

TESI: A Toolkit for Tangible and Embodied Sound Interaction

Francesco Di Maggio
Industrial Design
Eindhoven University of Technology
Eindhoven, Netherlands
f.di.maggio@tue.nl

Mathias Funk
Industrial Design
Eindhoven University of Technology
Eindhoven, Netherlands
m.funk@tue.nl

Bart Hengeveld
Industrial Design
Eindhoven University of Technology
Eindhoven, Netherlands
b.j.hengeveld@tue.nl

Rebecca Fiebrink
Creative Computing Institute
University of the Arts London
London, United Kingdom
r.fiebrink@arts.ac.uk

Abstract

Sound offers unique affordances for interaction designers, enabling immediate, embodied, and expressive experiences. Yet sound is often treated as peripheral, limited to simple notifications rather than being explored as a central design material. Designing meaningful auditory feedback typically requires low-level programming, audio-specific expertise, and fragmented toolchains that hinder early-stage experimentation. We present *TESI (Tangible and Embodied Sound Interaction)*, a modular toolkit that reduces these barriers by combining sensor-integrated hardware, open-source middleware, and a visual programming environment for real-time sensor-to-sound mapping. TESI enables interaction designers to prototype adaptive soundscapes across networked tangible interfaces with minimal setup. We describe the toolkit's architecture, illustrate its use through examples, and discuss future directions for embodied sound design in distributed systems.

CCS Concepts

• **Human-centered computing** → **User interface toolkits**; • **Applied computing** → **Sound and music computing**.

Keywords

Tangible, Embodied, Distributed, Networked, Sound, Interaction

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1 Introduction

Sound is increasingly recognized as a critical dimension in interaction design, offering embodied, spatial, and immersive qualities that complement visual and haptic modalities. Despite this potential, sound is often considered an afterthought, limited to sample

playback and alerts rather than being explored as a central design material.

Designing meaningful sound interactions typically requires specialized audio expertise and dedicated toolchains—barriers that may limit experimentation in early design stages. These challenges primarily affect interaction designers who want to integrate sound into their projects but lack sufficient technical knowledge to do so.

Furthermore, as interaction design moves towards more networked and embedded applications (commonly referred to as the Internet of Things), sound is no longer the predictable outcome of I/O mappings but rather something that is emergent. Therefore, designing for distributed systems creates not only technical challenges but also systemic complexity [16]: coordinating multiple devices, managing latency, and creating coherent sonic behaviors across distributed systems of smart objects. This complexity is both an engineering concern and a design challenge: how can sound support emergent behaviors across multiple devices and operate as a shared material rather than as isolated outputs?

To address these challenges, we developed TESI (Tangible and Embodied Sound Interaction), a bespoke modular toolkit for exploring sensor-to-sound mappings. TESI targets interaction designers who want to explore sound through physical and tangible modalities [2, 7], rather than being confined to on-screen GUIs. Applications can range from multi-room sound installations to designing smart-home adaptive soundscapes and accompanying everyday interactions. The main goals of TESI are:

- (1) Enable designers (including those with limited or no experience in sound design) to “almost immediately” explore expressive sound mappings in an embodied way, i.e., by physically manipulating the TESI modules;
- (2) Support in-situ design and exploration, i.e., in the context in which the sound design occurs, instead of having to move to a sound studio, by physically attaching the TESI modules to the environment (or oneself);
- (3) Provide a platform for exploring emergent sonic behaviors across networked tangible interfaces;
- (4) Enable exploration of multidimensional distributed mappings through interactive machine learning techniques.

We describe the motivations behind TESI, detail its hardware and software components, and illustrate how the toolkit can be used in practice. We demonstrate how TESI supports design with sound



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in physical, networked, and embodied contexts. Finally, we outline future directions and provide open-access repositories containing code, hardware files, and documentation to support continued development and reuse within the TEI community.

This work *contributes*: (a) a modular toolkit for tangible and embodied sound interaction that integrates distributed sensing, networking, and parameter mapping within a unified framework; (b) design rationale detailing implementation choices, constraints, and trade-offs in creating distributed sound-centered systems; and (c) open repositories containing hardware schematics, firmware, and example modules to enable reuse and further development.

