a unique opportunity for haptic feedback to aid the user in navigating the gestural control space.

In order to explore the applications of haptic feedback in the context of smart musical instruments, an actuator was retrofitted inside the body of the instrument. A 52mm Tectonic voice coil actuator (VCA) was selected for its wide bandwidth ensuring it would not constrain the vibrotactile feedback designs, and relatively low cost (∼$20USD). The 5th generation T-Stick feature removable side panels [16], which allowed the VCA to be easily glued inside the tube, and the wires thread out of a hole drilled at end of the T-Stick.

III. Sonic Touch Toolkit

Developed in Max/MSP, the Sonic Touch toolkit facilitates the rapid prototyping of audio-driven vibrotactile haptic effects The toolkit was introduced at NIME 2024 [17], and since then there has been further development to make mapping haptic design to instrument control parameters and performance gestures. The toolkit is built around a module architecture, with an emphasis on clean and simple user interface components. A vibrotactile effect is prototyped within the *Editing Buffer*, with the aim of allowing users to refine their haptic designs within a single "workshop space". Within the editing buffer, a vibrotactile effect is defined by a number of meta parameters: haptic event length (milliseconds), amplitude, number of repetitions, and delay between repetitions. The user is able to select from a number of predefined parameters, or enter custom values.

The toolkit's flexible architecture proved valuable for investigating haptic feedback strategies in smart musical instruments. The toolkit's existing mapping modules, particularly the Scale module, was able to accommodate the T-Stick's OSC-based communication protocol without modification, which enabled mappings between T-Stick sensor outputs (FSR pressure, IMU orientation, gesture recognition) and haptic effect parameters.

Along with the original haptic design modules, three mapping modules were developed. The first is the *Filter* module, which acts as a selective filter that only passes a value from inlet to outlet on a matching condition. The module has two inlets: the first for specifying the match criteria (such as a MIDI note number control change (CC) channel), and the second inlet for the value to pass through (such as MIDI note velocity or CC value). This allows the user to isolate specific MIDI values. The second addition is the *Trigger* module, which simply outputs a bang through the left outlet if the incoming message is greater than zero, and a bang through the right outlet when zero. This allows haptic effects to be triggered just on key press or key release. Finally, the new *Scale* module maps the incoming value to a specific range. The scaled value can be outputted through the left outlet (to be mapped for example to the amplitude or frequency of an oscillator module). Alternatively, trigger points can be set along the range of the incoming value, which will output bangs through the right outlet (for the triggering of buffer modules).

IV. Expert Validation Study

The workshops were based on a similar methodology by West [18] who took an exploratory approach to investigate how skilled music technology users devised mappings between an audio synthesis patch and a 4th generation T-Stick.

Three experienced T-Stick performers participated in individual workshops. As users of the T-Stick generally design their own custom synthesis patches, participants in the workshop were encouraged to connect their own synthesis patch to inspire ideas for the haptic feedback in their own musical contexts.

Participants were seated at a desk with the T-Stick, and a laptop running the Sonic Touch Toolkit patch in Max/MSP. The T-Stick was connected to an amplifier to power the embedded actuator, and the amplifier connected to the laptop through the 3.5mm headphone jack.

At the beginning of the workshop, the participant was asked to fill out a questionnaire detailing their musical background, experience with DMI development, and familiarity with haptic feedback and design. The questionnaire also includes a question of tactile feedback importance in DMI design (5-point Likert Scale), which was asked again in the post-workshop questionnaire.

The design stage lasted 60 minutes, with the participant free to stop the design session early if they felt they had achieved their goals. Participants were also advised that there was no "right or wrong" way to approach the vibrotactile designs and mappings. During this stage, video of the toolkit interface, toolkit audio, and conversation audio were recorded to track the participant's design processes.

Following the design stage, participants were asked to reflect on their vibrotactile design experience in an open-ended discussion. This was followed by a post-workshop questionnaire which consisted of 6 Likert Scale questions. These questions sought to quantify the impact of the vibrotactile feedback on the DMI, and to assess the ease of use of the Sonic Touch toolkit in achieving the participant's goals.