2 Motivation & Related Work

Sound has received increasing attention in HCI and TEI research, particularly through work on tangible musical interfaces, sound interaction design, and networked audio systems. Early examples such as ReacTable [9], PebbleBox [11], and CrumbleBag [11] established sound as a medium for real-time embodied interaction, emphasizing the integration of gesture and sound within spatial and interactive contexts. The field of Sonic Interaction Design [3, 12] has provided the conceptual and methodological foundations for designing interactive sound in everyday contexts. Studies have shown how sonic feedback can support perception, action, and navigation, contributing to a wider understanding of sound as a primary design material [4]. Locative and mobile audio systems have further explored how sound structures spatial experience and participation [3, 6]. Research on networked music systems has addressed the technical and conceptual challenges of distributing sound across connected devices. Studies on the Internet of Musical Things (IoMT) [14–16] describe the requirements for latency handling, synchronization, and data exchange in wireless audio networks.

However, this body of work reveals a persistent challenge: while the conceptual frameworks for sound interaction are well established and the technical infrastructure for networked audio continues to advance, there remains a significant gap in accessible tools that enable designers to prototype and explore distributed sound interactions during early design stages—to actually explore the form of and interaction with sound in the moment. Current platforms tend to either require specialized technical knowledge, isolate one from the design context, or limit the broader adoption of sound as an integral design material.

3 TESI Toolkit

TESI¹ is a modular toolkit that supports tangible and embodied sound interaction as a distributed system. It enables interaction designers to manipulate sound directly in their design context, linking gestures, materials, spatial relationships, and auditory outcomes.

TESI consists of three main components: (1) a hardware device integrating multiple sensors, (2) middleware for network communication, and (3) software for real-time sensor-to-sound mapping.

A TESI system commonly consists of 5 to 10 hardware devices, one middleware layer, and one mapping component. Each component can be independently configured and connected to external hardware or software. Designers can integrate additional sensors

while preserving the communication protocol and mapping, or develop sounds using external platforms. Multiple TESI boards are networked together and form a distributed system, either used as standalone devices or distributed across multiple locations.

The current work focuses on establishing the technical and interaction foundation, with embodied form factors to be systematically explored in future research phases.

3.1 Hardware

TESI is built on the Adafruit ESP32 Feather V2, chosen for its built-in Wi-Fi capabilities, compact form factor, and compatibility with diverse sensor modules.

The board functions as an integrated sensing platform, embedding multiple input types within a single unit (Fig. 1): motion sensing (BNO055 IMU), proximity detection (VL53L3CX Time-of-Flight), ambient light measurement (LDR), capacitive touch (MPR121), audio input (MAX4466 microphone preamp), and continuous control (potentiometer). A LiPo battery connector enables wireless and mobile use. This configuration allows designers to prototype interactions involving movement, touch, and environmental sensing without requiring additional hardware. Multiple TESI boards can be networked together to support distributed interaction scenarios.

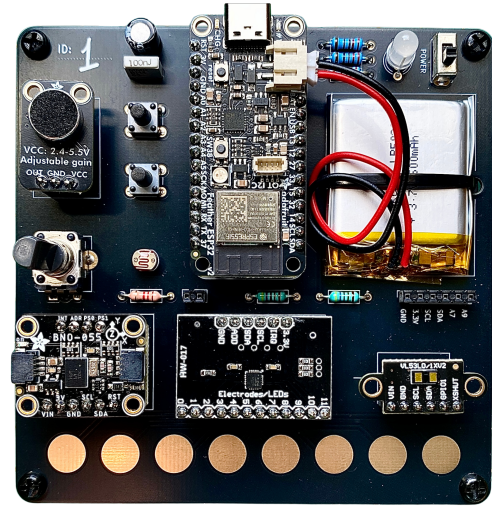


Figure 1: The TESI hardware.

3.2 Middleware

TESI uses OOCISI² (Out of Control for Semantic Interactivity) for real-time cross-platform data exchange, addressing key limitations of traditional protocols like OSC³ (Open Sound Control). While OSC requires predetermined target addresses and relies on client-side message filtering, OOCISI implements a client-server model over TCP that allows devices and software clients to publish and subscribe to named channels [1].

¹<https://github.com/francesco-di-maggio/tesi>

²<https://oocsi.net/>

³<https://opensoundcontrol.stanford.edu>

Features such as *channel presence* enable the system to detect when devices join or leave the network, which is essential for maintaining coordinated behavior in distributed setups. OOSI supports multiple environments, including Processing, Arduino/ESP, Python, and JavaScript, ensuring flexibility and integration.

3.3 Software

TESI operates within a networked architecture in which each device streams sensor data wirelessly to a host computer or other devices (Fig. 2). For sensor-to-sound mapping, we use *Max⁴*, a visual programming environment that operates by connecting functional blocks rather than using text-based code. Max is particularly well-suited for rapid prototyping of sound interactions, enabling designers to experiment with different mappings between sensor data and sound parameters in real-time. We developed a custom OOSCI communication module⁵ for Max to streamline the integration between sound synthesis platforms and the TESI hardware through dedicated output protocols, such as MIDI⁶.

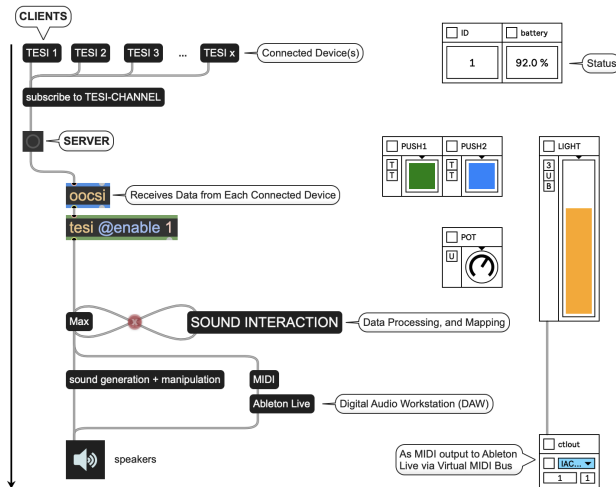


Figure 2: End-to-end data visualization pipeline from sensor acquisition to sound mapping and playback.

Unlike traditional OSC/MIDI setups that typically implement direct sensor-to-sound mappings on a single device, TESI is designed not only to explore sound for single devices but also for networks of devices. As such, TESI allows designers to explore the emergent soundscapes of the Internet of Things, as the modules interconnect and share data through a networked architecture. This distributed approach enables sensor data from one module to influence sound synthesis parameters derived from another module, creating emergent interaction possibilities.

3.3.1 Mapping. *Mapping* defines how sensor input translates into sonic output, representing the core of any interactive sound system [8]. The mapping process defines the interaction logic between

⁴<https://cycling74.com>

⁵<https://github.com/francesco-di-maggio/oocsi-max>

⁶<https://www.midi.org>

gestures and auditory feedback: how can movement, proximity, or light conditions translate into perceptible changes in sound?

Well-designed mappings influence how intuitive and responsive an interaction feels and shape how users understand and explore the system [10]. TESI enables flexible, real-time mapping between sensor data and sound parameters across networked devices.

Unlike traditional systems where mappings are constrained to individual devices, TESI’s distributed architecture allows any sensor parameter from any connected device to control sound synthesis anywhere in the network. Mappings can range from direct relationships (e.g., turning a knob to control pitch) to complex multidimensional structures, including cross-modulation, conditional logic, and dynamic layers. The system supports preset storage for quick configuration switching, enabling designers to adapt interactions for different contexts or user groups.

TESI supports multiple mapping strategies (Fig. 3):

- *Direct*: e.g., tilting the board directly modulates pitch.
- *Combined*: e.g., proximity modulates both reverb and sample playback speed.
- *Conditional*: e.g., touch triggers envelopes or mode changes.
- *Distributed*: e.g., multiple devices control sound spatialization or generate chords.

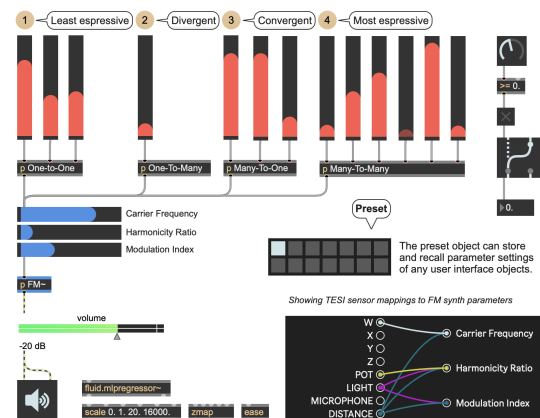


Figure 3: Examples of interaction behaviors between physical sensor input and sonic output.