Recording of participant's use of the Sonic Touch toolkit was watched while taking notes of how participants utilized the toolkit's design and mapping modules to achieve their goals. The design stage audio recording was also transcribed and time-stamped. Workshop audio was transcribed and time-stamped, and the screen recordings of toolkit in use were synchronized with transcripts. This was followed with line-by-line coding to identify: (1) design decisions, (2) stated rationales, (3) expressions of satisfaction/frustration, and (4) conceptual models of haptic functionality. Design decisions were categorized by intended function, revealing three primary categories: sensor-focused, algorithm-focused, and communication-focused feedback.

V. Findings

A. Participant Response Overview

T-Stick users were overall very positive to the addition of vibrotactile feedback. Post-workshop questionnaires showed

Statement	**P1**	**P2**	**P3**	**Overall**
Enhanced DMI Expressiveness	3	4	5	4.0
Enhanced Direct Engagement	5	2	5	4.0
Sonic Touch Toolkit Ease of Use	5	4	5	4.7
Satisfied with Feedback Design	5	5	5	5.0
Design Process Enjoyability	5	4	5	4.7
Tactile Feedback Importance (Pre-workshop)	4	2	3	3.0
Tactile Feedback Importance (Post-workshop)	4	3	5	4.0

TABLE I: Post-Workshop Questionnaire Ratings (1-5 Likert Scale)

high ratings for enhanced expressiveness (M=4.3) and direct engagement (M=4.7). The perceived importance of tactile feedback increased from an average of 3.0 pre-workshop, to 4.0 post-workshop when they were asked the same question, indicating that the workshops had a significant positive impact on the participant's perception of vibrotactile feedback. This positive sentiment is reflected in comments about subjective feelings and perception when using vibrotactile feedback. Participants described feeling a stronger connection to the instrument, with two participants ascribing this to a heightened level of control the vibrotactile feedback was enabling:

> *It's now a two, two way controller, which just conceptually is, is so cool. ...the idea that the computer can also talk to us, guide us, let us know something the two way, the back and forth, yeah, conceptually, kind of change the change the thing for sure.* (P1)

> *I think, like the informative part would help me with the expressiveness, because even if I don't really like this word, but expressiveness is, in fact, a lot about control, but very fine control... It's like you, you know where you are, what you're doing, and you're able to do like, some subtle variations, some more subtle things.* (P2)

P3 articulated how vibrotactile feedback transformed their conceptual model of the T-Stick from a simple controller to an embodied instrument:

> *It definitely it makes me feel like the T-Stick kind of fits better in my mental model of what the T-Stick is when I when I think about it... and like having that vibration, it's not so much just like waving a tube around.* (P3)

The shift towards viewing the T-Stick as a bidirectional communication device reflects the strength of vibrotactile feedback to enable coordination in networked scenarios.

B. Strategy 1: Sensor State Indication

The first haptic strategy address a fundamental challenge in IoMusT systems: providing sensor state information when visual feedback is limited or absent. P2 identified a key challenge of dealing with continuous sensors in gestural controllers:

> *[Haptic feedback] could be applied to the FSR, because it's very hard to have a feeling of the actual values. It's very hard to say if you are at 80 or 90%,*

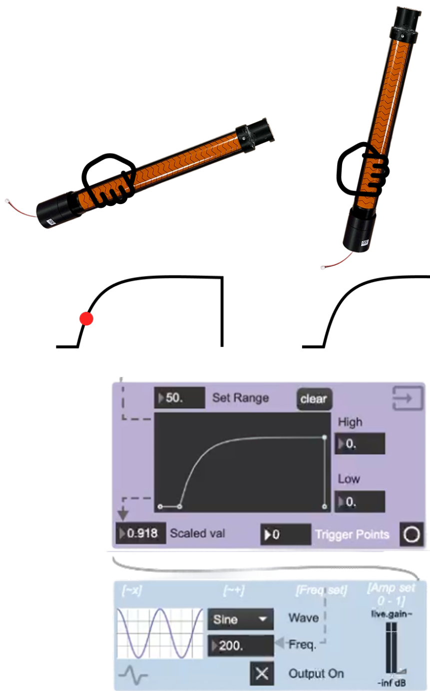

Fig. 1: Gyroscope data mapped to increase in vibrotactile feedback as user moves away from vertical orientation (P1).