The toolkit provides input possibilities that enable different modes of interaction, including continuous control, discrete triggers, or threshold detection (Fig. 4).

Beyond traditional mapping, TESI integrates interactive machine learning techniques to support dynamic and exploratory workflows. Using the FluCoMa toolkit [13], we implemented regression-based models to map multi-dimensional sensor data to sound synthesis parameters in the style of Wekinator [5]. This approach allows designers to “teach” the system through example interactions rather than predefining specific mappings, enabling the discovery of novel interaction patterns through exploration of the mapping space.

3.3.2 Sound. Within TESI, sound is treated as a manipulable material for exploration. As the primary synthesis engine, we use *Ableton*



Figure 4: Example modes of interaction: covering light sensor, tilting the board, and connecting the board to the environment.

*Live*⁷, a digital audio workstation (DAW) that offers a flexible environment for real-time control of sound synthesis modules and audio effects. In our implementation, sensor data from TESI devices is acquired and processed in Max, mapped to sound parameters, and then transmitted to Live via MIDI.

While Ableton Live offers a rich sonic palette, TESI remains platform-agnostic: designers can use any (audio) environment that supports OSC or MIDI, such as Apple’s Logic Pro or GarageBand, TouchDesigner, Unity, or Pure Data, as well as Processing and even web-audio platforms like strudel.cc.

To maintain design flexibility, we intentionally avoid prescribing specific sound design methodologies at this stage of development. Instead, we encourage designers to explore creative approaches suited to their particular contexts and artistic visions.

4 Future Work & Conclusion

Sound has long been recognized as a rich and expressive medium for interaction. Yet its integration into tangible and embodied systems remains technically challenging and often peripheral to design workflows. Existing sound prototyping tools are typically fragmented and require specialized knowledge, which limits sound exploration in early-design stages.

TESI addresses these gaps by contributing a modular toolkit that treats sound as a first-class design material. By combining sensor-integrated hardware, open-source middleware, and a visual

programming environment for sensor-to-sound mapping, TESI enables interaction designers to prototype adaptive soundscapes with minimal expertise.

Looking ahead, our first priority is to evaluate the TESI platform in action. To date, we have conducted an informal evaluation of TESI during a one-day workshop with 8 HCI researchers, and we are currently conducting two experimental case studies: one aimed at exploring the platform’s opportunities and limitations through a smart-home sound design scenario and the other aimed at better understanding how users with different levels of expertise navigate the system. We see several opportunities to expand the capabilities and accessibility of TESI. These studies will examine the experiential qualities that emerge when multiple interconnected modules create coupled sonic behaviors, as well as inform how we can further lower barriers while maintaining expressive control.

At this stage, TESI is an early prototype, and many aspects remain open for exploration. One promising direction is the modularization of the hardware platform. Currently, the TESI board is a platform-agnostic, single-unit system with multiple on-board sensors. We designed it this way intentionally to allow fellow designers and researchers to discover which physical shapes prove meaningful through use, rather than prescribing a particular interaction modality from the outset. Designing appropriate physical forms is planned as structured future work through co-design sessions.

A long-term development involves embedding sound synthesis directly onto the hardware platform. This approach would eliminate

⁷<https://www.ableton.com>

laptop dependency and enable distributed networks in which TESI boards autonomously connect, share sensor data, and generate sound locally. Our ambition is to develop TESI so that designers can not only embed sound into interactive environments but also access sound design in a direct and embodied way, giving shape to sound as the malleable and rich design material that it is.

These directions reflect our commitment to modularity and reusability, ensuring that TESI evolves into a sustainable and adaptable platform for tangible and embodied sound interaction. By lowering technical barriers and providing accessible tools, we aim to encourage broader exploration of sound as a central material in interaction design.

Documentation, schematics, and examples are available in our open repositories⁸⁹.

GenAI Usage Disclosure

In accordance with the ACM Policy on the Usage of GenAI, we disclose that no generative AI tools were used to produce or analyze data, generate or modify source code, or create any research artifacts. All technical content, figures, code, and data were conceived, developed, and validated by the authors.

Ethical Standards

All participants were informed about the purpose and nature of the workshop and gave their voluntary consent to participate. No personally identifiable information was collected, and all data were anonymized and used exclusively for research purposes.

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