It's very hard to feel it. To have the feedback to say okay, you are getting close to this threshold. (P2)

To address this, P2 designed a haptic effect using a mix of discrete pulses and continuous feedback to signal when their pressure on the FSR was approaching a predefined threshold. P3 likewise described interested in creating vibrotactile feedback to provide control-level detail of the T-Stick's gyroscope for pedagogical purposes. P3 mapped the amplitude of a sine wave at 200Hz to indicate when the user was moving away from vertical orientation (Figure 1).

I would be really interested next to do something with continuous value, maybe in terms of almost pedagogy kind of thing, like, let's say I want to practice having it super vertical... imagine you have a class of young T-Stick players, and they need to all be kind of in this range. (P1)

In both cases, the performers used haptic feedback to translate a digital data stream into a perceptible physical sensation, thereby enhancing their awareness and fine control of the instrument.

C. Strategy 2: Patch State Communication

The second strategy moves beyond raw sensor data to provide feedback about the state of the synthesis patch itself. For example, P3, whose patch triggered different musical events based on the duration of an FSR press, developed three vibrotactile designs to provide feedback on the length of time the FSR was pressed (Figure 2), a single pulse for the first interval and a double pulse for the second. The third haptic

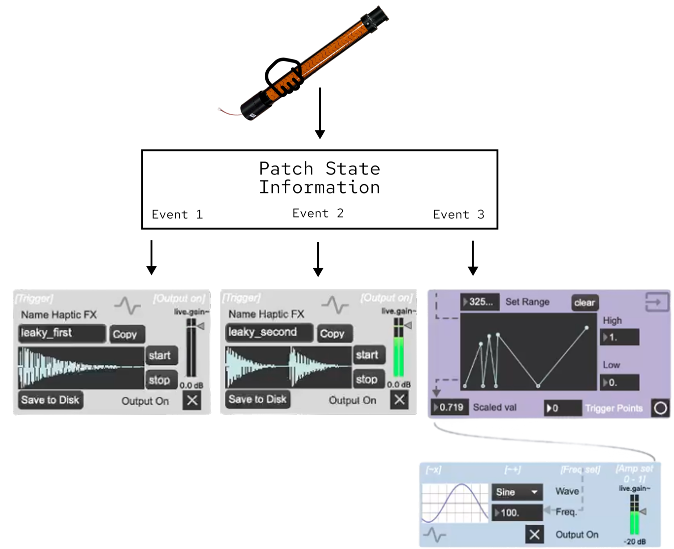

Fig. 2: Vibrotactile feedback to give user information regarding patch state (P3).

design featured a Scale module envelope with 4 peaks, each larger than the previous which scaled the amplitude of a sine wave set to 100Hz, providing continuous feedback to the user as they held down the FSR. This provided clear, non-visual confirmation of the patch's internal logic. In the post-workshop interview section, P3 further theorized how this strategy could be essential in even more complex performance contexts, such as monitoring the state of their multi-channel, agent-based patch:

I do think that having a haptic effect to that would be good to like know what presets I'm using, because, in theory, I should be able to identify them by ear, but we're smashing 24 objects in an eight channel panner down to stereo... when I do have to do something in stereo or in mono, all those kind of haptic effects would help me better, kind of distinguish all that from the general like muck. (P3)

This patch state information directly addresses what Wessel & Wright [19] identify as the performers memory 'burden' of keeping track of an algorithm's state at any given time. The authors proposed a visual aid as a solution, yet they acknowledge that looking at a computer screen for the entire performance is far from ideal. Therefore, as the internal mappings or sonic output of a patch becomes more complex, the haptic channel emerges as optimal, uncluttered medium for providing the performer without the distraction of a screen.

D. Strategy 3: Inter-Musician Communication

The third strategy conceptualizes the haptic channel as a means for silent, direct communication between musicians. P1 who described using haptic feedback as a communication protocol that could supplement traditional musical cues in collaborative performance.

> *I'm really interested in kind of silent communication with with our patches and stuff, and even with other collaborators. And so, you know, a T-Stick player being able to do some kind of combination of moment or whatever that can be communicated silently to another player, meaning like, "oh, let me start something", or, "oh, follow me." Or "begin the next section". You know, this is really something that interests me.* (P1)

This strategy re-frames haptic feedback not just a tool for self-monitoring, but as a social and collaborative medium. This is especially important in networked performance scenarios, where musicians may not be able to visually communicate with each other. In his work on mediated communication, Whittaker [20] explains that when a technology filters out one communication channel, other behaviors can substitute for the absence of that information. P1's vision for a haptic system is a direct example of such a substitution. Through this silent communication channel, musicians may achieve shared understanding without having to "over-elaborate" their primary musical expressions.

VI. Discussion

A. Gestural Control and Haptic Feedback

The first strategy presented, sensor state indication, offers a direct solution to the challenge of what O'Modhrain frames as a performer's 'sense of control' in the face of mapping complexity [7]. As P1 stated, it is very difficult for performers to have precise control of continuous sensor values, such as the FSR on the T-Stick. By providing discrete haptic cues at key thresholds, performers can build a more accurate mental model of the instrument's state and thus reduce the cognitive load that Turchet identifies as a key design consideration for SMIs [21]. P1 explicitly associated the informative benefits of the haptic feedback to a feeling of enhanced expressiveness and control: "*I think it helps in the end, having a finer control...It's like you, you know where you are, what you're doing, and you're able to do some subtle variations, some more subtle things*". This highlights that haptic cues are not just an important feature for the experienced performers, but a useful tool for making complex gestural instruments more learnable and controllable for beginning musicians.

The second strategy, patch state communication, addresses the complexity often arising from networked instruments. P2's desire for haptic cues to distinguish between presets in a complex multichannel patch highlights the limitations of relying solely on auditory feedback. In the post-workshop interview, P2 described how haptic feedback improved the experiential feeling of playing the T-Stick: "*It does improve the feeling of playing, I will at least say, and I feel like I'm more aware of what's happening other than just like the usual [state]*". Our findings show that integrated haptics provide a powerful, non-visual, and embodied enhancement to SMIs, allowing performers to receive crucial system information without breaking musical immersion.

Finally, the third strategy of inter-musician communication, addresses a key challenge in networked performance, namely 'communication deficit' caused by unreliable visual cues over high-latency networks [22]. P1's vision for a "silent communication" channel to cue collaborators supports the theory of mediated communication, which predicts when one channel is filtered out by technology (visual), users will find ways to substitute for the missing information (with haptic cues) [20]. By integrating this communicative function directly into the instrument, our participants envisioned a more embodied and unified system for collaboration, advancing a key goal for interconnected musical systems.

VII. Limitations & Future Directions

A. Limitations

Our study only involved three expert T-Stick performers, which limits the generalizability of our findings. Whilst the three participants provided rich insights into the applicability of haptic feedback in their own performance context, a larger cohort would be needed to validate the universality of the proposed design strategies across different performer backgrounds and skill levels.

This research focused solely on the T-Stick, therefore repeat study with other IoMusT devices would be necessary to assess its applicability to devices with different form factors, sensor configurations, and interaction paradigms. Keyboard based devices or percussion based interfaces may reveal interestingly differing strategies not captured in this study.

Finally, the workshops were conducted in a controlled laboratory setting rather than an authentic performance environment. Because of this, participants envisioned the potential usefulness of the haptic feedback without the opportunity to validate it in a performance context.

B. Future Directions

The findings from this study open several promising avenues for future research. This includes experimentation with haptic cues on the T-Stick in a collaborative performance context to study the specific inter-musician communication cues that P1 envisioned. This may involve developing further Sonic Touch toolkit modules to send haptic cues over a network to other haptically enabled devices, and designing standardized haptic "vocabularies" for common musical cues. The implementation of Strategy 3 (inter-musician communication) would require robust IoMusT networking protocols. Future work should explore integration with OSC-based wireless frameworks or the libmapper protocol for distributed device mapping [23] to ensure reliable, low-latency haptic message transmission across distributed performers.

The sensor state indication strategy suggests that future research could further explore the pedagogical applications of haptic feedback. This could include haptic cues to teach students timing accuracy and gesture consistency without the need for potentially distracting visual feedback.

VIII. Conclusion

This study presented advancements to the Sonic Touch toolkit with the goal of analyzing how expert performers conceptualize and implement haptic feedback for a gestural instrument, the T-Stick. Through a series of exploratory workshops, our findings identified three distinct design strategies: sensor state indication, patch state communication, and inter-musician communication. This study underscores the importance of including performers in the design process so we can develop the next generation of embodied, "two way" smart musical instruments.

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